BEYOND TRADITIONAL BOUNDARIES: REGIONAL AND GLOBAL DIMENSIONS OF NATIONAL WATER RESOURCE MANAGEMENT

A Thesis Submitted to the
College of Graduate and Postdoctoral Studies
In Partial Fulfillment of the Requirements
For the Degree of Doctor of Philosophy
In the Department of Civil, Geological, and Environmental Engineering
University of Saskatchewan
Saskatoon

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Abstract

This thesis introduces a framework that aims to support decision-making for enhanced water and food security, while adopting the understanding that water and food sectors are becoming increasingly unrestricted to specific borders or boundaries due to the globalization of resources and the interdependencies among the water, food, and other sectors. This framework is used, with some modifications, in three different applications that are presented in three respective peer-reviewed articles.

The first article introduces a novel framework, called the national water, food, and trade (NWFT) modelling framework, that consists of two components: a national model that simulates the supply and demand of water and food on a national level, and a data-driven international virtual water (food) trade model that captures national virtual water exports and imports associated with trade in agricultural and animal products. Egypt is used as a case study for the application of the NWFT framework, with the national water and food gaps evaluated for a baseline period (1986–2013) and projected up to 2050 based on four national development scenarios. Results indicate the alarming situation of Egypt's projected food gap by the year 2050, by which time food imports are projected to have to increase on average by 200% compared to 2021 values. The NWFT framework was able to successfully simulate the effect of water use and various socioeconomic variables, including population growth rate, on Egypt's historical food and water gaps. The framework could be easily adopted for other countries and regions.

In the second article, the NWFT framework is modified to be an optimization-simulation framework and is presented as a multi-objective approach that aids policymakers in water-food security assessment and management while taking into account the major non-agricultural water uses associated with national development scenarios, the globalization of resources through the food trade, and the performance of the proposed solutions under possible national and global changes. The framework is formulated to minimize the agricultural water demand, food imports, and economic cost of imports as well as maximize the national gross margin of agriculture. Egypt is considered as the case study, with a set of alternative cropping patterns generated and evaluated for the baseline period (1986-2013) as well as under future conditions up to the year 2050. The results show the framework is useful for proposing cropping patterns that could have worked better for Egypt during the baseline period, but also cropping patterns that outperform

the historical cropping pattern in each objective function for a wide range of future conditions.

In the third article, the water-food assessment framework is expanded in its sectoral representation to include hydropower generation as the most relevant component of the energy sector. The framework is configured for a regional case study of the Eastern Nile Basin (ENB) countries of Egypt, Sudan, South Sudan, and Ethiopia, and set to simulate the ENB's water resources, food production, and hydropower generation as a water-energy-food (WEF) nexus. The framework is calibrated and validated for the period from 1983 to 2016, then utilized to project a wide range of future development plans up to the year 2050. Four measures are used to evaluate the performance of the WEF nexus under each of these plans. A thematic pathway of development in the region that shows high potential for mutual benefits is identified and analyzed under several combinations of future social and climatic changes. Results show the ENB countries can reach significantly better food security conditions before 2050 and can generate an additional 42000 GWh/year of hydropower without significantly diminishing the downstream (Egypt) water scarcity problem. WEF performance measures of the ENB countries are significantly sensitive to climate change; however, under low population growth rates the climate change impacts on WEF security are less severe.

Acknowledgements

First and foremost, I would like to praise Allah [God] the Almighty, the Most Gracious, and the Most Merciful for His blessing given to me during my study and in completing this thesis.

I would like to express my gratitude to my supervisor Dr. Amin Elshorbagy for his valuable feedback, commitment, and constructive and timely reviews throughout the course of my PhD. I also could not have undertaken this journey without my thesis committee, I have been inspired by their long record of distinguished contributions to knowledge, special thanks to Dr. Howard Wheater, Dr. Mohamed Elshamy, and Dr. Lawrence Martz. I am grateful to Dr. Chris Hawkes for his efforts and support as the committee chair.

My appreciation is extended to my colleagues at the CANSIM lab for their peer support and valuable discussions that contributed directly and indirectly to improving my research work. I want to acknowledge my managers and peer engineers at Clifton Engineering Group Inc, for providing me the opportunity and support to develop my engineering skills while doing my PhD studies. I would like to acknowledge the devolved scholarship of the University of Saskatchewan granted to support my PhD program. In addition, the financial support for this research from the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Discovery Grant Program (# RGPIN-2019-04590) and the NSERC-DG grant # 403047 are much appreciated.

I would be remiss in not remembering my mother Omayma Kassem, my father Mohamed R. Abdelkader, and my sister Menna Abdelkader. Their unconditional love, support, and patience have kept my spirits and motivation high at several hard times throughout my PhD program, especially during the uncertain times of the COVID-19 pandemic.

Dedication

This work is completely dedicated to my respected parents and my sister whose constant support and prayers bring me help and comfort throughout my work and life.

In honor of my uncles, Sobhi and Farouk Abdelkader, who always believed in my ability to be successful in research. You are gone but your belief in me has made this journey possible. May Allah (God) grant them a place in Jannah (heaven).

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Chapter 1 Introduction

1.1 Research Background and Motivation

1.1.1 Water and Food Systems Integration

Water and food security are inseparable, especially in arid and semi-arid areas. Agriculture, which includes the production of various crops and commodities, is responsible for the largest proportion of global water use, with 70% of all freshwater appropriated for human use allocated to irrigation (Rosegrant et al., 2009). Although sufficient water is available to meet current global food needs, 10% of the global population suffers from chronic nutritional issues because they live in areas characterized by physical and/or economic water scarcity with diminished water and food accessibility (FAO, 2019). The United Nations declared access to clean water as a human right in 2010, but the right to water in the context of food is a complex issue. While drinking and cooking water is protected, water for food production is not. Major changes in water and food management and policies are required to ensure the best use of water resources to meet global water and food demands (World Water Assessment Programme, 2009).

The management of water and food systems is challenging because water and food demands are continuously growing due to population and socio-economic growth, while the supply is constrained by resource and capital availability (Boretti and Rosa, 2019; Jackson et al., 2001). For several regions (CIESIN, 2020), the supply does not meet the demand, which results in ever-widening water and food gaps. This leads to serious issues that hinder development, stress the economy, and impact the population’s well-being (Jägermeyr et al., 2016). Climate change exacerbates the problem as it may further widen these gaps by increasing the water and food demands while further reducing the supply (Wheeler and Von Braun, 2013). Accordingly, efficient management may need to close these water-food gaps by adopting integrated resource management approaches (Jägermeyr et al., 2016) that promote sustainable enhancement of the supply while moderating and controlling the demands, while considering uncertainties of different exogenous factors, in particular climate change (Delabre et al., 2021; Brown and Funk, 2008).

Energy is also an essential pillar that integrates with the water and food sectors to sustain human existence and support development. Significant amounts of energy are required for water pumping, transmission, treatment and desalination, and as an input to agriculture and food production processes. Reciprocally, the food and water sectors contribute to the energy sector. Some crops that humans and animals consume for food are used to produce energy (i.e., biofuels), and water is used for hydropower production and for cooling in thermal power stations. The water, energy, and food sectors also have interlinkages with many other sectors like manufacturing, fishing, navigation and transport, tourism, and the ecosystem (Venghaus and Hake, 2018). Such interlinkages can be explained through a contemporary example of the drought that impacted the Rhine in 2022, resulting in reduced water levels in the river. This hampered shipping of food and fuel to Germany, and restricted power generation in France due to cooling water reduction (Toreti et al., 2022). The major interdependencies between the water, energy, and food sectors, among other sectors, are now well recognized, as is the importance of their holistic management as one integrated system of systems. This is because managing each sector in isolation might result in undiscovered negative impacts on the other sectors (Dhaubanjar et al., 2017).

In this context, several integrated approaches have been proposed. In particular, the water-energy-food (WEF) nexus approach has attracted interest from policy and research communities (Khan et al., 2022; D'Odorico et al., 2018; Kurian, 2017). Different studies have developed WEF nexus frameworks and methodologies that differ in terms of their scope, objectives, and conceptions. The Qatar Environment and Energy Research Institute conceptualized a water-food nexus framework that focuses on resource scarcity and interlinkages to produce and import food, with no consideration given to interlinkages with other sectors (e.g., energy) or the ecosystem (QEERI, 2012). The United Nations Economic Commission for Europe introduced a methodology to assess the WEF-ecosystem nexus in transboundary rivers. In this method, the nexus is conceptualized as a chain of cause-effects and linear linkages that describes the connections between human decisions, environmental degradation, and availability of resources (UNECE, 2013). Smajgl et al. (2016) criticized static WEF assessment frameworks and illustrated the importance of considering the dynamic changes of WEF sectors and critical drivers such as population and climate. Akinsete et al. (2022) focused on the human agent within the WEF nexus, reflecting on the importance of understanding and representing the socio-cultural, economic, institutional, and decision-making dimensions while developing WEF nexus frameworks. Several studies presented improved resource use efficiency as an approach to promote WEF security and sustainability (Ringler et al., 2013; Samberger, 2022).

The WEF nexus approach was conceptualized to address global issues and was pursued in several research studies that introduced theoretical WEF frameworks and methodologies (Uen et al., 2018; Meza et al., 2015; Karabulut et al., 2016; El Gafy et al., 2017; Ravar et al., 2020; Molajou et al., 2021; Moghadam et al., 2023; Allam and Eltahir, 2019). However, further efforts are required to translate WEF nexus understandings into implementable regional and national management methods and policies that promote states of synergies and minimize the tradeoffs among the three WEF sectors (Wu et al., 2021; Benson et al., 2015; Scanlon et al., 2017).

1.1.2 Water and Food Systems Beyond Jurisdictional Borders

Managing the WEF nexus is more challenging in international transboundary river basins because the dynamics and interlinkages among sectors cross jurisdictional borders. Each riparian country is under pressure to maximize the utilization of shared resources to meet its increasing WEF demands. In several transboundary basins, this usually triggers conflicts over shared resources that are not easy to resolve (Bernauer, 2002). Addressing conflicts in a WEF nexus approach is advantageous, especially because a WEF nexus promotes the notion that conflict resolutions do not necessarily align with the planning objectives of a single sector or country. Instead, it encourages broader planning methods, such as equitable tradeoffs among WEF sectors, synergistic thinking, promoting shared benefits, and cooperation rather than conflict (Cai et al., 2018; Al-Saidi and Hefny, 2018).

Resource sharing in the context of transboundary basins has a limited spatial extent, but global food trade has led to significant resource sharing on a much wider scale. This has become more obvious over the past century, when improved means of agricultural food production and wide trade liberalization policies led to an exponential increase in global food trade fluxes (Ercsey-Ravasz et al., 2012). This also represented a significant increase in virtual water trade volumes (i.e., the water consumed to produce traded food products; Dalin et al., 2012).

Importantly, the global food and virtual water trade formed complex and dynamic networks, where countries with food/water surpluses export to countries with food/water gaps; this plays an important role in improving global food and water security (D'Odorico et al., 2019). Nonetheless, some negative consequences at the local and regional scale accompanied this rapid growth of the food/virtual water trade. The large dependence of poor, developing countries on the global trade market has left them susceptible to the risks of food shortage and disruptions when global trade is impacted by shocks; clear examples are the 2008 global crisis, the 2019 COVID-19 pandemic, and the 2022 war between Russia and Ukraine (Udmale et al., 2020; Câmpeanu, 2022). Furthermore, for some of those countries, if importing food becomes cheaper than producing it, the country may transition its agricultural labor force to other jobs with impacts on employment and socio-economic development, which sometimes leads to political unrest (Hendrix and Haggard, 2015).Serious food trade-related environmental impacts have been reported, e.g., elevated CO_2 emissions from increased animal production for export, and from the growing transportation of different traded products (Deng et al., 2016; Vora et al., 2017). Dalin et al. (2017) also showed how some countries unsustainably exploited their local water resources to boost their food production and export to the global market for short-term economic gain.

Regional resource sharing in the context of transboundary basins adds complexity to WEF management. Globalization of resources through food (virtual water) trade has resulted in a displacement of resource use and created connections between humans and the remote resources on which they rely. It is prudent to approach WEF nexus management while considering such transboundary complexities and connections with the global market and trade networks. Understanding the interactions and interdependencies between local, regional, and global dynamics can lead to better management, targeting reduced risks and fewer negative impacts (Carducci et al., 2021; Ortiz et al., 2021; Leventon and Laudan, 2017).

1.2 Research Gaps

This thesis contributes to the large body of literature on WEF nexus management by addressing two major research gaps. The first gap pertains to the lack of incorporation of the dynamics of the global water-food system into local (e.g., national) water-food management practices. Over the past decades, several global models were developed, primarily to project global impacts of climate change, but more recently, these models were used to study the global water-food management (Havlík et al., 2018). Global models have played an important role in understanding the current global water-food systems and in providing prospects of global water-food security (Robinson et al., 2015; Miralles-Wilhelm and Muñoz, 2017; Ermolieva et al., 2015; Deppermann et al., 2019; Ermolieva et al., 2021). These models can simulate the global water-food demand, supply, and trade between countries, driven by various socio-economic and climatic variables, and subjected to resources scarcity (Schull et al., 2020). However, for computational efficiency, they typically incorporate simplified and coarse representations of the local water-food systems (Calvin et al., 2019). These simplifications make these models unattractive to be used by local decision-makers who are interested in managing water-food at a finer-detailed level (Dermody et al., 2018). On the other side, the local models that decision-makers use to manage the fine water-food systems are usually constrained to specific jurisdictions/ borders with a limited to no considerations of the interactions with global water-food systems (MWRI, 2001; Zhang et al., 2020). This makes the two categories of models, and their users, function in isolated silos. Given the increasing connectivity between global and local water-food systems, driven by globalization of resources and food trade, it is crucial to address this gap for more effective water-food management practices (D'Odorico et al, 2018; Snyder et al., 2020). This could be achieved, either by enhancing the global models' representations of local systems for specific area(s) of interest (Valin et al., 2013; Dermody et al., 2018), or by integrating global and local models within a comprehensive framework that explores their similarities, discrepancies, and interlinkages. This thesis aims at accomplishing this integration, allowing to bridge this gap between global water-food modeling efforts and local water-food management decisions.

The second gap is related to the need for a comprehensive regional WEF nexus management framework for transboundary areas. There are several WEF nexus assessment frameworks that have been developed for local scales (e.g., sub-watersheds and countries; El-Gafy, 2017; Basheer and Elagib, 2019; Allam and Eltahir, 2019). This type of frameworks provides useful insights to local decision-makers, revealing WEF management decisions that result in tradeoffs or synergies (Han et al., 2020). However, in a given region that contains several countries, building a fragmented group of local frameworks provides limited insights regarding the regional scale WEF nexus, which is particularly significant in transboundary regions (Kibaroglu and Gürsoy, 2015). In a transboundary setup, where several countries utilize shared resources, managing the WEF nexus of individual countries in isolation may result in undiscovered adverse conditions for the other countries. In several cases, this potentially result in political tensions and even conflicts (Zeitoun and Mirumachi, 2008). Therefore, it is important to develop regional WEF management frameworks for transboundary regions lacking such frameworks, aiming to maximize the benefits for the region as a whole and to reduce the tradeoffs and conflicts between countries, which is achieved in this thesis.

1.3 Thesis Objectives

The overall goal of the thesis is to demonstrate the need for integrated resource (e.g., water, food, energy) management that is not constrained by traditional system boundaries and jurisdictional borders, and to develop a framework for implementing this understanding. This goal is addressed through the following two objectives:

- Objective 1: To investigate the links between global food market/trade networks and water resources management at the national scale. This will elucidate links between local water management decisions and global water and food dynamics and will also allow for an assessment of national water resources under various national and global changes.

- Objective 2: To evaluate the value added of managing water, energy, and food sectors within a multi-sectoral approach at the regional (multiple countries) scale. This will consider the benefits of regional cooperation to improve WEF security as an approach to addressing the problem of limited and conflicted shared water resources in an international transboundary river basin.

1.4 Case Study

Water and food security challenges might be different from one country to another. In this study, the focus is on countries that have root causes for water and food insecurity and chronic and pronounced water scarcity conditions. In this regard, Egypt, as one of the most arid countries in the world, was selected as a representative case study for the first objective. Intuitively, the Nile Basin becomes the logical choice to scale up from the national to regional scale; it is an international transboundary river basin with multiple socioeconomic challenges, including conflicts over water resources. In this study, the Eastern Nile Basin (ENB) was selected as the case study for the second objective of the thesis. More details on the study areas and the rationale for their consideration are provided in the following two sub-sections.

1.4.1 Egypt

Egypt is located in northeast Africa and has a total land area of 1×10^6 km^2, 94% of which is uninhabited desert and the remaining 6% is cultivated agricultural and urbanized land (Figure 1.1). The country is one of the driest on Earth with irregular rainfall averaging 50 mm/year. Internal water resources are very limited. The country's share of the Nile River flow is 55×10^9 m^3/year (United Nations, 1963), which provides 97% of Egypt's freshwater resources. A high population growth rate of 2% is increasingly stressing Egypt's scarce water resources, resulting in a low per capita renewable water share of 532 m^3/year (CAPMAS, 2021) that is under continuous decline. Throughout history, Egypt's agriculture has played a significant role in securing food for the Egyptian people. Currently, 94% of cultivated land is used for food production, and a significant portion (83%) of the country's scarce water resources is allocated to the fully irrigated agricultural system (MWRI, 2010). Egypt's agricultural land area is 9.2 million Feddan (Feddan = 0.42 ha; MWRI, 2010), mainly in the Nile valley and Delta, which is subjected to annual reduction due to urbanization. The substitution and new expansions usually occur by cultivating less fertile lands outside the Delta and the Nile valley. In recent decades, several important policies and decisions were implemented, leading to an improvement in crop yields and a significant increase in national food production (Hazell et al., 1995). Concurrently, the country enhanced its internal water availability, by increasing the reuse of drainage wastewater and increasing withdrawals from shallow and deep groundwater aquifers.

Nonetheless, the agriculture sector is still significantly constrained by water availability and is incapable of fulfilling the rapid increase in national food demand due to population growth. This has led to rapidly growing food (virtual water) imports. Egypt currently depends heavily on imported food, with the country now one of the world's biggest importers of wheat (imports cover 50% of its wheat consumption; FAO, 2021). Population growth in Egypt has a compound effect on water and food security: from one side, it increases the demand for water and food; and from the other side, population growth increases the water use for municipal and industrial uses, hence, it reduces the availability of water for agriculture, and reduces food production. This creates continuously expanding water and food gaps (i.e., difference between supply and demand; Wichelns, 2001) and makes Egypt a good example of a country with a complex water-food nexus.

Improving water and food security in Egypt for the future will be challenging as it might require increasing water availability. However, the potential for increasing internal water resources in a hyper-arid country like Egypt is very limited, where the drainage wastewater reuse and groundwater use are nearly maximized, and desalination, with the current technologies, is still economically infeasible to be used on a wide scale for agriculture. Increasing external water resources through the transboundary Nile flows is complex, as it is an issue lying at the heart of a difficult debate and diplomacy, given the growing competition over the utilization of the Nile water resources among all riparian countries (Swain, 2011). Egypt's dependence on food imports could alleviate the water-food security problem; however, it comes with high risks associated with domestic and global economics (e.g., price shocks) and global trade reliability and stability concerns. Egypt's rapidly growing population, aridity, the effects thereof on national water and food security, combined with the increased dependency on the global food trade market, make the country an ideal case study for the first objective of this thesis, which is to investigate the link between global food (virtual water) trade dynamics and local water-food management decisions.

1.4.2 Eastern Nile Basin Countries

The ENB region includes four countries (Egypt, Sudan, South Sudan, and Ethiopia) located in northeastern Africa with a total area of 4.6 million km^2. Characteristics of regional water, food, and energy systems are different among the four countries. Water resources in the region mainly center on the Nile River (Figure 1.1), which connects the four countries and sustains the livelihood of more than 50% of their populations. The Nile starts its journey at Lake Victoria, Uganda, flows through the ENB from South Sudan to Sudan, and then ends at Egypt. Along that course, several tributaries connect with the Nile, predominantly those that originate in Ethiopia and contribute 85% of its mean annual flow of 84×10^9 m^3/year. Ethiopia is the ENB's water-richest country, as it has the highest annual precipitation volume falling on its lands, in addition to 12 river basins, three of which connect to the Nile (Figure 1.1). South Sudan and parts of Sudan receive considerable amounts of precipitation but have no major rivers except the Nile and its tributaries. Although there is abundant water available in these three countries, access to it, especially for municipal uses, is notably deficient due to poverty and the absence of necessary infrastructure. Egypt is the water-poorest country in the ENB, but its population has better access to water resources. In the past 60 years, the ENB population has grown four-fold while renewable water resources did not change, resulting in increased water stress (Mekonnen and Hoekstra, 2016).

The high rainfall in Ethiopia, Sudan, and South Sudan allows them to produce most of their food from rainfed agriculture systems, while Egypt produces most of its food depending on irrigated agriculture. In the last 40 years, Egypt boosted its food production by adopting new technologies (i.e., fertilizers, soil enhancements, pesticides, use of highly productive strains of seeds, etc.) that significantly increased crop yields. In contrast, the other ENB countries mostly practice rainfed agriculture with much lower crop yields; as their agriculture lacks technology and is performed by poor farmers (Namara et al., 2008). Currently, Egypt's crop yield is, on average, two times higher than crop yield in each of the three other countries (FAO, 2021). Nonetheless, water scarcity results in Egypt suffering from widening water and food gaps. The remainder of the ENB is not doing any better; however, their food gaps can be attributed to the lack of technologies to enhance crop yield in addition to natural climate variability (Rockström et al., 2010). Egypt fills its food gap by importing food from the global market, while the low purchase power of the three other countries does not always permit this approach. Therefore, portions of their populations are left with unfulfilled food demands, resulting in malnutrition and occasional famines (Falkenmark and Rockström, 2004).

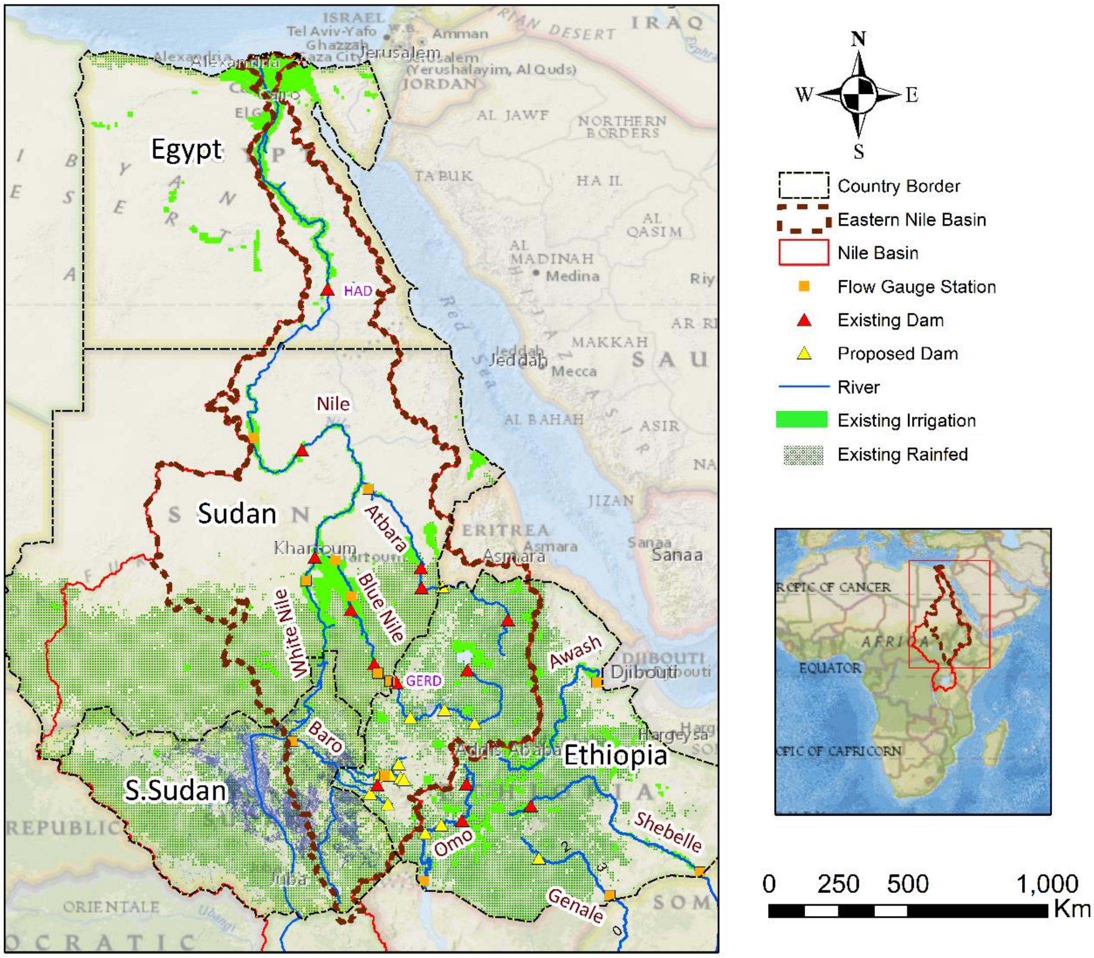

Figure 1.1: The study area of the Eastern Nile Basin countries.

Although the potential for energy production in the ENB is large, Egypt is the only country that has a high energy production that exceeds its demand, with the surplus exported; 100% of the population has had access to electricity since 2016 (World Bank, 2019). The three other countries of the ENB lack the capital and investments necessary for the production and distribution of energy, which leads to a significant energy deficit. South Sudan is the largest sufferer, with only 7% of its population having access to electricity, followed by 48 and 54% of Ethiopia and Sudan, respectively (World Bank, 2019). There is an immense necessity to improve the WEF conditions for the less fortunate portion of the 260 million people living in the basin, but also for the 170 million increase in population expected by 2050 (UN, 2015). This process might face many challenges; plans dependent on scarce resources (e.g., water) might contradict and result in adverse impacts on one sector or another, either within the same country or even across the ENB. A contemporary example is the huge hydropower dam (i.e., Grand Ethiopian

Renaissance Dam; GERD) under construction in an upstream tributary of the Nile (i.e., Blue Nile; Figure 1.1). The GERD has triggered objections and political tensions between Egypt and Sudan on one side and Ethiopia on the other. The future situation might become worse, and future conflicts are more likely to occur given the uncoordinated plans for building several other dams and withdrawing more water from upstream shared water resources. Therefore, there is a significant need to evaluate the benefits of managing the water, food, and energy sectors in an integrated manner and determine the potential to reduce tradeoffs and enhance synergies among sectors of one country and among the countries of the ENB as a region.

1.5 Thesis Layout

In the remaining part of this thesis, three chapters are dedicated to explaining and presenting the research conducted in accordance with the stated objectives. Chapters 2 and 3 are articles that were published in peer reviewed journals, Chapter 4 is a draft manuscript submitted to a peer reviewed journal for possible publication. **Chapter 2** introduces a framework developed for the assessment and improvement of water and food security, called the national water, food, and trade (NWFT) modeling framework. **Chapter 3** describes modifications to the NWFT undertaken to perform a multi-objective simulation-optimization that is suitable for the generation, analysis, and assessment of alternative cropping patterns in arid regions (ACPAR). This modified framework takes in consideration the dynamics and changes of global food conditions (production, consumption, and trade) while planning for national water and food conditions. ACPAR and the NWFT framework together address the first objective of this thesis. **Chapter 4** describes modifications to the NWFT framework to address the second objective of this thesis, in which the number of sectors was increased from only the water and food sectors to include the energy sector. The model was also configured for larger study area that includes all ENB countries instead of only Egypt. This modified NWFT framework was called the water, energy, and food nexus assessment framework (WEFNAF). It simulates the ENB's water, food, and hydropower sectors and was used to project future WEF conditions with the aim of identifying less conflicting development paths for the region. Chapters 2, 3, and 4 were written as manuscripts and submitted to relevant peer-reviewed journals to be published as scientific articles. The last chapter (**Chapter 5**) includes a summary and conclusions derived from the whole thesis, as well as the research contributions, study limitations, and recommendations for future research.

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Chapter 2 National Water, Food, and Trade Modeling Framework: The Case of Egypt

This chapter is a slightly modified version of the published article (Abdelkader *et al.*, 2018), modified to make it consistent with the format and body of the thesis. This chapter is the final accepted draft of the paper prior to copyediting or other production activities by the journal.

Citation: Abdelkader, A., Elshorbagy, A., Tuninetti, M., Laio, F., Ridolfi, L., Fahmy, H., & Hoekstra, A. Y. (2018). National water, food, and trade modeling framework: The case of Egypt. Science of the total environment, 639, 485-496. DOI: 10.1016/j.scitotenv.2018.05.197. This article was published under the creative commons license (CC BY-NC-ND 4.0), and the permission for article reproduction is included in Appendix A.1.

Authors Contributions and The Contribution of This Chapter to The Overall Study

The following are the contributions from the different authors of this (chapter) published manuscript. A. Abdelkader contributed to the conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing-original draft, and visualization. A. Elshorbagy contributed to the conceptualization, data curation, methodology, writing - original draft, supervision, and funding acquisition. M. Tuninetti, F. Laio, L. Ridolfi, and A.Y. Hoekstra, contributed to the conceptualization, writing - review & editing. H. Fahmy contributed to the writing - review & editing.

This chapter introduces a novel modeling framework for the analysis of real and virtual water side by side. This work addresses the first objective of this thesis and fills an important gap in global virtual water trade (VWT) modeling, in which a well-known category of VWT models, introduced in section 2.5, were improved such to preserve the global virtual water trade balance (i.e., the sum of global VW exports from all countries was not equal to the sum of global imports). Moreover, this chapter contributes to addressing a major research gap of incorporating the knowledge from extensive research done on global (food) virtual water trade modeling into the water management decisions taken on the national scale.

2.1 Abstract

This chapter introduces a modeling framework for the analysis of real and virtual water flows at national scale. The framework has two components: (1) a national water model that simulates agricultural, industrial and municipal water uses, and available water and land resources; and (2) an international virtual water trade model that captures national virtual water exports and imports related to trade in crops and animal products. This National Water, Food & Trade (NWFT) modeling framework is applied to Egypt, a water-poor country and the world's largest importer of wheat. Egypt's food and water gaps and the country's food (virtual water) imports are estimated over a baseline period (1986-2013) and projected up to 2050 based on four scenarios. Egypt's food and water gaps are growing rapidly as a result of steep population growth and limited water resources. The NWFT modeling framework shows the nexus of the population dynamics, water uses for different sectors, and their compounding effects on Egypt's food gap and water self-sufficiency. The sensitivity analysis reveals that for solving Egypt's water and food problem non-water-based solutions like educational, health, and awareness programs aimed at lowering population growth will be an essential addition to the traditional water resources development solution. Both the national and the global models project similar trends of Egypt's food gap. The NWFT modeling framework can be easily adapted to other nations and regions.

2.2 Introduction

The natural hydrological cycle and the diversity of climatic regions in the world result in an uneven distribution, spatially and temporally, of precipitation on land. Traditionally, societies relied on the engineering solution of constructing dams and creating artificial storage reservoirs to supply water-deficient regions with water at times of shortage. However, the engineering redistribution of water has a limited spatial impact when compared with the socioeconomic redistribution of water in its virtual form, which crosses national and continental boundaries. Water virtually embedded in products (Hoekstra et al, 2011) has its own human-induced cycle that can be seen as a socio-economic pendant to the natural hydrological cycle. People intervene on the hydrological cycle through water withdrawals from rivers, lakes and aquifers (i.e., blue water) and employing rainfall (i.e., green water) for agricultural production and other purposes. Through global trade networks (Dalin et al., 2012), virtual water flows along socioeconomic gradients, often from places of water surplus to places of shortage, sometimes reversely. Some countries even overexploit their water resources for economic gains through exports (Dalin et al., 2017). Globally, the large variability in water presence and the diversity of its use led to a global virtual water trade (VWT) network with bi-directional flows at every node – with each region being both a virtual water exporter and importer.

There is a significant body of literature on VWT (Allan, 2003; Hoekstra, 2013; Yang et al. 2006; Chapagain and Hoekstra, 2008; Hanasaki et al., 2010) and the development of VWT networks (Dalin et al., 2012; Suweis et al., 2011; Tamea et al., 2014). Most studies focused on the network structure and the variables controlling its behavior. For example, Dalin et al. (2012) found that the flows in the network can be reasonably explained with each nation's gross domestic product, mean annual rainfall, agricultural area, and population. Suweis et al. (2011) agreed with Dalin et al. (2012) regarding the importance of the gross domestic product and the annual rainfall. It was also concluded that the importing nations are expected to play an increasingly important role in the evolution of the future network dynamics. The increased connectivity of the global network highlights the risk of systemic disruptions and the resultant vulnerability of the global food supply, especially when exporting countries change to non-exporting at times of scarcity. Puma et al. (2015) suggested that this could happen in particular with regard to wheat and rice. The fact that over 80% of countries have low food self-sufficiency emphasizes the importance of investigating the VWT network and its future projections. The use of complex network theory (Barabási and Albert, 1999; Newman et al., 2006) to characterize the global VWT network has been the common approach used, along with probability distributions to describe the number and strength of trade links (Konar et al., 2011; Carr et al. 2012). While studying the VWT network, Konar et al. (2012) also distinguished the trade in blue and green water, and found that as countries attempt to increase their food export, they tend to utilize more blue water (irrigation). Tuninetti et al. (2015, 2017) noted that there is a significant spatio-temporal variability in the water footprint of major crops, which of course contributes to global water savings and losses as a result of VWT (Chapagain et al., 2006).

The gravity model of international trade, a multivariate regression approach to explain bilateral trade flows, is a common approach to explain the trade flows in a VWT network (Tamea et al. 2014). Acknowledging its potential contribution to understand the global redistribution of virtual water flows, this stand-alone global modeling approach, in its current form, cannot attract potential users and policy makers at scales where decisions are typically made. In order to be beneficial, virtual water trade information needs to better align to the needs of (water) resource managers and policy makers at the national scale (El-Sadek, 2010a; Wichelns, 2001), and VWT models need to be used in combination with water models typically applied at national level to inform water allocation decisions.

Numerous studies focused on VWT on the national scale. For example, Schyns and Hoekstra (2014) assessed the added value of including the analysis of VWT in a national water resources study for Morocco. Schyns et al. (2015) analyzed Jordan's water security in the light of its high domestic water scarcity and high reliance on virtual water imports. In a case study for Tunisia, Chouchane et al. (2018) analyzed VWT patterns in relation to environmental and socioeconomic factors. Mekonnen and Hoekstra (2014) assessed Kenya's water resources use and availability and how the country can mitigate its water scarcity by increasing imports of water-intensive products. Karandish and Hoekstra (2017) demonstrated the importance for national water policy formulation of considering both international and interregional VWT in a case study for Iran. Zhuo et al. (2016) developed water footprint and virtual water trade scenarios for China, considering five driving factors of change: climate, harvested crop area, technology, diet, and population. El-Gafy (2014) developed a model to estimate the water footprint of wheat produced in Egypt and crop-related VWT under different scenarios and found that water saving can be achieved as a result of VWT. Sallam (2014) used the water footprint as a concept to be a measuring tool for the equitable utilization of shared water resources of the Nile. Even though many studies on national VWT consider changes of water use and VWT over time, very limited studies combined the analysis of national water use dynamics and global trade dynamics (Sallam, 2014). Future scenarios of changing national VWT should be validated or put in the context of future global VWT scenarios.

Water resource management cannot be seen as something restricted to just one specific nation or river basin (Hoekstra, 2011). On the one hand, consumption of food and other products in a country usually translates to water demands elsewhere (related to imported products); on the other hand, water demand in a country that relates to producing export products, aggravates national water demand beyond what one would expect given the consumption pattern of the national population. Thus, water resources management on national scale should consider water in its entirety, i.e., in real and virtual forms.

Water-poor countries are in pressing need to manage their water needs (real and virtual forms), which demands an approach that goes beyond managing the nationally available water resources. The aim of this paper is to introduce a new modeling approach for the analysis and possible management of both real and virtual water at a national scale. This approach should have the ability to accommodate the notion that national water resources analysis is to be embedded in and put in the context of a global analysis of water resources availability. Therefore, it should be possible to assess the virtual water trade with the rest of the globe, and the projected changes in imports and exports under different national and global scenarios. We consider here the case of Egypt, a water-poor country, a major food importer (FAO, 2017a), and the world's largest wheat importer, to exemplify the development of a national water, food, and trade (NWFT) modeling framework. The framework includes a system dynamics model of national water-food supply and demand and a gravity model of international virtual water trade, running in parallel for analysis and comparison.

2.3 Virtual Water Trade Modeling: Challenges and Possible Solutions

Existing virtual water trade (VWT) models (e.g., Carr et al., 2013; Fracasso, 2014; Sartori and Schiavo, 2015) are mainly data driven, employing some logically governing variables (drivers) to characterize historical VWT. The VWT models capture the patterns of exports and imports. A conceptual concern regarding the models is that each virtual water flux between two nodes in the network (VWT from region *i* to region *j*) is typically estimated by two gravity models (Tamea et al., 2014): one demand-driven export model to estimate trade of country *i* to country *j*, and another supply-driven import model to estimate trade of country *j* from country *i*. Eventually, a single flux value can be estimated as the average of the two calculated values of the same flux (Tamea et al., 2014; Tuninetti et al., 2016). As a result of the approach, the models do not preserve the global food (or virtual water) balance, i.e., the sum of all regions' exports is not equal to the sum of all imports, although averaging the dual estimates improves the models' fit of the data.

In this study, we consider only one of the two estimates of the virtual water flux from node *i* to node *j*. The export model estimate was chosen, because it typically has higher R^2 values than the import model (Tamea et al., 2014). The estimated export from *i* to *j* is considered as the import of *j* from *i*. This is logically acceptable and eliminates the dual estimates issue. A food balance equation (tonne/y) can be written at each node as equation (2.1) shows:

$$PROD + IMP = EXP + CONS + LOSS + \Delta S \tag{2.1}$$

where PROD is food production, CONS food consumption, LOSS the food losses, ΔS the increase in food stocks, EXP the total food export, and IMP the total food import. Corresponding to the previous food balance equation is the following virtual water balance equation (Hoekstra et al., 2011), which was adopted at each node of the model:

$$\mathrm{WF_P + VW_{imp} = VW_{exp} + WF_C + WF_L + WF_S} \tag{2.2}$$

where WF_P represent the water footprint of national production, WF_C the water footprint of national consumption, WF_L the water footprint of food losses, WF_S the water footprint of stock increase, VW_{imp} the virtual water import and VW_{exp} the virtual water export (all balance components in m^3/y). The VWT model is explained in more details in Section 2.4 below.

2.4 The NWFT Modeling Framework and the Case Study

The national water, food, and trade (NWFT) modeling framework, consists of two parallel-running components (Figure 2.1). The first component, the national water and food (NWF) model of Egypt, estimates (i) food production and consumption and water consumption on the basis of national variables and available water resources, and (ii) then estimates the national food and virtual water trade through food and water balances. The second component, the global virtual water trade (VWT) model, characterizes the annual virtual water trade between

Egypt and the rest of the world, which is here grouped into nine regions. The following subsections provide more details on the modelling framework and background information about the case study of Egypt. The two models are not coupled, but rather running in parallel for the purpose of identifying discrepancies or issues at the global scale that might be worth attention from policy makers at the national scale.

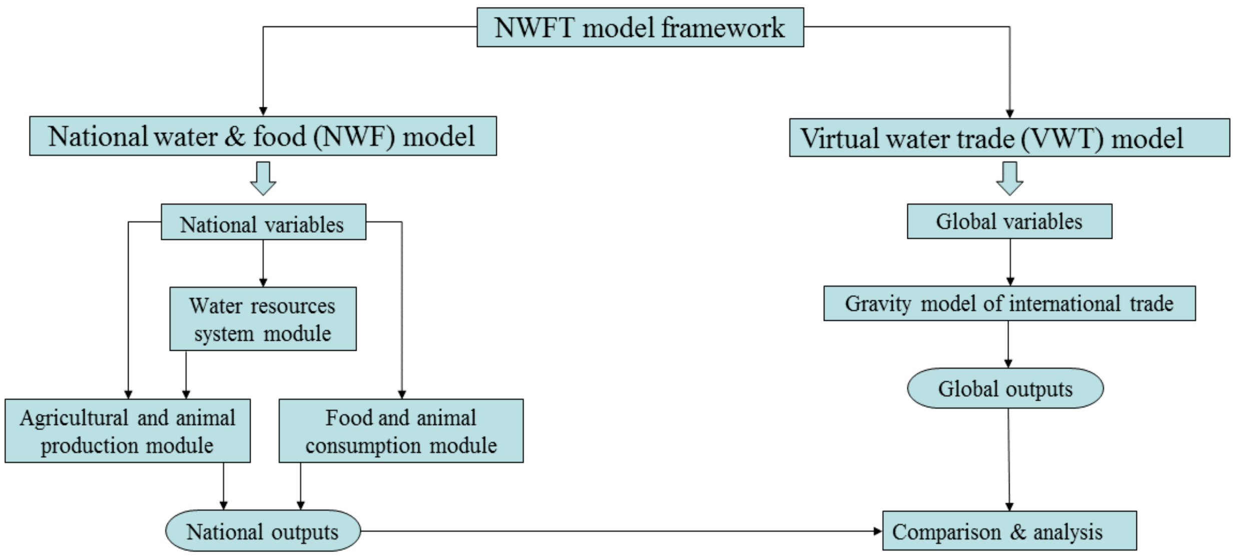


Figure 2.1: Simplified schematic diagram of the NWFT modeling framework.

2.4.1 Egypt: The growing Concerns Over Water and Food Security

Egypt is the most populous country in North Africa and the Middle East, with 92 million people in January 2017 and an annual population growth rate of about 2% (CAPMS, 2017). Egypt's large desert plateau is interrupted by the Nile Valley and Delta, which forms 4% of its 1 million km^2 area (FAO, 2017a) but is inhabited by 95% of the country's population.

The cultivated area in Egypt, surveyed in 2015 (CAPMS, 2017), is 9.1 million feddan (3.8 million ha). The agricultural sector employed about 25% of the country's manpower in 2016 (CAPMS, 2017) and contributed 14.5% to Egypt's gross domestic product, which was estimated in 2014 to be around US$ 287,000 million (FAO, 2017a). About 97% of the cultivated land is irrigated (El-Nahrawy, 2011; FAO, 2017a). Egypt imports about 40% of its cereals and exports some vegetables, citrus, dates, rice, and cotton. The water resources system in Egypt is unique; the country depends on the renewable water flowing into it from Nile Basin upstream countries for almost 97% of its water uses (FAO, 2017a), with internal rainfall and renewable groundwater contributing the remaining 3%. With its current renewable water resources, 630 m^3/y/capita, as in the year 2016, Egypt is already below the amount needed for being able to be food self-sufficient (Falkenmark, 1989). In 1959, Egypt and Sudan signed the Nile Waters Agreement that secures 55.5×10^9 m^3/y to flow into Egypt. This water, which sustains all forms of life in Egypt is controlled by the High Aswan Dam in southern Egypt. Figure 2.2 depicts the water resources of Egypt and their uses. According to the water balance of 2010 (MWRI, 2010), the agricultural sector annually receives 4.85×10^9 m^3 of water from shallow groundwater, which is recharged from the Nile and the surface irrigation system itself, 2×10^9 m^3 from deep groundwater, and 16×10^9 m^3 from drainage water reuse. The municipal and industrial sectors have higher priority than agriculture, so they are allocated water first.

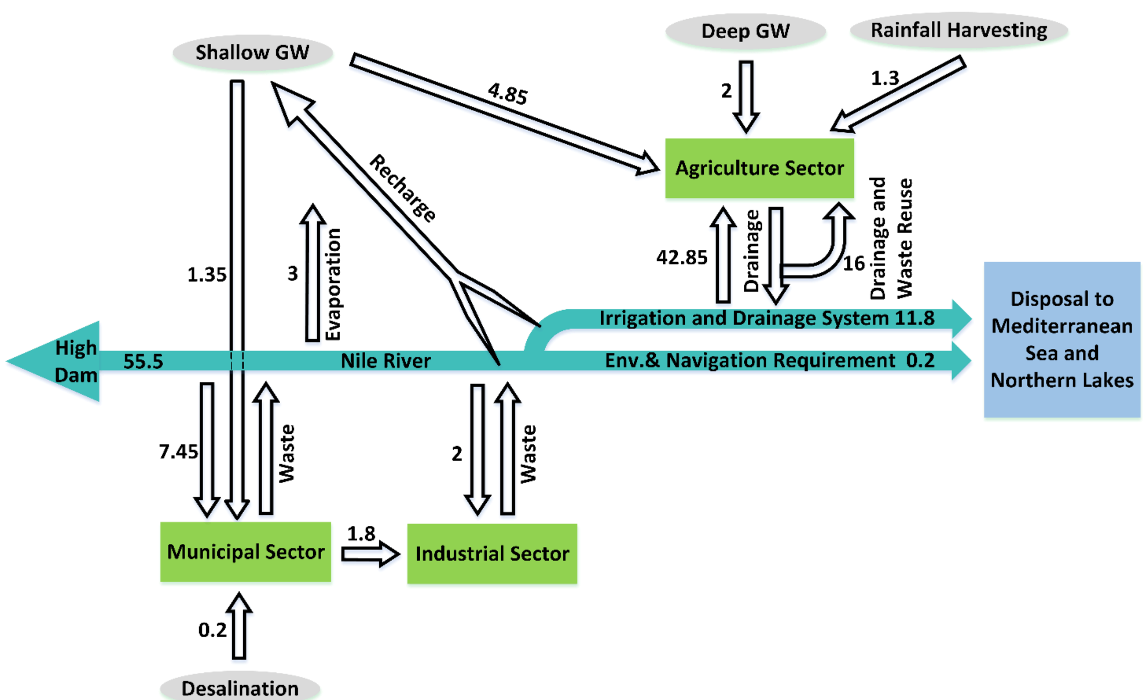


Figure 2.2: Water resources system in Egypt. All numbers are in 10^9 m^3/y. Source of data: MWRI (2010).

2.4.2 The National Water-Food Component in the NWFT Modeling Framework

The national water-food (NWF) model was built using the system dynamics approach (Ford, 1999), which uses stocks, flows, interactions and feedback loops to represent system elements and their relations. System dynamics has been used in modeling integrated water resources systems (Simonovic et al., 1997; Winz et al., 2009; Hassanzadeh et al., 2016a; 2016b) because of its ability to simulate natural and socioeconomic processes in one simulation environment. In this study, Stella Architect 1.4.3 (https://www.iseesystems.com) was used as the simulation environment. The NWF model runs with an annual time step and comprises three interlinked modules: (i) crop and animal production, (ii) food consumption, and (iii) water resources system.

2.4.2.1 Crop and Animal Production Module.

For a total of 78 crops (72 food crops, 3 non-food crops, and 3 fodder crops), harvested areas (ha) and yields (tonne/ha) were obtained per year for the period 1986-2013 from FAO (2017b). Egypt's annual production (tonne/y) per crop was calculated by multiplying harvested area and yield. The simple productivity function from Doorenbos and Kassam (1979) was used to modify yields under scenarios of water shortage:

$$\left(1-\frac{Y_i}{Y_{max}}\right)=k_i\left(1-\frac{CW_i}{CWR_{max}}\right) \quad (2.3)$$

where Y_i is the actual yield of crop *i*, Y_{max} is the maximum yield if the actual water available for the crop (CW_i) is equivalent to the crop water requirement (CWR_{max}), and k_i is a crop-specific yield response factor, available through FAO (2017b), representing the effect of a reduction in *water availability* on yield. Notably, the Y_{max} can be improved through technology, also CWR_{max} is subjected to variations according to climate conditions and technology improvements. We investigated the future uncertainty of these two variables as part of the uncertainty analysis explained in section 2.6.1.

Production of animal products was calculated with a similar approach used for crop production. Animal feed is the major component that contributes to the total water footprint of animal production. In Egypt, the major feed crop is berseem (Egyptian clover), followed by concentrate feeds that are mainly composed of grains. In the NWF model, a separation was made between food and feed to prevent duplication in calculations. Annual animal feed consumed per head was estimated as in Mekonnen and Hoekstra (2012) and the water consumed to produce this feed was then estimated based on the water footprint per unit of feed crop from Mekonnen and Hoekstra (2011). In addition, animals and animal products require drinking and service water (m^3/head), which was obtained for Egypt from Chapagain and Hoekstra (2003). Crop and animal production were added to obtain Egypt's total agricultural production (tonne/y). The production of food crops and animal products were added to get national food production (tonne/y). The way this production module was built allows for investigation and scenario analysis of individual products, if such details are needed. More details on crop and animal production module are provided in appendix B.1.1.

2.4.2.2 Food Consumption Module

The food crops and animal products considered in the consumption module of the NWF model are 81 items. This is more than those in the production module because of imported food products, which are consumed but not produced in Egypt. The consumed food mix (kg/y/capita) in Egypt was obtained from the food balance sheets by FAO (2017b). The national food consumption (kg/y) for each food item is calculated by multiplying the food consumption mix by annual population. The nutritional energy intake (kcal/day/capita) of the population is calculated by multiplying the nutritional value of each item (kcal/kg) by the amount of food consumed. This configuration allows for manipulating the food mix and consumption pattern, while keeping track of the calories intake. It was observed that the national average calories intake of the Egyptian population has been increasing with the gross domestic product and stabilized over the past few years at the level of 3,400 kcal/day/capita, which is similar to that of developed countries.

Green and blue water footprints (m^3/tonne) of crops and animal products consumed and produced in Egypt were obtained from Mekonnen and Hoekstra (2011, 2012), and then used to calculate the water footprints of production and consumption (m^3/y). Surplus (production in excess of consumption) or deficit (consumption in excess of production) were calculated and assumed to be equivalent to Egypt's exports and imports, respectively. The exports and imports were calculated in terms of product trade (tonne/y) and virtual water trade (m^3/y). The modeled imports and exports were compared with FAO records of Egypt's actual imports and exports.

The modules of production and consumption were configured based on the time series of Egypt's food balance sheet provided by FAO (2017b) for each year of the historical record (1986-2013), and no calibration parameters were needed.

2.4.2.3 Egypt's Water Resources System Module

The water resources system module is a national-scale water accounting and allocation model that represents the system shown in Figure 2.2. The annual municipal water use was calculated based on the population and the municipal water use rate (m^3/y/capita). All desalination water, current and future expansion, is allocated to municipal water use (El-Sadek, 2010b). The municipal sector, then, receives 15% of its demand from shallow groundwater (Allam and Allam, 2007; MWRI, 2010), and the rest is supplied from the Nile. Twenty percent of the industrial water use is accounted for already within the municipal sector, and the remaining industrial needs are supplied from the Nile (MWRI, 2010). Data on industrial water demand are available for the years 1990, 2000, and 2010 from Abu Zeid (2007), Allam and Allam (2007), and MWRI (2010). Linear interpolation was used to fill the annual time series from 1986-2013. The consumptive use ratios of industrial and municipal water are 37% and 25% respectively (MWRI, 2010). Portions of the municipal and industrial wastewater (treated and untreated) are returned to the Nile and irrigation system and is accounted for in the reuse of water for agriculture.

Agricultural water consumption (evapotranspiration), which was estimated to be 4,700 m^3/feddan/y (feddan = 0.42 ha) as a national average, was calculated within the agricultural production module based on the crop areas of each crop and the corresponding blue water footprint. The total irrigation requirement was calculated by dividing the consumptive use of agriculture by irrigation efficiency. The amount of water needed for animal production was calculated and added to the crop irrigation water to calculate the total water supply for agriculture. The agricultural sector receives water from deep and shallow groundwater, the Nile, and drainage water reuse. The renewable shallow groundwater aquifer can provide a safe yield of 8.4×10^9 m^3/y based on the water balance in 2010 (MWRI, 2010). This safe yield was estimated every year based on the proportional change in recharge, which is affected by Nile water supplied to agriculture and the irrigation system efficiency (details are in Appendix B.1.3). The abstraction from the shallow groundwater for both municipal and agricultural purposes was calculated every year to ensure that it does not exceed the safe yield. The amount of agricultural drainage water is estimated based on the water supplied for irrigation and the irrigation efficiency. The total drainage water available for reuse is the summation of agricultural, municipal, and industrial return flows. The drainage reuse in 2013 was around 57% of the total drainage water. The model allows the agricultural sector to access the drainage water reuse as specified in the scenario, with a maximum of 60% of the available drainage water. The limit of 60% is set by the Egyptian MWRI to maintain a reasonable level of water quality. Around 0.2×10^9 m^3/y is secured for instream flows to allow for navigation. The unused drainage water is discharged to the northern lakes and the Mediterranean Sea to balance water salinity and substitute lake evaporation, a process which is essential for healthy aquatic system. The only variable that was marginally fine-tuned to reproduce the recorded data is the irrigation system efficiency in Egypt. The irrigation system efficiency is known to range from 44%-66% (IWMI, 2013), with improvement over time due to the improvement in irrigation methods and technologies. With minimum manual calibration, we found it to increase from 40% to 63% over the baseline period (1986-2013). More details of the water resources module are provided in Appendix B.1.3.

2.5 The Trade Component in the NWFT Model

The main purpose of this model is to characterize the virtual water trade into and out of Egypt. Therefore, there is less emphasis on individual countries, and thus, countries were integrated into nine regions to make the model and its links smaller and more parsimonious. The country under consideration, Egypt in this study, is kept as an individual. The nine regions are: Africa (AF), Middle East and North Africa (ME), East Asia and Pacific (EA), South Asia (SA), East Europe and Central Asia (CA), Europe (EU), North America (NA), Latin America and Caribbean (LA), and Oceania and New Zealand (OC). For developing countries, we used the aggregation into macro-regions proposed by the World Bank (http://www.worldbank.org/en/where-we-work), then we added developed countries grouped into Europe, North America, and Oceania. This way, the VWT model has 90 inter node links along the entire period of 1986-2011, instead of the original thousands of links (e.g., 16254 links in year 2011, established among 213 countries) in Tuninetti et al. (2016).

In this study, after aggregating the country level data into regions, the model became simpler with only Population (*P)*, *GDP*, and WF_P found to be influential drivers. Therefore, the gravity equation in the region-based VWT model developed in this study takes the following form:

$$VWT(i,j) = \beta_{oi} \cdot (P_j)^{\beta_{1i}} \cdot (GDP_j)^{\beta_{2i}} \cdot (WF_{P,j})^{\beta_{3i}} \quad (2.4)$$

where $VWT(i,j)$ is the virtual water trade from region *i* to region *j*, all parameters denoted by β are related to the exporting region *i* and estimated based on the data using ordinary least squared method, applied to the logarithm of fluxes and the logarithm of drivers. Significant variables were identified with the Student's t-test considering a 5% significance level. The drivers are the independent variables pertaining to the importing region *j*, and as defined earlier. As described in Section 2.3, the flux estimated using equation (2.4) is the same as the import of region *j* from region *i*. Accordingly, the 10-regions (node) based VWT model has a total of 10 equations of the form as equation (2.4) and 40 parameters, as well as 10 equations of the form as Equation (2.2). The 40 parameters were calibrated using a total of 2340 observations, namely 90 flows for each year between 1986 and 2011. Even though WF_C was not used as a driver in the gravity equation, WF_C of each region was used as shown in Equation (2.2) to account for the virtual water balance and estimate the losses and stock variation for every region. The data between 1986-2011 were used for the VWT model because it is the time frame within which all data were available. Population and agricultural production and consumption-related data are available publicly through the FAO (2017b). The blue and green water footprint of each product (m^3/tonne) was obtained from Mekonnen and Hoekstra (2011) and multiplied by the production quantity (tonne) to calculate the water footprint of each product (m^3). The water footprint of all food produced and consumed were summed up, then divided by the population to calculate WF_P and WF_C, respectively. The *GDP* data were obtained from the UN (2017). The VWT model was developed and evaluated based on the baseline period (1986-2011), then it was used to project the future VWT up to 2050 using the future socioeconomic shared pathways (SSPs). Details of developing the future projections and the SSPs are provided in Section 2.6.

2.6 National and Global Scenarios

The proposed NWFT modeling framework is not intended to do forecasting, but rather to allow the investigation of the water-food nexus at the national level, assessment of the influential variables and impacts of policy decisions, and analysis of potential scenarios for future projections at the national and global levels, along with the change that they might cause relative to the baseline conditions. For this purpose, scenarios of future projections at both the global and national level of Egypt were generated and analyzed.

2.6.1 National Scenarios

Egypt's Ministry of Water Resources and Irrigation (MWRI, 2010) developed three future scenarios, *Critical, Balanced, and Optimistic*, regarding water resources supply and demand in Egypt till 2050. The scenarios consider various water and socioeconomic combinations in their formulation. Variables considered are: (1) possible increase in Nile water inflow from projects of water saving in upstream countries, (2) different levels of internal water resources development of shallow and deep groundwater, reuse of drainage water, desalination, rainfall harvesting, and evaporation losses from the surface irrigation system, (3) socioeconomic variables, such as population and industrial growth, and (4) policy variables, such as agricultural land expansion and municipal water use reduction. In this study, a *Reference* scenario was added, which represents business as usual, with no significant changes relative to the past trends. The details of the four scenarios are provided in Table 2.1.

MWRI's scenarios do not assume changes in land productivity, and do not include the food consumption pattern. These two variables were added to complete the scenarios. The changes specified by the MWRI were used in all categories, and we did not change the land productivity except for uncertainty analysis. For both the Critical and Reference scenarios, the food consumption pattern was not changed. However, in the Balanced scenario, we increased meat consumption by 26% to match the expected behavior with the economic growth (Alexandratos and Bruinsma, 2012), which led to a 4% decrease in cereals to keep the nutritional energy intake at about the same current level. For the Optimistic scenario, we tried to reflect also optimism in the consumption pattern by keeping the meat consumption unchanged, while increasing the consumption of vegetables and fruits by 20%, which led to 3% decrease in cereals consumption.

Table 2.1: Potential scenarios of Egypt's water supply and demand (2013-2050).

Driver	*Reference**	*Critical*	*Balanced*	*Optimistic*	Uncertainty range
Annual population growth rate	2%	2%	1.8%	1.65%	±10%
Food consumption pattern	Unchanged	Unchanged	Increase in veg. & fruits (20%) and meat (26%), decrease in cereals (4%)	Increase in veg. & fruits (20%) and decrease in cereals (2.6%)	Unchanged
Increase in available water resources over the period 2013-2050 (10^9 m^3/y)*	**+ 2.42**	**+ 6.82**	**+ 4.22**	**+ 4.22**	
	Nile flow + 0	Nile flow + 0	Nile flow + 2	Nile flow + 4	±5%
	Shallow GW + 1.9	Shallow GW + 1.9	Shallow GW + 1.1	Shallow GW + 1.1	±10%
	Deep GW + 0	Deep GW + 1.63	Deep GW + 1.63	Deep GW + 1.63	±20%
	Reuse + 0	Reuse + 2	Reuse -2.3	Reuse -4.8	±20%
	Desalination + 0	Desalination + 0.77	Desalination + 1.27	Desalination + 1.77	±50%
	Rain harvesting + 0.02	Rain harvesting + 0.02	Rain harvesting + 0.02	Rain harvesting + 0.02	±30%
	Evaporation + 0.5	Evaporation + 0.5	Evaporation + 0.5	Evaporation + 0.5	±20%
Municipal water demand (m^3/y/capita)*	From 114 in 2013 to 79 by 2050	From 114 in 2013 to 79 by 2050	From 114 in 2013 to 82 by 2050	From 114 in 2013 to 82 by 2050	0% to -50% (114 to 57)
Annual growth in industrial water use (%)	0 %	0.65 %	1%	1.35%	±50%
Agriculture water consumption (m^3/Feddan)	4700 (unchanged)	From 4700 to 4500	From 4700 to 4400	From 4700 to 4300	±5%
Irrigation efficiency	63% (unchanged)	From 63% to 65%	From 63% to 70%	From 63% to 75%	±10%
Agriculture expansion (million Feddan)	No increase	Increase to 10	Increase to 10.8	Increase to 11.8	±20% for the target
Land productivity (tonne/Feddan)	unchanged	unchanged	unchanged	unchanged	±20%
Annual animal growth rate	unchanged	unchanged	Increased to match increase in consumption	unchanged	±20%

**Some inevitable and expected changes were considered in the Reference scenario as they are currently happening. Feddan = 0.42 ha.*

Table 2.2: Sensitivity analysis ranges used with Egypt's NWF model.

Model component	Variable	2013 value	SA range
Production	Agriculture area (million Feddan*)	9.2	9.2 to 15**
	Nile water (10^9 m^3/y)	55.5	45.5 to 65.5
Consumption	Annual population growth (%)	2.0	2.0 to 0.5
Water resources	Desalination (10^9 m^3/y)	0.23	0.23 to 4.0
	Deep groundwater (10^9 m^3/y)	2.36	2.36 to 4.0
	Irrigation efficiency (%)	63	63 to 80
	Municipal network efficiency (%)	70	70 to 90
	Municipal water use (m^3/y/capita)	114	114 to 57

* *Feddan = 0.42 ha.*

*** increasing the agriculture land area to 15 million Feddan is a hypothetical assumption for the purpose of sensitivity analysis, while actual potential to expand agriculture area is constrained by water availability and land suitability and will be likely less than this number.*

For such a complex water-food nexus at a national scale, it is important for policy makers to understand the influential variables in the system. For this purpose, sensitivity analysis (SA) was conducted with the most important variables that affect the production, consumption, and water resources modules. The Reference scenario was used in this analysis to measure the relative change as a result of variable perturbation. We used the system dynamics concept of *reference mode* that is perceived to be a representative index, in the form of a time series, of the system performance (Ford, 1999). Either of the food (or water) gap or food (or water) self-sufficiency can be used for this analysis. Even though scenarios represent probable realistic future conditions guided by historical trends and data, SA quantifies the influence of major variables by perturbing their values (Table 2.2) beyond the ranges of the various scenarios, so the consequences of more acute policies are tested. For example, the Nile water inflows to Egypt were changed in the range of ± 10×10^9 m^3/y. The SA was conducted by perturbing one model variable (or a group of variables) at a time while maintaining the other variables unchanged.

Uncertainty analysis (UA) was also conducted with the NWF component to reflect the uncertainties in the various variable values in the four investigated scenarios. UA is different from the SA in two aspects; first, the ranges of uncertainty (Table 2.1) were kept limited and realistic to reflect best estimates of uncertainty. For example, only 5% uncertainty was considered regarding the Nile water flows in each scenario (± 2.75×10^9 m^3/y) as this is in the range of the typical variability in the annual flows released from the High Aswan Dam.

Desalination plans and industrial growth in Egypt are highly uncertain as the country may be far from the scenario ranges in either side, especially in light of the recent significant socioeconomic and political changes. Therefore, the range was increased to ± 50%. Similarly, other variable ranges were relaxed or narrowed depending on their nature and future possibilities. The second difference between SA and UA is that in UA, all variables were perturbed simultaneously (all at a time) to reflect the reality of uncertainty. The Latin Hypercube sampling approach built in Stella Architect was used to compose 1000 sample values within the specified input variable ranges. Accordingly, the model was used to perform 1000 runs for those samples, and the resulted uncertainty ranges for model output variables (i.e., food gap) were reported.

2.6.2 Global Scenarios

The climate change research community developed five scenarios of global societal development, called the shared socioeconomic pathways (SSPs) (O'Neill et al., 2017). These SSPs consider changes in demographics, economy and lifestyle, policies, technology, natural resources, and human development for distinguishing the five scenarios.

IIASA (2016) provides the population, gross domestic product and urbanization data of all SSPs for all countries for the period of 2000-2100. Data on population (*P*) and gross domestic product (*GDP*) were extracted for all countries up to year 2050 and processed to match the ten world regions distinguished in this study. The future values of water footprint of agricultural production (WF_P) are unknown for each region. These values depend on many factors that vary by region, like the water resources availability, the agriculture policy and management decisions, and the degree of development and technology (Ercin and Hoekstra, 2014; Jin et al., 2016). So, an ideal way to estimate WF_P is to develop a model like NWF for every country in the world and simulate the future values based on assumptions for the controlling factors, which is considered beyond the scope of this study. Instead, two different experiments were adopted. In Experiment I, data on WF_P per region (expressed in m^3/y/capita) at the end of the baseline period (2011) were assumed to remain constant up to the year 2050. This implies that each region attempts to keep the food production per capita at the level of 2011, assuming that the water footprint of production in every region keeps pace with regional population growth. In Experiment II, even if resources availability is not a problem for some regions (Shiklomanov, 2000), other factors like water quality and socio-economic factors (Simonovic, 2002; Duchin & López-Morales, 2012) might make them fail to maintain 2011 levels of per capita food production. Hence, some other regions would increase their per capita food production over 2011 levels to trade more food. In this experiment the per capita WF_p is assumed to be varying, for some regions it will increase while decrease for others. Iterations were needed to solve equations (2.2) and (2.4) in the trade model using the IIASA's P and GDP data and by assuming no significant change to food waste per capita compared to 2011 levels (Kummu et al., 2012). The annual WF_P series up to 2050 were generated for all SSPs in the ten regions and can be found in Appendices B.2 and B.3. Finally, the VWT model was used to generate the virtual water (food) imports of Egypt till year 2050 under the five SSPs.

2.7 Results

2.7.1 National Water-Food Model Results

NWF model simulates Egypt's food production and consumption and its food and water gaps for the baseline period 1986-2013 and the future up to 2050. In all scenarios, the increase of food production is projected to be slower than that of the baseline period due to the limitation of freshwater availability (see Figure 2.3). Agricultural production has been increased in the past due to the increase of agriculture land and improvements in crop yield (tonne/ha), at the same time, Egypt maximized its reuse of drainage water and improved irrigation efficiency. Interestingly, MWRI's Balanced and Optimistic scenarios are not significantly different with regard to food production (Figure 2.3a). However, when the national food consumption (Figure 2.3b) is taken into consideration, the Optimistic scenario becomes obviously better with regard to the national food gap (Figure 2.3c). The Optimistic scenario is projected to have a 25 million tonne smaller food gap compared to the Balanced scenario. Even though the Balanced scenario projects higher food production than the Critical scenario, it was set off by the projected increase in meat production and consumption, which consumed water that would have been otherwise used for crop production. This is an important effect of food consumption behavior on the food and water gaps. The food gap translates into a water gap (Figure 3d), based on the internal water footprint of each crop and animal product. Under all scenarios, Egypt's food and water gaps are projected to widen with rates higher than those of the baseline period. This occurs because the negative effect of the low rate of production increase is exacerbated by the high rates of national food and water consumption increase due to the high population growth.

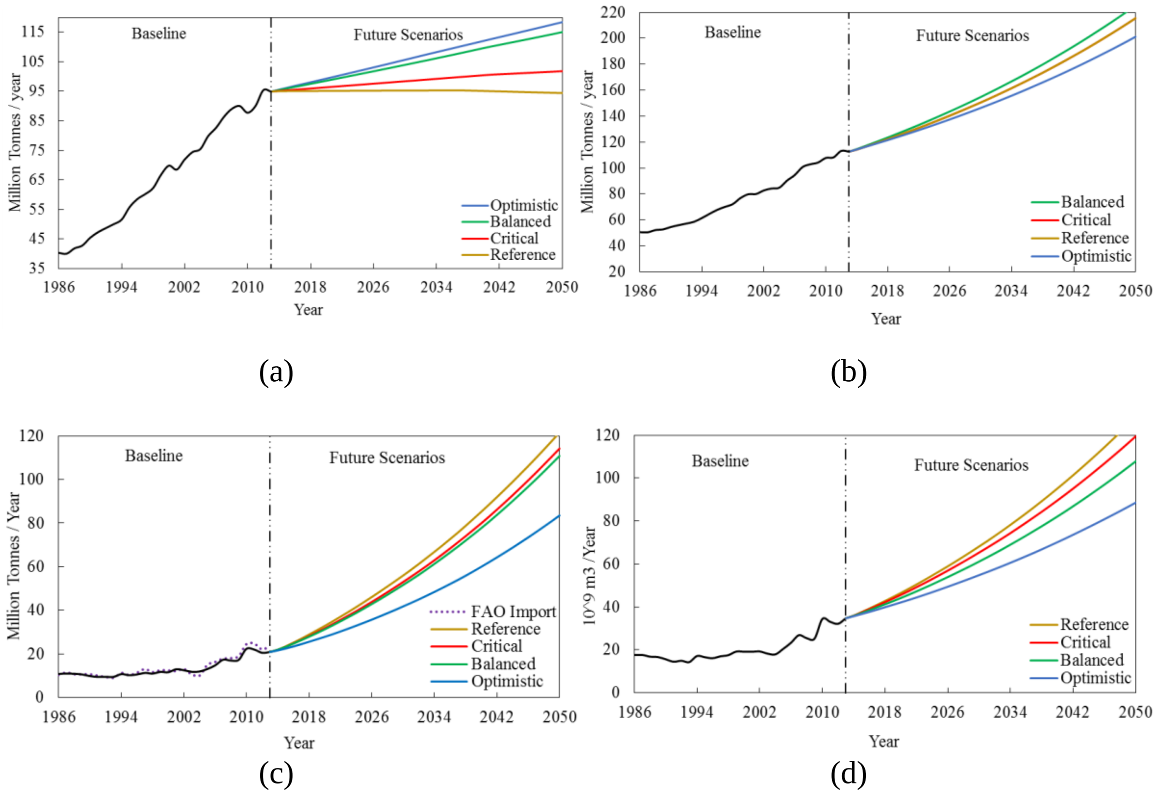


Figure 2.3: Egypt's baseline and projected variables of (a) national food production, (b) total domestic food supply (national food consumption), (c) national food gap (imports), and (d) national water gap.

As the municipal and industrial water uses have higher water allocation priorities than agriculture, the demand growth in municipal and industrial sectors affects the water available for agriculture and food production. Figure 2.4 shows the total water resources supplied and the percentage of water use (allocation) for each sector under the Balanced scenario (detailed water uses for different scenarios are provided in Appendix B.5). The increase in water resources supplied between 1986 and 2013 is mainly due to the expansion in water reuse and groundwater extraction. Such increase in the future is limited because very small potential for expansion exists. The sectoral shares in total water use change over time: municipal and industrial water use increase their percentage of usage at the cost of agriculture, which has almost a fixed allocation of 67×10^9 m^3/y between 2013 and 2050. Taking year 2013 as a reference, an annual growth rate in Egypt's population of 2% leads to 2% (187 million m^3) increase in municipal water use, 2% (1.9 million tonne) increase in food consumption, and thus, 7.1% (1.5 million tonne) increase in the national food gap.

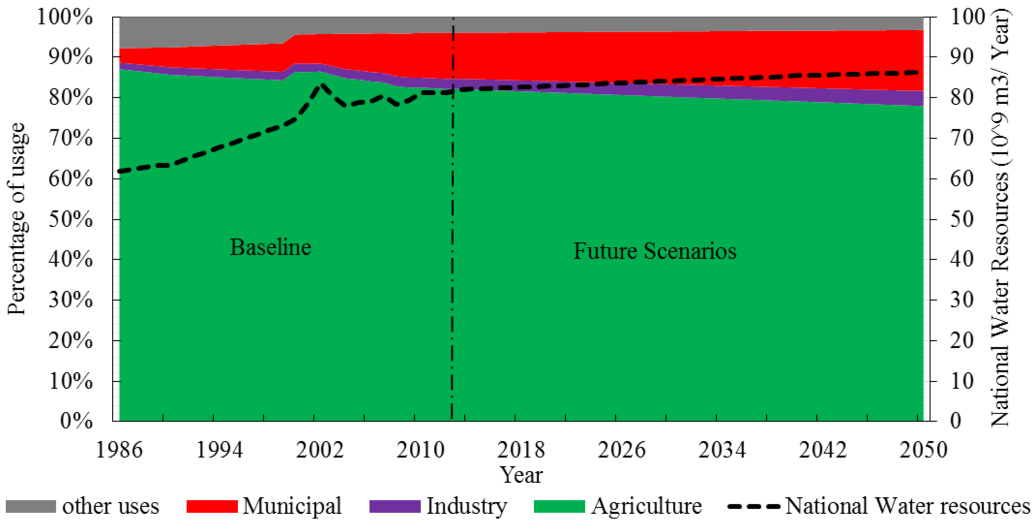


Figure 2.4: National water resources supplied and the progression of the percentages of usage by different sectors in baseline and future Balanced scenario.

While Egypt is a major food importer, the country also exports some agricultural products (Figure 2.5). Egypt's food exports are small compared to the food imports (Figure 2.3), with total exports amounting to 20% of the imports. The NWF model shows a slightly lower accuracy in modeling the exports, which does not affect the overall balance due to their small values. The evolution of the national food and water gaps over time in Egypt can be quantified and visualized using the self-sufficiency index (Figure 2.6). Self-sufficiency is the amount of the resource available domestically divided by the total need. The current food self-sufficiency (tonne/tonne) of 80% is projected to decrease to a level between 45-59% by year 2050. The corresponding values of Egypt's water self-sufficiency are 70% (currently), decreasing to a range of 40-50%. The low values of the projected food and water self-sufficiency in Egypt, mainly due to its limited water resources compared to its population needs, explain the nation's sensitivity to any dispute over Egypt's share of the Nile water and its sustainability.

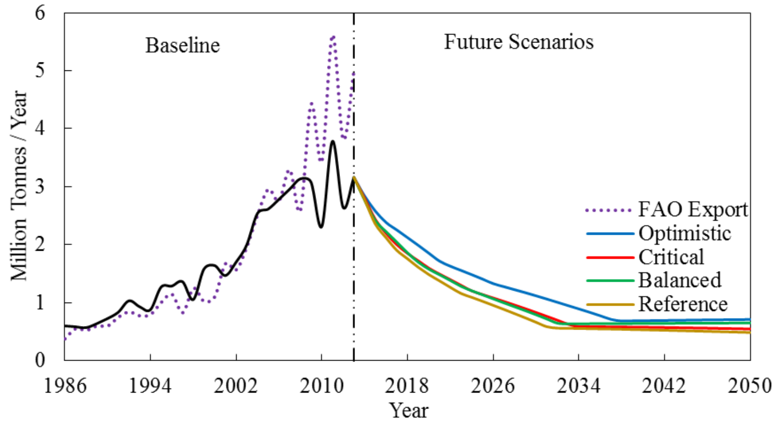
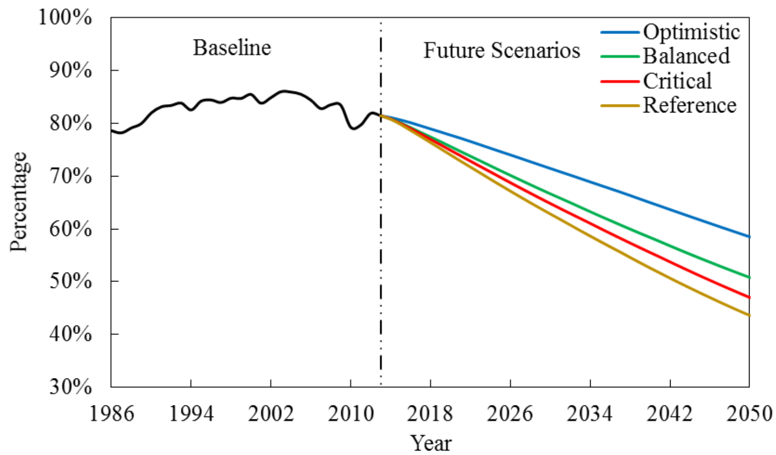
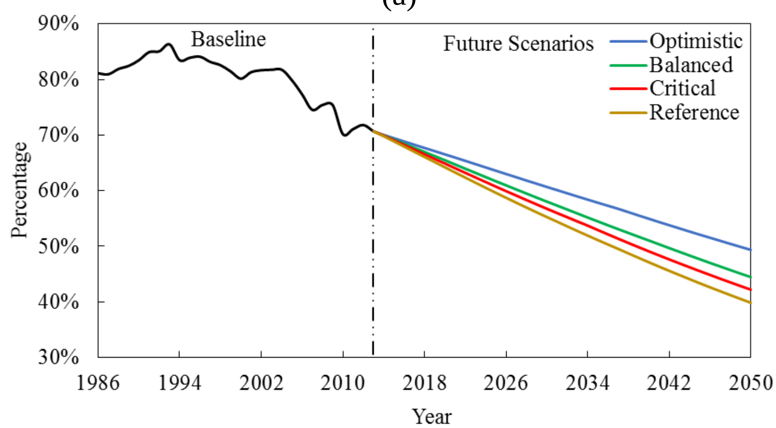


Figure 2.5: The food exports from Egypt over the baseline period and projected for the future under various national scenarios.



(a)



(b)

Figure 2.6: Egypt’s (a) food self-sufficiency, and (b) water self-sufficiency.

2.7.2 Sensitivity Analysis

Increasing the mean annual Nile water by 10×10^9 m^3/y (a number stretched beyond the MWRI's Optimistic scenario) reduces Egypt's food gap from 121 to 106 million tonne in 2050 (Figure 2.7), provided that all other variables are kept unchanged. Such increase in the external water resources of Egypt is estimated to require an investment of around US$ 10,000 million (MWRI, 2017). A similar effect is achievable by a combination of policy instruments and developments of Egypt's internal water resources, by decreasing the municipal water use from 114 to 80 m^3/y/capita, increasing the municipal water distribution network efficiency from 70% to 82%, increasing the overall irrigation system efficiency from 62% to 73%, increasing the deep groundwater use from 2.36 to 3.4×10^9 m^3/y, and enlarging the desalination capacity from 0.23 to 2.5×10^9 m^3/y (Figure 2.7). The required capital investment for such combination of measures is around US$7,700 million (MWRI, 2017). However, internal water resources developments entail significant amounts of annual operating cost and energy use, especially for desalination, deep groundwater use and the newer irrigation systems. Such investments, which are approximately 10-15% of Egypt's annual budget, will reduce Egypt's food gap in 2050 by only 12%. This reflects the severity of Egypt's water resources problem.

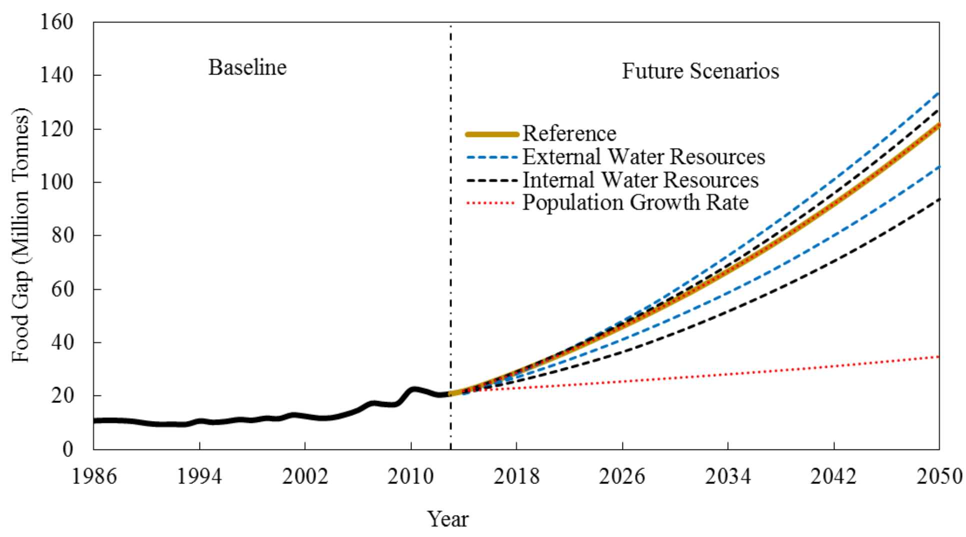


Figure 2.7: The sensitivity of Egypt's food gap to: external water resources (Nile water), internal water resources development, and the population growth rate.

As noted earlier, and shown in Figure 2.7, population growth has a dramatic effect on Egypt's food and water gaps. The 15 million tonne reduction in the food gap in 2050 can be achieved by lowering the population growth rate from 2.0% to 1.79%. Figure 2.7 shows the extreme case of lowering Egypt's annual population growth to the current level of some European nations (0.5%), and its huge impact on the national food gap. This is a strong indication that investment in educational, health, and awareness programs for lowering the population growth rate can be a major part of the solution of Egypt's severe water problems. Population growth consumes water for drinking, which leaves less water available for agriculture. Population growth has thus a compound effect on the food gap: it increases food consumption and decreases food production. The above quantitative example supports the growing realization that addressing water resources problems may not be through a water-based solution. Other figures and results of the sensitivity analysis with regard to the individual variables are provided in Appendix B.6. IIASA's various SSPs project lower population growth of Egypt up to year 2050. For this reason, we include also in Appendix B.7 the projected food gap of Egypt based on IIASA's population projections. However, three of the SSPs, for example, project Egypt's population to reach 102 million in 2030, when this number is projected to be achieved before 2020 by the local authorities (CAPMS, 2017).

2.7.3 Uncertainty Analysis

Figure 2.8 depicts a summary of the uncertainty analysis of the NWF model, using the food gap (million tonne) as the performance index. Results are available throughout the simulation period (2014-2050); however, three years were selected for the analysis: the first year of the projection into the future (2014), 2030, and 2050. In 2030, the uncertainty range is reasonable with standard deviation values in the range of 3.9 to 5.5 million tonne for the four scenarios. Because of the differences in the mean value, the coefficient of variation (CV) is a better measure. Both the Reference and Critical scenarios have CV values of 0.06 and 0.07, respectively. This uncertainty increases to 0.11 for the Balanced scenario. The uncertainty increase in the Balanced scenario is attributed to the increase in animal stock that was considered to supply the increase in meat consumption. Increasing meat production places a high demand on water resources, which affects the water available for agriculture. Obviously, the uncertainty is growing over time as we look further into the future. Moving from 2030 to 2050, the uncertainty, quantified by CV, increases in the range of 30% to 43% relative to 2030, with the maximum increase in uncertainty in the "meat" scenario. Considering the mean (or median) values of all scenarios, one can easily rank them with regard to the resulting food gap, with the Optimistic scenario leading to the best results for Egypt. However, the uncertainty ranges show that the four scenarios are overlapping, and their results may not be much different from one another, especially in the near future (2030).

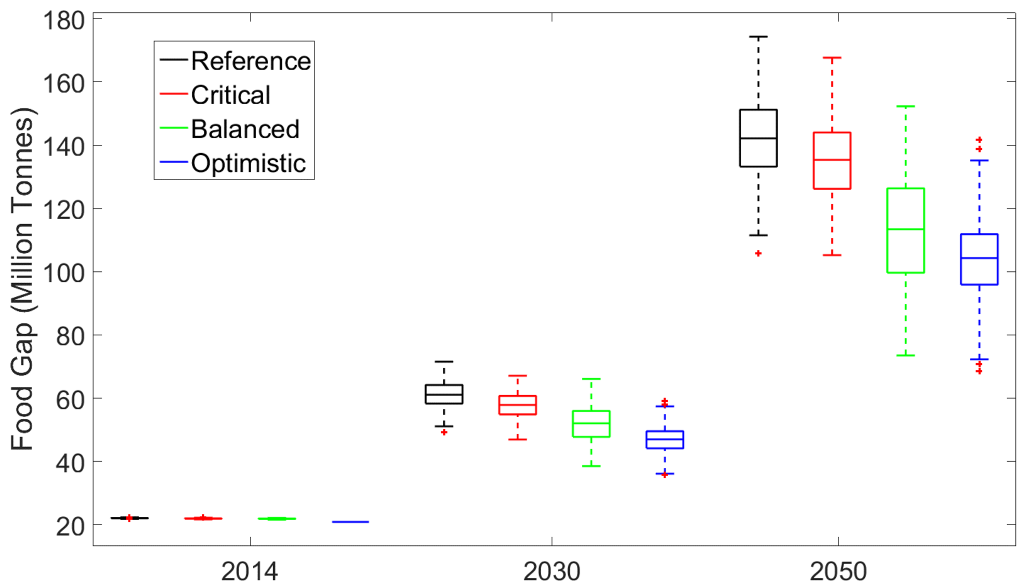


Figure 2.8: The evolution of Egypt's food gap over time and its uncertainty under the various scenarios.

2.7.4 Global Virtual Water Trade Model Results

For the baseline period 1986-2011, the predicted food imports of Egypt, converted into virtual water units, are shown in Figure 2.9 along with the actual imports reported by FAO (2017b). The FAO reports exports and imports of food in million tonne and we converted the values into billion cubic meters of water by multiplying food imports by the water footprint of producing the same food items in Egypt. The global virtual water trade (VWT) model shows acceptable performance in capturing the pattern of the global trade with an overall adjusted R^2

value of 0.79. Even when a two third-one third split sample was tested to conduct a traditional calibration-validation with the model, a satisfactory performance was still achieved with a validation R^2 value of 0.68. However, due to the limited length of the available data, the model developed with the entire dataset of 26 years was used in this study.

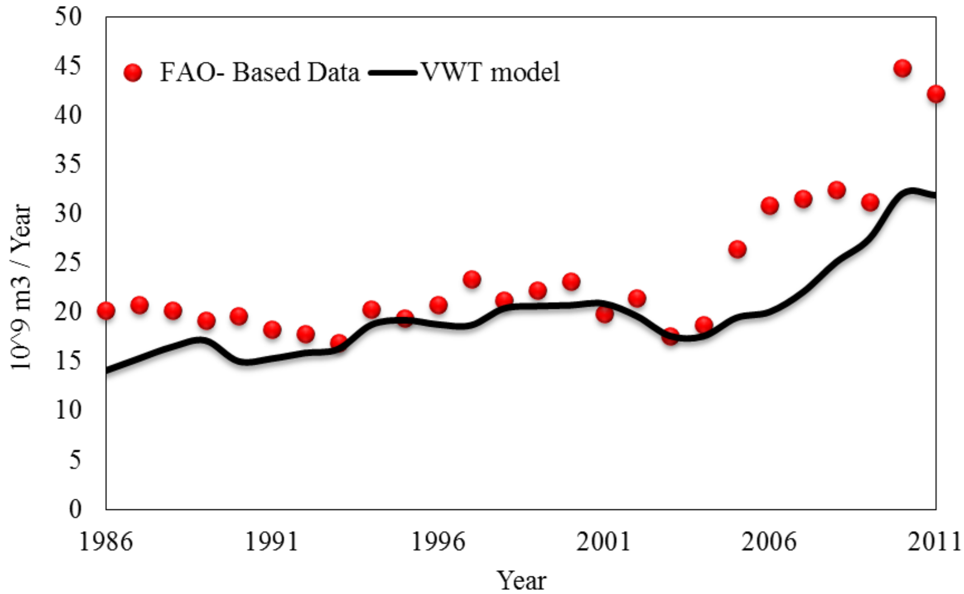


Figure 2.9: Actual and modeled food imports of Egypt, converted to water units (virtual water), during the baseline period (1986-2011).

The VWT model was fed with the IIASA's SSPs to project Egypt's imports till 2050. In experiment I, when the WF_P (m^3/capita) was kept constant in the future in all regions, Egypt's virtual water import increased to 76 up to 135×10^9 m^3/y by 2050, with an average value of 103×10^9 m^3/y (Figure 2.10a). This constant future value of WF_P implies a significant increase in Egypt's production over the years to match the pace of population growth, and thus, imports can be kept to the lowest possible level. However, this future scenario may not be realistic as the VWT model generated unrealistically high or low waste and stock variations to keep the global food balance between exporting and importing regions. The results are provided in Appendix B.2.

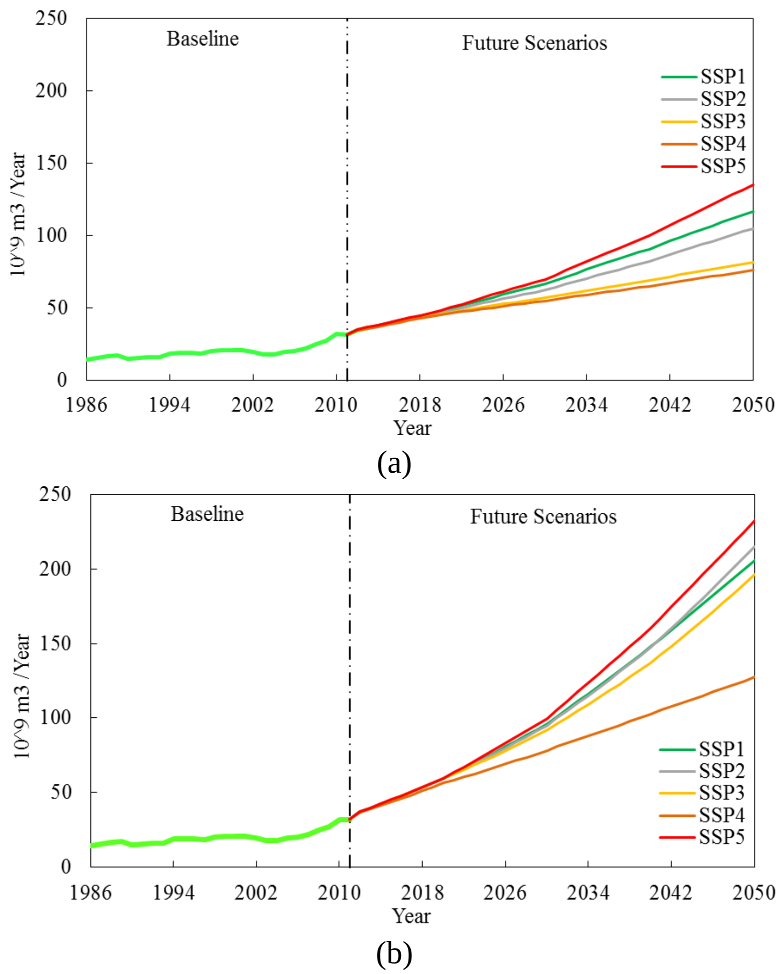
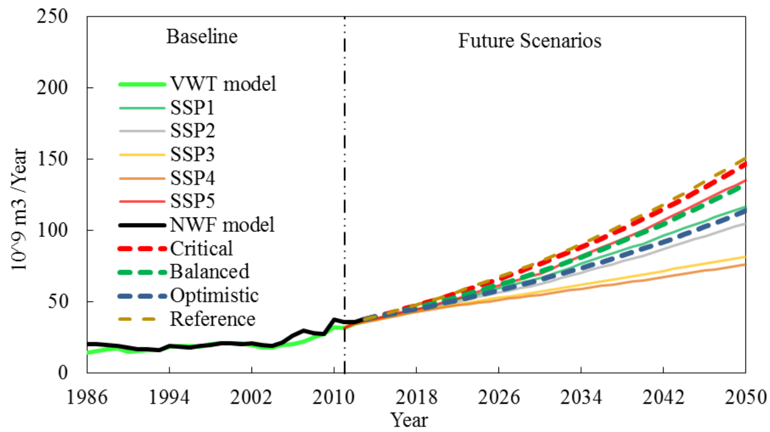


Figure 2.10: The baseline and projected future virtual water imports of Egypt under the five SSPs, (a) Experiment I: constant WF_P in the future and (b) Experiment II: varying WF_P values based on stabilized food waste in the future.

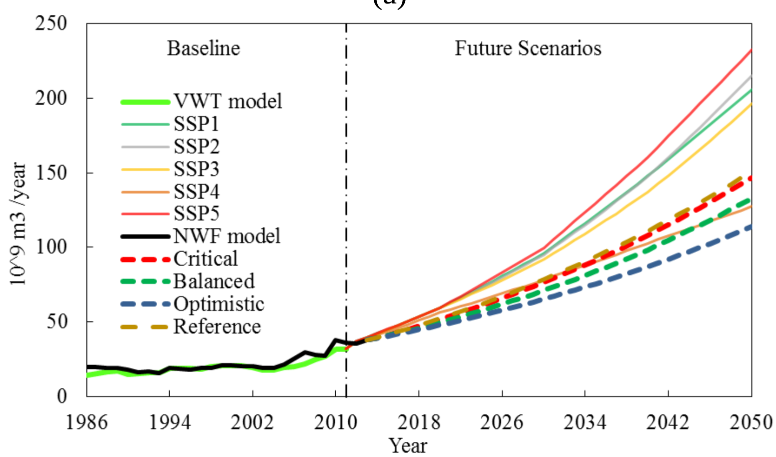
In experiment II, the generated WF_P values (m^3/capita) increased in certain regions (e.g., Eastern Europe and North America) and decreased in others (e.g., Middle East and South Asia) in the future, and we find this to be more realistic. The advancement in technology and the differences in population growth rates among the world's regions support the varying WF_P values. The new projections of Egypt's imports are shown in Figure 2.10b. The imports range from 127-232×10^9 m^3/y by 2050 with an average value of 195×10^9 m^3/y in 2050. We also find the projections to be reasonable as the lowest imports projections of Egypt, in other words exports to Egypt from the other nine regions, happen in SSP3 and SSP4, characterized by global fragmentation and inequality where policies are oriented towards security, including barriers to trade (Fujimori et al., 2017; Calvin et al. 2017). On the other hand, the highest imports are found for SSP5, the conventional development scenario that is characterized by conventional development towards economic growth, and policies geared towards redundancy to minimize disruption (Kriegler et al., 2017). Egypt's virtual water imports are projected to increase from all regions, but the most significant increases occurred from Africa, Latin America, and East Europe and central Asia regions (detailed tables can be found in Appendix B.4).

2.8 Discussion

The general pattern and trend of Egypt's food imports simulated in the baseline and projected in the future by both the global and national models in the NWFT modeling framework are consistent, which is encouraging and supporting the credibility of both models (Figure 2.11). However, taking into consideration an average value of the five SSPs, the VWT model estimates Egypt's food import in year 2050 to be 150 million tonne, which is 39% higher than the average estimate resulting from the national model (averaging the four national scenarios). SSP4 provides a close estimate to the national model, with an estimated food import in 2050 that is 8% lower than the average of the national scenarios. Ideally, developing a national model for each country, similar to Egypt's model, to estimate national surplus and shortage of each country, taking into account the national socioeconomic and development plans, and reiterating to maintain a global balance is probably the best way to project future global virtual water trade. For the purpose of this study, and for the practical use of a country like Egypt, it is useful and important to ensure that the national 2050 strategy and its associated future scenarios can be made possible from a global perspective, which can be assessed using the VWT model to a reasonable level. If Experiment I (Figure 2.11a) provides the realistic global picture, it means that some of Egypt's projected future food needs are far beyond what is anticipated based on the global food availability and trade network. In this case, it is an alarming situation that requires introducing serious policy instruments that can change Egypt's food gap.



(a)



(b)

Figure 2.11: Virtual water (food) imports of Egypt over the baseline period and the projected future under various national and global scenarios, (a) Experiment I: constant WFP values in the future and (b) Experiment II: varying WFP values based on stabilized food waste in the future.

The NWFT modeling framework presented in this study has a few limitations that are worth further improvements in future studies. First, the VWT model needs to be improved, either through using the country-based model, rather than the nine-region model, or through adding more conceptual components. The food production, water use, and food consumption components need to be captured with finer levels of details in each region. Second, the NWF model can benefit from including more socioeconomic factors, like for instance food prices. Explicit accounting of the food prices, which might affect the national consumption both in pattern and quantity, can affect the country's imports, which in turn can affect prices and add another feedback loop in the consumption modeling component. It is challenging to capture this behavior based on historical data when more than 75% of the population enrolled in food subsidy program and acquired food at non-market prices. Third, the future dynamics of water uses and supply might alter water quality, which could have impacts on the aquatic system of the Nile and Delta, and might be worth investigation in more detail.

Fourth, the NWF model of Egypt's water-food nexus can be extended to include energy. Currently, because of the limited contribution of hydropower and the small amounts of cooling water for thermal power, relative to other water uses, and the negligible use of Egyptian crops in bioenergy, the energy role in the nexus is limited. Nonetheless, there is a considerable input of energy in water and food supply, mainly due to the use of fertilizers and machinery in agriculture and pumping systems in irrigation and water extraction (El-Gafy et al., 2017). Also, an increase in desalination can enhance the need to include energy, and study the trade-offs of its uses in industry, agriculture, and drinking water. Fifth, in this study, the uncertainty of the future projections of the global virtual water trade model were expressed in the form of the global scenarios that feature number of changes to model variables. However, another source of uncertainty is this model's parameters. It is recommended to perform parameter uncertainty analysis and assess its implications for the future VWT projections.

2.9 Conclusions

Virtual water traded internationally in the form of food, and other products, makes water a global resource; national water analysis and management should not only address the (real) water resources within the country, but import and export of water in virtual form as well. The NWFT modeling framework developed in this study can be instrumental for this purpose. The water-food nexus in Egypt was captured and modeled in this study in a system dynamics simulation environment. A set of future scenarios of Egypt's water and socioeconomic conditions up to the year 2050 were evaluated using the national water-food (NWF) model, and they all revealed that Egypt is facing challenge of widening food and water gaps. However, there are scenarios that were assessed to be more optimistic than others, and those ones require investments to develop some internal water resources through desalination, the use of fossil groundwater, improving irrigation and municipal water efficiency, lowering the population growth rate, and securing additional amounts of the Nile water flowing from upstream countries. The sensitivity analysis revealed that the high population growth rate in Egypt plays a critical role in pushing the national water and food gaps to alarming levels.

The global virtual water trade (VWT) model, executed in parallel to the NWF model, considered the world countries aggregated into nine regions, while keeping Egypt as an explicit node. Egypt's imports of virtual water (food) were projected, up to 2050 under five different scenarios based on the socioeconomic shared pathways (SSPs). Both the global and national models projected similar patterns of Egypt's future food imports, which in turn represent Egypt's food and water gaps. The similarity in the projected patterns of both models is a good indication of the validity of both the national and the global models. The NWFT modeling framework can be easily adapted to other countries and also to expand the nexus to other sectors, such as energy. The approach of analyzing water in its real and virtual forms, rather than only one of them, can be a useful approach to quantify the water-food (and perhaps energy) nexus and bridge an important gap between water resource managers and policy makers at the national level. Furthermore, the study also provides a way for policy makers at national scale to benefit from the emerging research in global virtual water trade.

2.10 Acknowledgment

The Funding of NSERC of Canada to Amin Elshorbagy is greatly appreciated, and also the University of Saskatchewan devolved scholarship to Ahmed Abdelkader is acknowledged. Marta Tuninetti, Francesco Laio, and Luca Ridolfi acknowledge funding support provided by the European Research Council (ERC) through the project "Coping with water scarcity in a globalized world" (ERC-2014-CoG, project 647473).

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Chapter 3 ACPAR: A Framework for Linking National Water and Food Security Management with Global Conditions

This chapter is a slightly modified version of the published article (Abdelkader and Elshorbagy, 2021), modified to make it consistent with the format and body of the thesis. This chapter is the final accepted draft of the paper prior to copyediting or other production activities by the journal.

Citation: Abdelkader, A., and Elshorbagy, A. (2021). ACPAR: A framework for linking national water and food security management with global conditions. Advances in Water Resources, 147. DOI: 10.1016/j.advwatres.2020.103809. The permission of reproduction is presented in Appendix A.2.

Authors Contributions and The Contribution of This Chapter to The Overall Study

The following are the contributions from the different authors of this (chapter) published manuscript. A. Abdelkader contributed to the conceptualization, methodology, formal analysis, investigation, data curation, writing - original draft, and visualization. A. Elshorbagy contributed to the conceptualization, methodology, writing - review and editing, supervision, and funding acquisition.

This chapter introduces a modification of the NWFT to be suitable for national cropping pattern planning that target enhanced water and food security conditions. This work addresses the first objective of this thesis, and it adds to the huge body of literature on cropping pattern modeling, in two major aspects namely: (a) showing the value in framing the problem as multi-objective form; and (b) incorporating an approach to formally address future uncertainty of planning decisions. Moreover, this chapter contributes to addressing a major research gap of incorporating the knowledge from extensive research done on global food (virtual water) trade modeling into the water management decisions taken on the national scale.

3.1 Abstract

In this chapter, we identify cropping pattern as a major policy variable and introduce a framework for the generation of alternative cropping patterns (ACPs) in arid regions, called ACPAR, which can be used for assessing water and food security. ACPAR is applied to the case study of Egypt, for which a simulation-based national water, food, and trade (NWFT) model exists. ACPAR is formulated to minimize the agricultural water demand, food imports, and the economic cost of imports as well as maximize the national gross margin of agriculture. These four objective functions are optimized simultaneously to generate ACPs that have different tradeoffs. Additional filtering criteria are employed to account for fertilizer use as well as the stability of the set objectives. The ACPs are generated and evaluated for the baseline period (1986-2013) as well as under future conditions up to the year 2050. The results show that ACPAR is useful for proposing ACPs that could have worked better for Egypt during the baseline period, but also ACPs that outperform the historical cropping pattern in each objective function for wide future conditions. Some of the generated future ACPs can perform well regarding irrigation water use and cost of imports, without compromising food self-sufficiency. The quantified tradeoffs between the identified objective functions are the key contributions of this study, representing important information for policymakers to aid in water resources planning. The ACPAR framework connects national water resource management decisions to global food production, consumption, and trade dynamics.

3.2 Introduction

Globally, agriculture utilizes 50% of the habitable land area and 70% of the freshwater withdrawals for irrigation (Bruinsma, 2017). The growing population and global economy are leading to stresses on the limited natural resources available for agriculture. The increasing food demand necessitates the exploitation of more resources, which are challenged by increasing urbanization and pollution rates that lead to deterioration of both the quantity and quality of land and water resources (Degefu et al., 2018). These finite resources are further subjected to increasing competition for different uses, projecting a world that is more susceptible to water and food shortages. Climate change poses additional threats (Pastor et al., 2019; Steffen et al., 2015), as it might increase water demand and decrease water supply in various regions. Agricultural growth in arid and semi-arid regions, where land reclamation for agriculture is conditional on water availability, is subjected to the greatest water constraints. In these areas, water is already insufficient to cover various national uses. As a result, agricultural production is less likely to meet consumption demands, resulting in food gaps and creation of economic burdens that hinder the socioeconomic growth of developing countries (Schmitz et al., 2013; D'Odorico et al., 2019). Developing countries around the world are challenged in this way, with 48% of the land area of struggling economies lying in hyper-arid and arid areas (Figure C.1, in Appendix C.1).

In the last century, the increased food production and liberated trade policies contributed to a significant increase in global food trade (D'Odorico et al., 2014), which in turn benefited arid and water-poor countries. As for those countries, importing food from the global market represents a better option when compared to the economic and physical constraints of transferring water to increase their local food production. When food is traded, the water consumed to produce this food is virtually traded as well (Tamea et al., 2014). Around 22% of global water used in agriculture is traded in virtual form (Hoekstra and Chapagain, 2008; Dalin et al., 2012). Virtual water trade (VWT) participates in filling the persistent water and food gaps of water-poor countries, which is thought to reduce conflicts, famines, and massive emigrations (Allan, 1998). However, the increasing dependency on food trade (VWT) increases the risks of food shortage at times of market disruptions (Puma et al., 2015). There is a strong need to consider food and virtual water trade dynamics when planning for national water resources (Abdelkader et al., 2018). The invisibility of virtual water and the difficulty of connecting it to its consequences on the national scale remains a major challenge (Gawel and Bernsen, 2013).

On the global scale, the potential for expansion in agricultural land area is very limited (Tilman, 1999), as it comes with significant environmental costs (Foley et al., 2005). States might enhance and maximize the benefits of currently cultivated land (Garnett et al., 2013). Hence, the optimal use of scarce water resources to maximize economic gains and strengthen food security without compromising other water uses, including environmental considerations, is important for future agricultural planning (Falkenmark, 2006; Jägermeyr et al., 2016). Unfortunately, many water-scarce countries suffer from lack of proper agricultural planning and resource management. Dalin et al. (2017) show how some water-scarce countries overexploit their non-renewable water resources for short-term economic gains through crop exports. Moreover, the lack of basin cooperation and mismanagement of rainfall water in transboundary river basins, such as the Nile basin, prevents the basin countries from achieving greater basin-wide economic gains and better food self-sufficiency (Siderius et al., 2016). Several studies show that more food production with higher profits can be achieved (Vico and Porporato, 2011) and, in some cases, with less water use (Smilovic et al., 2018; Davis et al., 2017). Water-scarce nations desperately need to manage their limited water resources wisely while enhancing agricultural benefits, but these are seemingly conflicting objectives as the agricultural sector is usually the major water user.

Cropping pattern is a critical agricultural variable that is connected to different socioeconomic and environmental aspects. Crops differ in their water requirements, profitability, use of fertilizers, and relative demand. Thus, selecting one cropping pattern over others could have multiple consequences that should be considered while making planning decisions. Cropping pattern planning refers to the problem of distributing crops over a specified land area, while considering three essential components: (i) representation of the biophysical processes underlying crop production system, (ii) definition of the objectives of the stakeholders under consideration, and (iii) inclusion of constraints that exist on the crop production system (Dury et al., 2012). The problem is extensively discussed in diverse forms but mostly simplified in the form of linear relationships between the decision variables and the objectives and constraints (Jothiprakash et al., 2011). However, other studies argued that non-linear forms provide results that are more accurate and consistent with reality (Benli and Kodal, 2003). In early formulations of the problem, only a single monetary objective to maximize economic profits or minimize production costs was considered (Heady, 1948; Louhichi et al., 2010; Benli and Kodal, 2003; Omar et al., 2021). Lately, as stakeholders became more interested in other non-economic objectives, the problem was formulated by considering various objectives, usually in a bi-objective form as to maximize the irrigation water saving and to maximize the economic returns (Ghazali et al. 2018; Wang et al., 2012). Reddy and Kumar (2008) highlighted the possibilities of maximizing irrigation net benefit while maximizing irrigated area under water supply deficit. Nouri et al. (2020) indicated that cropping pattern changes for the Litani Basin in Lebanon would decrease the water demand for agriculture, increase food production, and increase agriculture economic returns. Davis et al. (2019) showed that shifting the Indian cropping pattern to increase cereal production would increase the nutrition value of food supply, reduce the demand for water and other resources, reduce greenhouse gas emissions, and enhance the resilience to climate change, without the need to increase the cropland area. Omar et al. (2021) indicated that cropping pattern adaptions could help improve food security and reduce the socioeconomic impacts of climate change on Egyptian agriculture. MWRI (2001) developed the Egyptian Agriculture System Model (ASME), which maximizes the producer-consumer surplus and uses cropping pattern as one of the major decision variables, while water and land resources are used as constraints. Schyns and Hoekstra (2014) concluded that partial relocation of crops would significantly save water compared to national water demand reduction plans in Morocco. Other studies incorporated the growing awareness of environmental aspects in the cropping pattern planning problem (Karandish et al., 2020). Dogliotti et al. (2005) minimized the environment exposure to pesticides and nitrogen surplus, and Femeena et al. (2018) minimized the nutrient load reaching the freshwater system while minimizing crop production costs. Interestingly, in the reviewed literature, it was noted that there is less focus on multiobjective problem formulations (Sarker and Ray, 2009). In such complex problems, neglecting the higher dimensionality of conflicting objectives (i.e., considering fewer objectives than required) would result in several types of decision bias (Hogarth, 1981; Gettys and Fisher, 1979). Hence, considering the cropping pattern planning in a multiobjective context would minimize the possibilities of misleading decisions (Brill et al., 1990).

The cropping pattern planning problem is typically solved using numerous methods, but mostly optimization (Dury et al., 2012). Linear Programming (LP) was commonly used to solve single-objective problems because of its simplicity; however, it fails to solve non-linear and discontinuous problems (Vedula and Rogers 1981). LP was extended into Goal programming (GP), which is commonly used to solve multiobjective linear problems; however, it requires selecting multiplier weights or target values for the objective functions before optimizing them, which is always challenging to decision makers (Sarker and Quadus, 2002). Recently, many modifications were considered for LP and GP to improve their performance and reduce their limitations, but more importantly, evolutionary optimization algorithms (EAs) were introduced as a substitute that can overcome deficiencies of LP and other traditional methods (Nicklow et al., 2009). EAs are not limited to a specific mathematical formulation as the case of LP, but can even solve non-linear, discontinuous, and non-differentiable functions (Yao, 2002). In contrast to GP, Multiobjective evolutionary optimization algorithms (MOEAs) are considered a posteriori decision support tools as they adopt the concept of Pareto optimal solutions that present the explicit tradeoffs between the conflicting objective functions, before the decision-makers express their priorities and preferences. Moreover, they use a population of evolving solutions, thus, perform simultaneous optimization of conflicting objective functions and generate many solutions in a single run (King and Rughooputh, 2003). Accordingly, MOEAs are powerful tools that can be used in solving multiobjective cropping pattern planning problems. There is a large body of literature and models available for cropping pattern planning; nevertheless, the majority of them are concerned with bi-objective formulations in the form of direct economic benefits of crop production while maximizing irrigation water saving at a small scale (i.e., farm or district level). However, in arid countries, future cropping pattern planning is crucial not only to save water and maximize direct profit but also to enhance food security and economic stability at the national level, all the while not compromising the environment and other water users, e.g., municipal, industrial, power generation.

Therefore, the objective of this study is to introduce a more comprehensive national cropping pattern planning framework that adopts the understanding that water is a global resource that is being virtually traded. There are implications of such trade on national water and food security, and the complex interrelationships between food security and other national development plans that rely on water. The framework for the generation, analysis, and assessment of alternative cropping patterns in arid regions (ACPAR) is introduced in this chapter as a multiobjective framework that aids policymakers in water and food security assessment and management. ACPAR takes into account the major non-agricultural water uses that might be associated with national development scenarios, the globalization of water through the food (virtual water) trade, and the performance of the proposed solutions under possible national and global changes.

3.3 Egypt: The Imbalance of Supply and Demand

Egypt is located in northeast Africa and has a total land area of 1×10^6 km^2, 94% of which is uninhabited desert and the remaining 6% is cultivated agricultural and urbanized land. Egypt's climate is characterized by hot dry summers and mild winters. Internal water resources are very limited, and rainfall is irregular and very low with an annual average of 50 mm/year, leading to rainwater harvesting of only 1.3×10^9 m^3/year (FAO, 2018a; MWRI, 2010). In addition, Egypt withdraws 2×10^9 m^3/year from its fossil deep groundwater aquifers, and desalinates 0.2×10^9 m^3/year of seawater. The majority of Egypt's freshwater resources (97%) flow from upstream countries into Egypt via the Nile River. In 1960, Egypt built the High Aswan Dam to control its Nile water share of 55.5×10^9 m^3/year (MWRI, 2010). Under the pressure of water insufficiency, Egypt recently increased its water uses by increasing both the reuse of agricultural drainage water and abstraction from shallow groundwater aquifers. Egypt currently reuses a total of 16×10^9 m^3/year, and withdraws 6.2×10^9 m^3/year of its 8.4×10^9 m^3/year shallow groundwater safe yield (Abdelkader et al., 2018; MWRI, 2010). According to the Egyptian Ministry of Water Resources and Irrigation (MWRI), agriculture is the biggest water user, amounting to 67×10^9 m^3/year, followed by municipal water uses of 9×10^9 m^3/year and industry withdrawals of 2×10^9 m^3/year (MWRI, 2010).

Agriculture is an important sector of the Egyptian economy that contributes 14.5% of the gross domestic product of $287 Billion USD and employs 25% of available Egyptian manpower (CAPMS, 2017; FAO, 2018a). The major part of Egyptian agriculture aims to produce food, where 94% of the cultivated land is used for food production that is mainly consumed locally, as only 3% of the national food production is exported (FAO, 2018b). In recent decades, crop yields have increased significantly, leading to an increase in national food production from 40×10^6 tonnes/year in 1986 to 95×10^6 tonnes/year in 2013. Despite these increases, Egypt's food self-sufficiency (i.e. the ratio of food produced domestically to the total food consumed in Egypt) for the period between 1986 and 2013 was kept fixed at 80% but with a drop in the national water self-sufficiency (i.e. the ratio of national water supplied for all uses to all national water demands including net virtual water import) from 81% to 70% over the same period (Abdelkader et al., 2018; 2003; FAO, 2018b). However, the national water, food, and trade (NWFT) model developed by Abdelkader et al. (2018) projects alarming levels of deteriorating water and food security in Egypt to an average level of 50% self-sufficiency by 2050 due to sharp increases in population and water demand. Clearly, the agriculture sector that is currently constrained by water availability is incapable of fulfilling the rapid rate of increase in national food demand, which will lead to an increase in the nation's food (virtual water) imports. The Egyptian food consumption pattern is highly reliant on agriculture-based food, where 98% of the per capita daily calorie intake comes from agriculture sources (FAO, 2018b). Accordingly, population growth has a compounding effect that causes the water and food gaps to increase non-linearly; that is, the demand for food will increase while agriculture food production decreases due to the decrease in water availability caused by withdrawing more water for municipal and industrial uses, which have higher priority for water allocation (MWRI, 2010). Egypt now depends heavily on imported food, mainly cereals, to fill its growing food gap. The country is one of the world's biggest importers of wheat, with such imports covering 40% of its wheat consumption (FAO, 2018b).

Improving food self-sufficiency in Egypt will be challenging in the future, as it requires more water availability. The potential for increasing internal water resources in Egypt is very limited, and increasing external water resources through the transboundary Nile flows is an issue lying at the heart of a difficult debate and diplomacy, given the growing competition over the utilization of Nile water resources among all riparian countries (Swain, 2011). Egypt's dependence on food imports could alleviate the water-food security problem; however, it comes with high risks associated with domestic and global economics (e.g., price shocks) and global trade reliability and stability. Egypt can seek solutions by managing and planning some of its agricultural sector variables. Cropping pattern is a major decision variable in agriculture that influences economic and water conditions in the country. Hence, considering cropping pattern planning should take priority in remediating the anticipated water and food crises of Egypt. Egypt is an ideal case to demonstrate the proposed ACPAR framework due to its aridity and the effect thereof on national water and food security, the nation's position at the heart of the conflict over Nile River water, the availability of three documented national target water resources scenarios up to 2050 developed by the Egyptian government (MWRI, 2010; Tables C.1 and C.2 in Appendix C.2), and the ability of the NWFT model to handle Egypt's water-food nexus (Abdelkader et al., 2018) and its connection to the global virtual water trade. Although the government does not have full control over the cultivated crops (Shousha and Pautsch, 1997), suitable policy instruments and awareness programs could motivate farmers to adopt crop changes. For example, in 2018 the government regulated the cultivation of rice as a water-intensive crop. However, the extended and long-term impact of such policies on economic and water resources conditions has not been addressed.

3.4 Methodology

ACPAR is a hybrid policy-driven optimization-simulation framework that aims to assist decision makers in policies that shape the national cropping pattern. The framework incorporates an approach for cropping pattern planning process, which can be used to investigate policy change consequences on the national long-term hydro-economic and water-food security states, while taking into considerations the national water development plans and the global food trade dynamics. It consists of: (i) identifying the objective functions to be optimized in a multiobjective functions approach; (ii) generating an initial random population of alternative cropping patterns (ACPs) that represent diverse feasible cropping patterns; (iii) executing the simulation-based NWFT model to evaluate the objective functions, (iv) using a multiobjective optimization algorithm in an iterative mode to keep perturbing and evaluating the ACPs until a preset maximum number of iterations is met and a set of Pareto optimal ACPs are finalized over the baseline period (1986-2013). In our case study, 200 Pareto optimal ACPs were generated; (v) identifying additional filtering criteria that can be specified by decision-makers to narrow down the ACPs into a smaller and more manageable set. This filtering process provides decision-makers with flexibility regarding their criteria of choice and their threshold values, and it aims to allow them to intervene in making selections. Figure 3.1 depicts the ACPAR procedures as outlined above. The framework is configured to be executed under baseline conditions to understand the system under consideration and repeated under future conditions to identify changes from the baseline and make planning decisions. Different types of analyses were used under both conditions as explained in more details in the sub-sections below. The optimization method explanation and its parameterization process are provided in Appendix C.3.

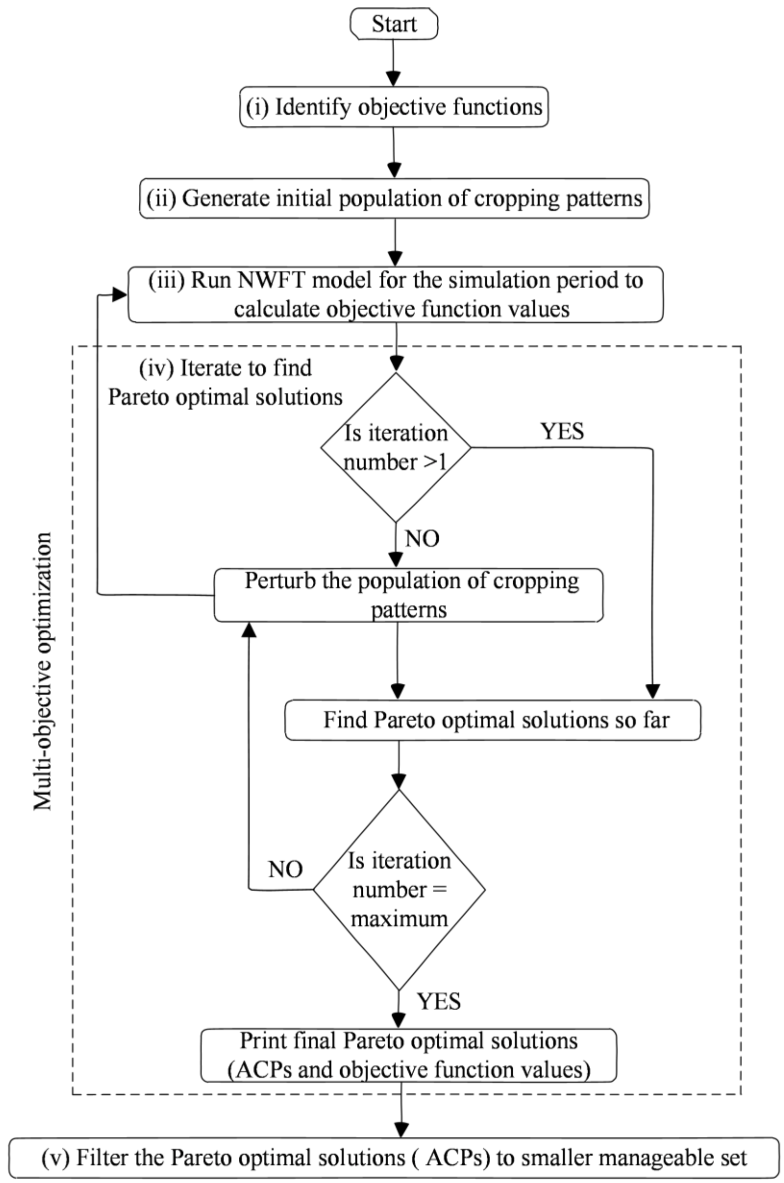

Figure 3.1: Flowchart of the main steps in the ACPAR framework.

3.4.1 The National Water, Food, and Trade (NWFT) Model

The NWFT model (Figure 3.2) is a national water and food supply and demand model in which the economic and population growth rates, along with per capita water demands are considered while estimating the annual water demands of municipal and industrial sectors. The model allocates available water annually according to supply priority rules, in which municipal, followed by industrial sectors are allocated water first, then, the agriculture sector can access the remaining water. The model considers the cropping pattern as a sole decision variable, and once it is determined, the NWFT model estimates water demand for agriculture, taking into consideration crop water requirements and annual irrigation efficiency. Subsequently, this water demand for agriculture is compared against the annual water available for agriculture and accordingly, crop yields are revaluated to account for water deficit's effect on crop yield (Doorenbos and Kassam, 1979). Using the estimated crop yields and the cropping pattern, the NWFT model calculates the annual national food production. On the other hand, the national food consumption (demand) is estimated based on per capita food consumption pattern, population, and economic growth rates. At this step, the national food trade can be calculated by comparing the national food production and consumption quantities, where food imports are estimated as the deficit in demand compared to production, and the food exports as the surpluses of production compared to demand. Those traded food quantities are translated to virtual water import and export. In addition, the model considers also the economic and environmental consequences of a cropping pattern change. The agriculture gross margin and economic costs of imports are evaluated, while the national fertilizer application rate is calculated within the environmental component of the NWFT model.

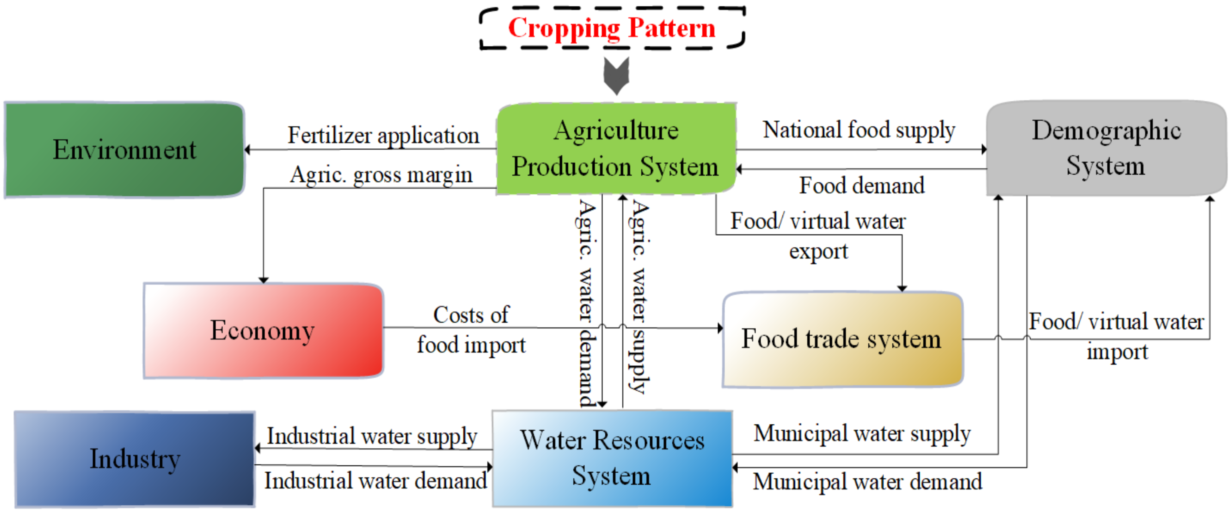

Figure 3.2: Simplified schematic diagram for the NWFT model structure with focus on cropping pattern as the decision variable, the diagram reflects the cropping pattern's complex Socioeconomic and environmental interrelationships as represented in the model.

In performing the above-mentioned calculations, the model uses a group of key variables, some of them were inevitably constrained to account for resources availability limitations. Those variables and their constraints are explained in appendix C.4 and Table C.6. Moreover, the following sections present the major calculations performed in the NWFT to estimate the values of all objective functions and filtering criteria, while all the detailed methods and equations used in NWFT calculations, along with the model validation, can be found in Abdelkader et al. (2018).

3.4.2 Objective functions and Decision Variables

Four hydro-economic objectives were selected to reflect the interests of decision makers in the conflicting objectives of maximizing national economic benefits while saving more water and maximizing food security as follows: (1) gross margin (GM, USD/year) within the agriculture sector, which is defined as the difference between the revenue of a crop (market price) and the variable production costs (Brink and McCarl, 1978). In this study, the GM objective function was evaluated annually and maximized (Eq. 3.1) based on the average value over the entire simulation period. The GM was calculated as the summation of the national product of crops (tonnes) multiplied by the net revenue (USD/tonne) based on the local market price. The global market price was used for the portion of crops that was exported. Data related to local and global prices of crops consumed and produced in Egypt, for each year, were gathered from the FAOSTAT database (FAO, 2018b). The variable costs of crop production were retrieved from the Egyptian Ministry of Agriculture and Land Reclamation (MALR, 2016); (2) economic cost of imports (ECI, USD/year), which is the cost of imports of each crop, expressed as the price of each crop in the global market multiplied by the quantity of the imported crop, then summed over all crops. The simulation period average ECI was minimized in this study (Eq. 3.2). This excludes transportation costs and any taxes or duties; (3) the national annual water demand for agriculture (WDA, m^3), which was calculated as the crop water requirement multiplied by the crop area, summed over all crops. This objective function was minimized (Eq. 3.3) to rationalize the water use in Egypt; and (4) the virtual water import (VWI, m^3), which is the amount of water consumed to produce the imported crops (water footprint of imported crops). The rationale behind this function is to reflect the country's reliance on imported food and the global trade. To maximize Egypt's food self-sufficiency, this objective function was minimized (Eq. 3.4). It also represents Egypt's global responsibility to minimize any overexploitation of global water resources. The NWFT model can estimate both annual WDA and VWI.

$$maximize\ GM = \frac{\sum_{t=T_0}^{T}\sum_{i=1}^{n}\left(\left(PL_i(t)-VC_i(t)\right)*Y_i(t)*A_{ij}(t)+\left(PG_i(t)-PL_i(t)\right)*EXP_i(t)\right)}{T-T_0+1} \tag{3.1}$$

$$minimize\ ECI = \frac{\sum_{t=T_0}^{T}\sum_{i=1}^{n} IMP_i(t)*PG_i(t)}{T-T_0+1} \tag{3.2}$$

$$minimize\ WDA = \frac{\sum_{t=T_0}^{T}\sum_{i=1}^{n} CWR_{ij}*A_{ij}(t)}{T-T_0+1} \tag{3.3}$$

$$minimize\ VWI = \frac{\sum_{t=T_0}^{T}\sum_{i=1}^{n} VWI_i(t)}{T-T_0+1} \tag{3.4}$$

where T_0 and T are the first and the last year of the simulation period, respectively, n is the total number of crops, $PL_i(t)$ is the local market price of crop i in year t (USD/tonne), $VC_i(t)$ is the variable costs of production for crop i in year t (USD/tonne), $Y_i(t)$ is the estimated crop yield subject to the amount of available water for crop *i* in year *t* (tonnes/ha, Doorenbos and Kassam, 1979), $A_{ij}(t)$ is the area assigned to crop *i* in cropping season *j* in year *t*, $EXP_i(t)$ is the national exported quantity of crop *i* in year *t* (tonnes), $PG_i(t)$ is the average global market price of crop *i* in year *t* (USD/tonne), $IMP_i(t)$ is the national imported quantity of crop *i* in year *t* (tonnes), and CWR_{ij} is crop water requirements for crop *i* in season *j* (m^3/ha).

The set of decision variables *X* shown in Eq. (3.5) is the cropping pattern, which comprises the percentage of each crop area (x_i) of the total land available for a number of crops *n*, which are 14 major crops and crop groups for the case of Egypt. The land available for agriculture can change from year to year, and is affected by urbanization, grazing, and reclamation rates. The cropping pattern (i.e., *X*) was assumed fixed throughout the simulation period for a particular simulation run. The purpose of optimization was then to find the optimum pattern through the whole simulation period given the predetermined constraints.

$$X = \{x_i, \ldots.., x_n\} \qquad x_i \in (0,1) \qquad (3.5)$$

3.4.3 The Optimization Method

ACPAR incorporates a method named Uniform Spacing Multiobjective Differential Evolution (USMDE; Chichakly and Eppstein, 2013), which comprises a synergy of good features compiled from different EAs. USMDE's basic algorithm is Differential Evolution (DE), which is a single objective search operator that proved to converge significantly faster compared to other EAs (Storn and Price, 1997). The USMDE can solve multiobjective problems as it adopts the features of the well-known algorithm of non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002). However, the main advantage of USMDE to decision makers is that it expresses the tradeoffs between the objective functions in more diverse and consistent way compared to other methods (Chichakly and Eppstein, 2013). Accordingly, the USMDE was considered an appropriate choice for the ACPAR framework, however, it requires proper parameterization to generate reliable Pareto optimal solutions, and in this study, we performed a parametrization exercise for ACPAR and its application to Egypt as explained in details in Section C1.3. This parameterization process concluded that ACPAR should produce 200 Pareto optimal ACPs in order to be accurate and well representative of the search space. The 200 ACPs can be reduced further using policy-driven filtering criteria.

3.4.4 Filtering Criteria

Filtering criteria represent a group of variables that are of specific interest to decision-makers; however, they are less important than objective functions. Thus, rather than including them as objective functions and increase the dimensionality of the problem, decision-makers would rather be interested in monitoring their values and compare them against satisfaction thresholds (i.e., filtering criteria). Filtering criteria are meant to be flexible, so they can be set after the ACPs are generated, and used to reduce their number to a manageable set that represents the ACPs of the most interest to decision-makers. There could be many trials of setting the filtering criteria and filtering the generated ACPs until the decision-makers are satisfied with the resulting ones.

Four variables were selected in this study as filtering criteria due to their significance and relevance. Two of them secure a pre-determined level of economic stability: the stability of agricultural gross margin (GM_s) and the stability of the costs of food imports (ECI_s), which are of high importance for proper economic planning in a country like Egypt with a less advanced economy. In the objective functions, we considered the period-averaged GM and ECI, which represent the average of annual values over the baseline period of 28 years (1986-2013), as well as for the future scenarios (2014-2050). In the filtering criteria, we set a threshold (Table 3.1) for the coefficient of variation (CV) of both *GM* and *ECI*, which is the standard deviation divided by the average value (GM_s and ECI_s). Lower GM_s and ECI_s values indicate less inter-annual variability, which reflects less uncertainty. The third filtering criterion is national food self-sufficiency (NFSS, kcal/kcal), which is defined according to Equations 3.6 and 3.7. Given the increasing food imports of Egypt (Abdelkader et al., 2018), it is important to select cropping patterns that do not lead to significant deterioration of Egypt's NFSS (Table 3.1). The last variable is the nation's average fertilizer application per unit area (NFAR, kg/ha), which is estimated using Equation 3.8. The fertilizer application rate in Egypt is one of the highest in the world (Potter et al., 2010), and this has negative effects on surface water quality and therefore, human and aquaculture health; hence, selecting cropping patterns that have lower fertilizer rates is environmentally desirable.

Table 3.1: The thresholds of the filtering criteria. NFAR stands for the country's average fertilizer application per unit area, NFSS is the national food self-sufficiency, and GM_s, ECI_s are the stability of agricultural gross margin and the costs of food imports, respectively.

Filtering criteria	Value
NFAR (kg/ha)	< 420
NFSS (kcal/kcal)	> 0.6
GM_s	< 0.23
ECI_s	< 0.6

$$NFSS(t) = \frac{National\ food\ consumption\ (t) - Imported\ food\ (t)}{National\ food\ consumption\ (t)} \quad (3.6)$$

$$NFSS = \frac{\sum_{t=T_0}^{T} NFSS(t)}{T - T_0 + 1} \quad (3.7)$$

$$NFAR = \frac{\sum_{t=T_0}^{T} \sum_{k=1}^{3} \sum_{i=1}^{n} FAR_{ijk}(t) * A_{ij}(t)}{\sum_{t=T_0}^{T} A_{ij}(t)} \quad (3.8)$$

where $FAR_{ijk}(t)$ is the fertilizer application rate (tonne/ha; FAO, 2005) of fertilizer nutrient k for crop i in cropping season j in year t, n is the total number of crops, and $A_{ij}(t)$ is the cultivated area (ha) of crop i in cropping season j in year t. The values in Table 3.1 were selected somewhat arbitrarily in this study to demonstrate the method; however, the values were meant to avoid major or unrealistic changes in the current agricultural practices in Egypt. The national fertilizer application rate (kg/ha) was set not to exceed the historical level by more than 15%, the food self-sufficiency not to go below 75% of the historical level, and the inter-annual variability (coefficient of variation) of the ECI and the GM not to exceed the historical value and 80% thereof, respectively.

3.4.5 Implementation of the ACPAR Framework

The considered 14 crops and crop groups (Table C.7) were assigned to two major cropping seasons as practiced in Egypt, so they can compete with their realistic substitutes during the implementation of the ACPAR framework. The framework was applied for the baseline period (1986-2013) and generated 200 ACPs whose performances were normalized (i.e., scaled between 0 and 1) relative to the maximum and minimum objective function values to easily evaluate them against each other. The normalized value of an objective function was estimated to ensure that improvements to the objective functions occur when the value approaches 1.0 (Eq. 3.9). Thus, the calculation method depends on whether the objective function is minimized (i.e., WDA, ECI, and VWI) or maximized (i.e., GM). The normalized ACPs were then analyzed, clustered into groups, and compared with historical cropping patterns (HCPs) in Egypt. The ACPs were reduced further using the filtering criteria and were analyzed to understand how cropping pattern changes affect the national hydro-economic state.

$$N(U^y) = \begin{cases} \frac{\max(U) - U^y}{\max(U) - \min(U)}, & \text{if } U \text{ is minimized} \\ \frac{U^y - \min(U)}{\max(U) - \min(U)}, & \text{if } U \text{ is maximized} \end{cases} \tag{3.9}$$

where $N(U^y)$is the normalized value of objective function U for Pareto optimal solution $y \in \{1, 2, \ldots, 200\}$, $N(U^y) \in (0,1)$. The ACPAR framework was also implemented under future scenarios of change, considering both national and global change conditions. Three different national target scenarios that represent three possible combinations of national water resource availability, water supply and demand, socioeconomic development plans, improvements in infrastructure, and population growth up to year 2050 were used: *Critical*, *Balanced*, and *Optimistic*. Abdelkader et al. (2018) modified the per capita food consumption pattern of the Balanced and Optimistic scenarios to reflect the impact of socioeconomic changes on food demand in Egypt. In this study, we added the changes to the crop yield and crop production losses to match the degrees of economic growth reflected by each scenario and its impact on the food production system. Details of the three scenarios as well as the baseline scenario are provided in Tables C.1 and C.2 in Appendix C.2.

The study required future global and local crop prices projected until the year 2050, which were available through the International Food Policy Research Institute (IFPRI, 2017). The IFPRI used the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT; Robinson et al., 2015) model, which connects global shared socioeconomic pathways (SSPs) and the IPCC's climate change scenarios to water availability and food supply, and their effect on market prices, to project future scenarios of global crop prices. Table C.1 and C.3 show the scenarios available through IMPACT and considered in this study, along with their major assumptions. Other scenarios are available through IMPACT, but those adopted in this study cover the whole range. Combining the three national scenarios of Egypt with the four global scenarios considered, resulted in a total of 12 different future scenarios to be investigated (Table C.4). Projections of local prices in Egypt are not available; however, based on correlations detected between the local and global prices over the baseline period, regression models were developed to project the local prices of various crops in the future based on the projected global prices. Examples of the regression models are presented in Figure C.4, in Appendix C.6.

ACPAR implementation under future conditions included similar steps as for the baseline but repeated for the 12 scenarios. Through optimization, under each of the 12 scenarios, the Pareto optimal 200 ACPs for each scenario were identified. Those ACPs were further narrowed down by applying the filtering criteria to the 200 solutions of each scenario separately. The filtered ACPs of the future (from all scenarios) were grouped with the filtered ACPs of the baseline period to form one group of ACPs. To select an ACP while addressing future uncertainty, we adopted the concept of planning under uncertainty, which is widely used in water resources research (e.g., Maier et al. 2016). The evaluation and selection of any ACP would not be based on its performance under any single scenario but under all 12 scenarios. In particular, each ACP was evaluated based on the mean of its objective function value calculated across the 12 scenarios and based on the robustness of each objective function under those future scenarios. This process necessitated that each of the filtered ACPs be simulated in the NWFT model to estimate its objective functions under each of the 12 future scenarios. Then, for an ACP "y", the mean of its objective function U^y across scenarios (i.e., $M(U^y)$) was calculated using Eq. 3.10. There are many ways to define and estimate the robustness (Herman et al., 2015); however, all of them reflect that robust plans should be insensitive to future conditions (Maier et al. 2016). We evaluated the robustness (R_u^y) of an ACP y for each objective function U, according to Eq.

3.11, as the number of scenarios under which the performance of y is satisfactory for objective U ($Sn(U^y)$) relative to the total number of scenarios under consideration (S_t), which is similar to the measure used by Paton et al. (2014). Under any scenario s, an ACP y is considered to have satisfactory performance in objective function U, only if the value of U^y under this scenario ($U_s{}^y$) does not violate a global threshold determined by decision-makers – valid for all scenarios (i.e., U_{th}). This threshold could be a desired future value for this objective (e.g., a minimum target gross margin of 35 billion USD/year).

$$M(U^y) = \sum_{s=1}^{S_t} \frac{U_s{}^y}{S_t} \tag{3.10}$$

$$R_u^y = \frac{Sn(U^y)}{S_t} \tag{3.11}$$

$$Sn(U^y) = \begin{cases} \sum_{s=1}^{S_t} 1\,\{U_s{}^y \leq U_{th}\}, & \text{if } U \text{ is minimized} \\ \sum_{s=1}^{S_t} 1\{U_s{}^y \geq U_{th}\}, & \text{if } U \text{ is maximized} \end{cases} \tag{3.12}$$

Where $U_s{}^y$ is the objective function of ACP y evaluated under scenario s, S_t is the number of scenarios under consideration (i.e., 12 scenarios). $Sn(U^y)$ is the number of scenarios under which the objective function U of an ACP y meets a threshold criterion (U_{th}).

3.5 Results

3.5.1 Baseline Application of the ACPAR Framework

The optimization of cropping patterns during the baseline period (1986-2013) resulted in 200 Pareto optimal solutions (ACPs). The normalized values of the objective functions were used for comparison of the 200 ACPs, where 1.0 and 0.0 denote the best and worst outcomes, respectively. The absolute values of objective functions were used to express the differences in magnitudes between the filtered ACPs.

3.5.1.1 The Objective Functions Tradeoffs

Figure 3.3 illustrates the tradeoffs, among cropping pattern objectives, for the case of Egypt during the baseline period, and it shows that the normalized gross margin improvement (approaches 1.0) can be achieved with improvement of water demand for agriculture (approaches 1.0, meaning less water demand and more water savings). Nevertheless, bubble colors turning into red and sizes become bigger, meaning higher ECI and more VWI, respectively. Thus, water-saving cropping patterns are those that can come with high agriculture gross margin, but they lead to higher costs of food imports and higher virtual water of imports, which means less food self-sufficiency.

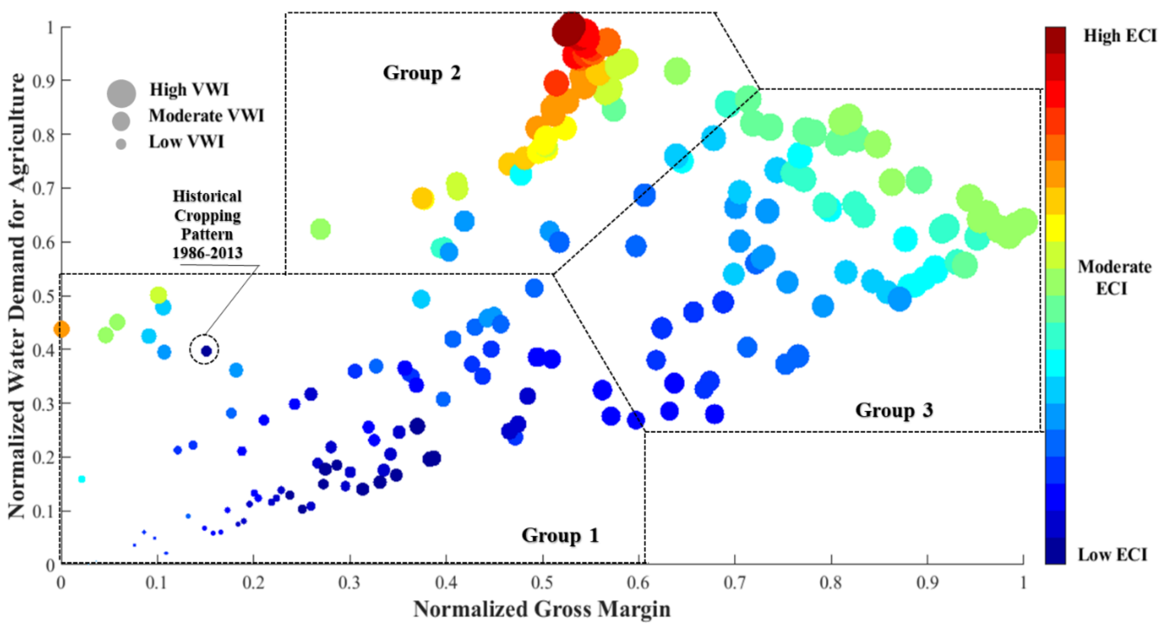

Figure 3.3: Bubble chart of the Pareto optimal solutions (ACPs) in the baseline period (1986-2013)and their corresponding normalized objective function values. The size of each bubble reflects the virtual water import (VWI), where a larger size means more VWI. The color of the bubble reflects the economic costs of food imports (ECI); the lowest ECI values are blue and the highest are dark red. Dashed lines represent K-means clustering of the Pareto optimal ACPs into three groups.

3.5.1.2 Clustering Analysis

To understand the link between various cropping pattern compositions and their corresponding objective function tradeoffs, the Pareto optimal ACPs were clustered into three distinguished groups using the k-means clustering method. The K-means started by randomly assigning centroid values for the three clusters (i.e., random location in the 4-dimensional objective function space). Then, based on the ACPs' objective function values, they were assigned to their nearest cluster, identified by its centroid. Iteratively, the new cluster centroids were recalculated, and then the 200 ACPs are reassigned to the nearest cluster, until the centroids do not change.

The dashed lines on Figure 3.3 indicate the three ACP groups, where each group represents a tail end condition in at least one of the objective functions. Figure 3.4 is complementary to Figure 3.3 as it shows the corresponding crop compositions of each group. Both figures implicitly reflect the existence of three thematic alternatives (with some exceptions) that characterize cropping pattern planning for Egypt. The first cluster contains more wheat than fodder crops (both are competing for land, as they are cultivated in the same season) while maintaining a balanced ratio distribution of other crops (group 1). This enhances food self-sufficiency, lowers VWI, and decreases ECI, but also leads to higher WDA and lower GM. The second cluster contains cropping patterns that have more fodder crops than wheat and significantly higher percentages of other cereals (group 2). This would yield the maximum water savings as other cereals and fodder crops require relatively less WDA, with also a reduced areas for high WDA crops like sugar cane and rice, while maintaining moderate GM because of the relative higher profitability of fodder crops in the local and global markets. The last cluster contains cropping pattern similar to the second one but rather than the relatively high ratio of other cereals, it contains significant vegetables ratio (group 3). This would yield the highest GM because of fodders' and vegetables' high profitability while maintaining moderate water savings. However, the undesirable aspects of groups 2 and 3 are the increase in VWI and ECI, meaning more costs of food imports and less national food self-sufficiency. As Figure 3.3 and Figure 3.4 show, the first group was practiced during the historical period (1986-2013); the historical cropping pattern (HCP) of Egypt falls in group 1, and has the lowest ECI, when compared with the 200 ACPs. This reflects that the collective decisions of stakeholders (i.e., farmers and decision makers) in selecting historical cropping patterns in Egypt seem to have been influenced by local market food demands and prices, leading to cropping patterns that favor reduced food import costs and maintain high food self-sufficiency, even though it required high WDA and yielded lower GM compared to other ACPs. Notably, the majority of the cropping patterns of the three groups have areas allocated to rice that is less than that of the HPC, which highlights the role of reducing rice areas as an essential crop change to save more water and to provide better optimal WDA values.

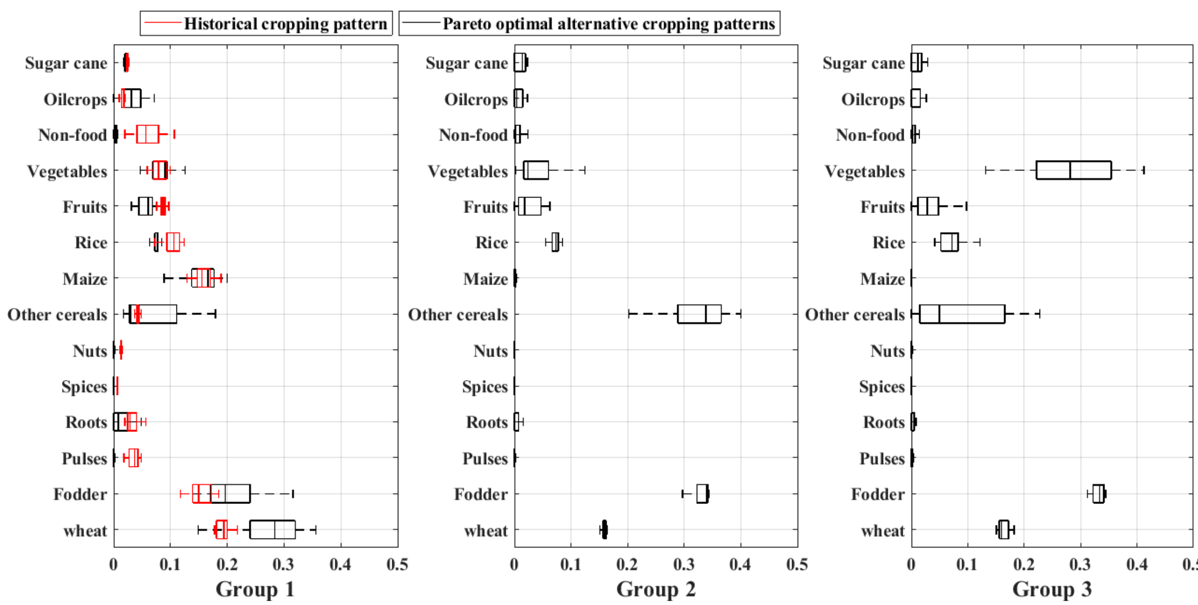

Figure 3.4: Box plot of the Pareto optimal alternative cropping patterns (ACPs) of each of the three groups and the historical cropping pattern (HCP). The x-axis represents the proportion of the cultivated area.

3.5.1.3 Narrowing Down the Set of Feasible Alternative

The 200 ACPs produced are considered equally good, unless decision makers' preference structure is identified. As it might be difficult to select from this large number of solutions, additional filtering criteria (explained in detail in Section 3.4.4) were used to keep only the ACPs that are of most interest. Applying the filters resulted in 19 solutions, presented in Figure C.5, in Appendix C.7, which all turned out to belong to group 1 as the HCP. The filtering criteria ensured that the ACPs show economic stability and acceptable fertilizer application and food self-sufficiency. A visual comparison between the 19 filtered ACPs and the HCP is given in Figure 3.5 and Figure C.6 (in Appendix C.7), which show that the HCP is superior with respect to its low ECI and VWI values, but moderate with regard to the WDA, and is the worst with respect to both the GM and GMs. This can be attributed to the fact that, unlike the generated ACPs, the HCP is not a fixed cropping pattern through the 28 years of the baseline period. The major change was the gradual replacement of cotton (i.e., part of non-food) by vegetables because of their relatively higher profitability, leading to higher variation in the GM, thus, making it a less stable option with a lower period-averaged value.

The filtered ACPs reflect different levels of tradeoffs between the objective functions, but ACP-18, in particular, has interesting characteristics. This alternative would have been a good substitute for the HCP. ACP-18 has food self-sufficiency (NFSS) and ECI that are comparable to the HCP, it could have slightly improved the food self-sufficiency from 80% to 82%, and slightly increased the ECI from 4.3 to 5.4 billion USD/year. However, it would have significantly increased the GM from 17.2 to 19.9 billion USD/year (i.e., net gain of 1.6 billion USD/year), and maintained better stability for GM and ECI. Two disadvantages for this ACP are the increased demand for water (increase of 5×10^9 m^3/year) and the slightly higher fertilizer application rate (increase of 35 kg/ha/year; see Figure C.6 in Appendix C.7). The major difference between ACP-18 and the HCP is more wheat and fodder crops and less non-food crops and pulses. Details of the cropping patterns are provided in Table C.8, in Appendix C.7. ACP-2 is another remarkable ACP, it would have been desired if the GM and saving water were given priority over having a high food self-sufficiency and low ECI. ACP-2 would have increased the GM of the HCP from 17.2 to 22.6 billion USD/year, but also increased ECI from 4.3 to 8.5 billion USD/year, and maintained better stability for GM and ECI. Moreover, it would have saved 1.3×10^9 m^3/year of agriculture water, but at the cost of increasing the VWI by 6.5 $\times 10^9$ m^3/year. There are two major disadvantages of this ACP; it would have decreased food self-sufficiency from 80% to 69% and increased fertilizer application rate by 26 kg/ha/year. The major changes of this cropping pattern compared to the HCP are the significant increase in fodder crops and other cereals and the decrease of wheat, rice, non-food, fruits, and pulses (Table C.8, in Appendix C.7). Analyzing cropping patterns in the baseline period provides information on what could have been done in the past to reach desired water, economic, environmental, and food self-sufficiency states.

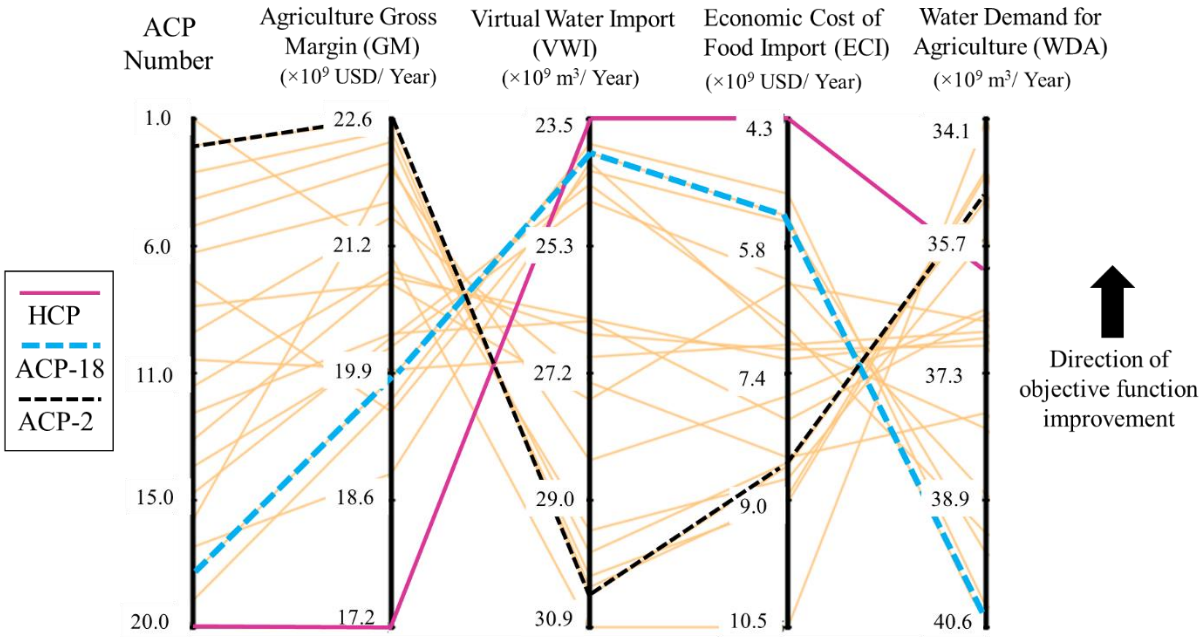

Figure 3.5: Parallel coordinate plot shows the four objective functions for the 19 filtered ACPs found in the baseline period (1986-2013), and the historical cropping pattern (HCP). Axes value increase from top to bottom except for the second axis (i.e., GM).

3.5.2 Application of the ACPAR Framework under Future Scenarios

The 19 filtered ACPs of the baseline period, as well as the HCP, are not necessarily suitable solutions for the future. Thus, to search for ACPs that might be superior under future conditions, the simulation-optimization framework was repeated under the 12 future scenarios for the period between 2014 and 2050. Through optimization, 200 future ACPs were generated under each scenario (i.e., 2400 in total). Those 2400 ACPs were further narrowed down by applying the filtering criteria on each scenario separately. Consequently, a total of 460 filtered ACPs were finalized from all 12 scenarios. Those 460 ACPs were grouped with the 19 baseline ACPs and the HCP to form one group of 480 ACPs. Finally, each of those 480 ACPs was simulated in the NWFT model to quantify their objective function values under the 12 future scenarios. For each ACP the mean of each objective function across the 12 scenarios was calculated. Moreover, to assess their response to future changes, the robustness of each objective function for each ACP was calculated using Eq. 3.11. In the remaining part of this section, a comparison between the baseline ACPs, including the HCP, versus the 460 filtered ACPs of the future is provided.

Then, the impact of future scenarios on the four objective functions of the different ACPs is discussed. Finally, we show how future decisions could be made to select one of the ACPs for consideration in future policies.

3.5.2.1 Comparison between Filtered Alternative Cropping Patterns

Figure 3.6 shows a comparison between 20 ACPs (the HCP and 19 baseline ACPs) versus the 460 ACPs found under future conditions (i.e., future ACPs). Interestingly, under future conditions, the baseline ACPs and the HCP lose their major advantage of having low ECI and VWI. The majority of the baseline ACPs have relatively good GM and WDA values, however, all of them have poor VWI and ECI values, compared with the future ACPs (Figure 3.6a). The reasons behind these changes are revealed by analyzing the differences in cropping patterns between the baseline and future ACPs. Our modeling framework recognizes wheat as an important crop whose area should increase in the future to maintain the superiority of an ACP in the objective functions of ECI and VWI. Wheat is an important crop for Egyptians; it constitutes 30% to 40% of the daily calorie intake, however, Egypt currently has a significant shortage in its wheat production, and it imports 40% of its demand. Under the three future national development scenarios, Egypt’s population grows sharply (Table C.2), driving Egypt's demand of its most consumed and imported crop (i.e. wheat) to increase. If this increase in demand is met by increasing wheat import, this would negatively affect the ECI and VWI. Accordingly, to help lower the ECI and VWI, the local production of wheat should increase. The ACPAR framework shows that the agriculture area allocated to wheat still needs to increase (Figure 3.6b) to maintain the low levels of ECI and VWI (minimize cost of import and maximize food self-sufficiency).

Increasing the area of wheat would have some disadvantages, wheat has a considerable water footprint (some other crops require less water to produce the same tonnage), and moderate profitability (significantly increased in the future, Table C.3, but still some other crops have higher profitability). Accordingly, increasing wheat area would likely increase the WDA and decrease GM. To substitute for this negative impact and keep the ACPs of the future competitive on minimizing WDA and maximizing GM, ACPAR balances the increase of wheat area by decreasing the area of crops with high water footprint and less profitability, such as other cereals and non-food, and expands the area of highly profitable crops with less water footprint, such as vegetables (figure 3.6b).

The only advantages of the baseline ACPs in the future are their low WDA and high GM, which do not seem to be exclusive characteristics, as there are some of the future ACPs that have comparable (or even better) GM and WDA values, with even better ECI and VWI values. This comparison indicates that decision-makers are less likely to favor any of the baseline ACPs nor the HCP in the future. Most probably, they would increase the area of wheat (among other changes indicated in figure 3.6b) to shift toward one of the 460 ACPs generated under the future conditions.

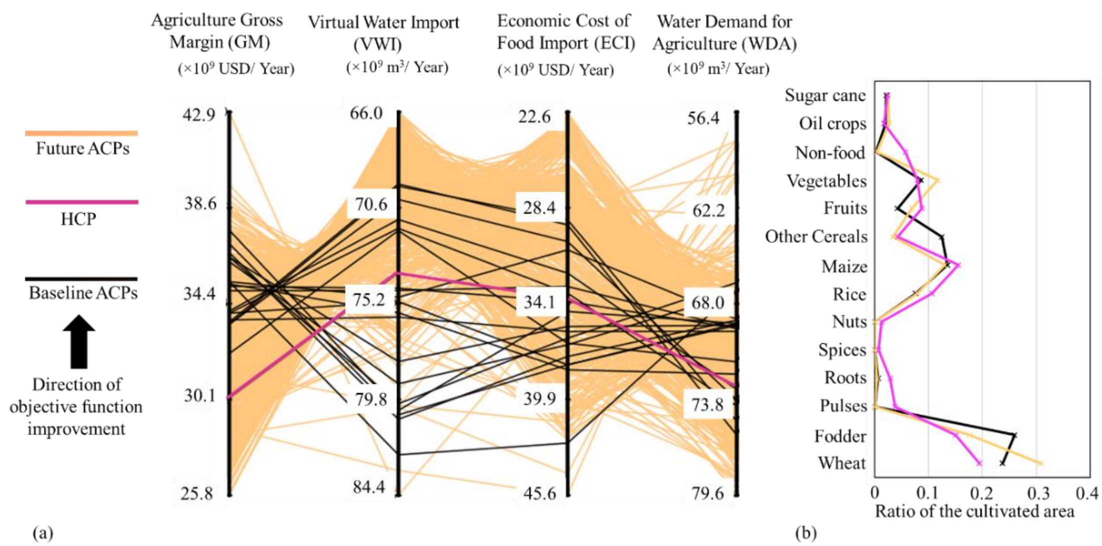

Figure 3.6: Comparison between the 460 ACPs identified under the future conditions versus the 19 ACPs identified under the baseline and the HCP considering: (a) their future objective functions evaluated for the period between 2014-2050 (each objective function is expressed as the mean across the 12 future scenarios, and axes value increase from top to bottom, except for the first axis); and (b) their median cropping patterns.

3.5.2.2 Future Changes in the Values of Egypt's Objectives

It is important to understand how the objective functions of the ACPs respond to the different future scenarios used in this study and how their values might change from their baseline conditions. Figure 3.7 reflects the average response of all the filtered 480 ACPs for Egypt. The GM seems to increase under all future scenarios compared to its baseline value; this is mainly because the prices increase under all considered scenarios (assuming fixed cost to price ratio; Table C.3). Additionally, GM is also influenced by the quantities produced of each crop, which is also increased under all future scenarios. Under future national development scenarios, the average agricultural area, crop yields, and water availability increase in comparison with the baseline, leading to higher crop production. The greatest improvement in GM occurred under the Optimistic national scenarios (scenarios 9 to 12) due to the relatively greater availability of water for agriculture, the largest expansion in agricultural land area, and the highest improvement in crop yields. Interestingly, the effect of climate change on GM can offset the effects of some national future developments. For example, the GM values under the Critical scenario, combined with climate change (Scenario 4) is as high as the national Balanced scenarios without climate change (Scenarios 5, 6, and 7). This can be attributed to the fact that food prices under the climate change scenario (SSP2-HGEM), as predicted by the IMPACT model, are higher than other price scenarios, leading to higher GM values. It is important to note that the GM of the agriculture sector improved under all scenarios, however, before considering this as a positive outcome, decision makers should also consider how the increase in crop prices are factored in this improvement, and how this might affect future food affordability.

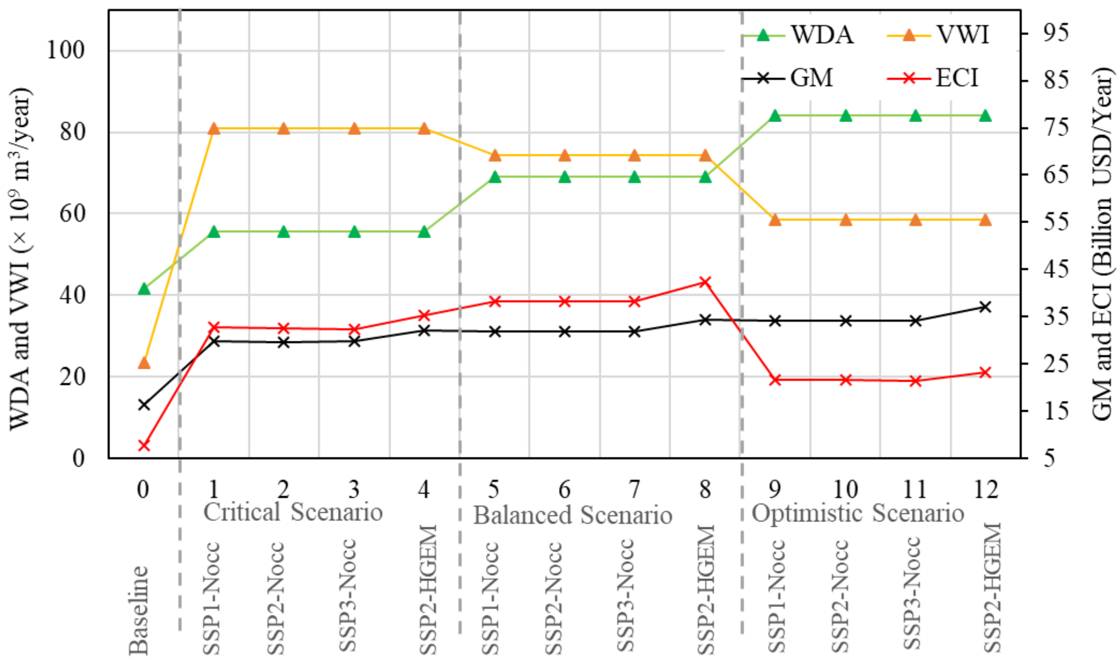

Figure 3.7: Impact of future scenarios on the four objective functions of crop pattern planning in Egypt (GM, VWI, ECI, and WDA). Each point represents a specific objective function value under a specific scenario, calculated as the mean across all the cropping patterns of the 480 filtered ACPs. The objective functions of the same 480 cropping patterns were calculated under the baseline conditions for comparison. The horizontal axis indicates the number and composition of each of the 12 scenarios and the baseline.

The increase in all four global price scenarios would increase the ECI relative to the baseline. The sharp increase in Egypt's population, embedded in all three national scenarios, leads to an increase in the ECI due to the increase in the food gap (Abdelkader et al., 2018). Importantly, however, these scenarios feature variations in food consumption patterns, population growth rate, and increased demand for crops, while crop production is constrained by varying levels of water availability. Under the Balanced scenario, ECI increases the most, possibly because of the change in the food consumption pattern from a cereals-based diet to one with more vegetables and meat, which are more expensive. Climate change (scenarios 4, 8, and 12) always results in additional negative impacts on the ECI of Egypt as food prices are higher than scenarios with unchanged climate. The influence of national development scenarios on the ECI is higher than their effects on GM, which means population growth and food consumption affect the ECI more than prices. Figure 3.7 shows that the best ECI future values are associated with the Optimistic scenario due to the greater water availability for agriculture in Egypt and the least population growth compared to other scenarios, leading to lower costs of food imports.

The VWI and WDA vary only in national development scenarios and remain unchanged under global price scenarios, which is an outcome of the formulation of our model, assuming that their values depend only on the national conditions (development scenarios), which is logical. This formulation was meant to allow for investigating the effect of cropping pattern, as a national policy variable, on the objective functions. Egypt's future is obviously and significantly better under the national Optimistic scenario, where the key variables are a lower population growth rate, which makes more water available for agricultural land expansion, and a consumption diet that is less dependent on meat (Table C.2). Egypt's conditions are also worse under the so-called Balanced scenario than the Critical scenario, which can be attributed to a more water-intensive food diet and more municipal and industrial water use under the Balanced scenario that makes less water available for agriculture.

Although future scenarios might affect the objective functions of all the 480 filtered ACPs in a similar direction (e.g. make an objective function increase for all the ACPs), the magnitude of this effect can vary largely among the ACPs according to their cropping pattern composition. Accordingly, decision-makers would be interested in ACPs that are less sensitive to deterioration under the widest portion of future conditions, which we express by the robustness measure of an ACP. As presented in Eq. 3.11, decision-makers would determine a threshold or a target for each objective function, such that the robustness would measure the ability of an ACP to surpass this target under the widest spectrum of future conditions. For this study, we determined the mean objective function values of the HCP under future scenarios (see Figure 3.6a) as the threshold values of 30.2 billion USD/year, 75×10^9 m^3/year, 34 billion USD/year, and 73×10^9 m^3/year for GM, VWI, ECI, and WDA, respectively. In this regard, the ACP that is more robust in a specific objective is the one that surpasses the mean future value of the HCP in this objective for the widest future conditions (more future scenarios), as explained in Eq. 3.12.

The robustness of ACPs can be investigated for each objective function separately, however, we found that a considerable number of the 480 ACPs has good robustness in all four objective functions simultaneously. Accordingly, those ACPs with good robustness were isolated and considered for further analyses as they are of much higher utility for decision making. This was achieved by dividing the 480 filtered ACPs into three groups according to their robustness: (i) the highly robust ACPs, Ih includes the ACPs that surpass the HCP in all objectives for more than 70% of the future scenarios (robustness ≥ 0.7 for all objectives); (ii) the moderately robust ACPs, which includes the ACPs that surpass the HCP in all objectives for more than 50% of the future scenarios (i.e. robustness ≥ 0.5 for all objectives); and (iii) the low robust ACPs, which includes ACPs not surpassing the HCP for more than 50% of the future scenarios in at least one objective. Only the first two groups were considered for further analyses, interestingly, the 19 filtered ACPs of the baseline were all part of the third group (i.e. low robustness), which gives an additional reason for decision-makers to unfavor them for future selection.

Figure 3.8 shows these two groups with good robustness, both groups have ACPs with good performance in gross margin (GM) and water use (WDA), but group 1 (highly robust) has lower cost of import (ECI), while group 2 (moderately robust) has higher food self-sufficiency (lower VWI). To understand what could have made an ACP more robust than the other, the cropping pattern of the three groups was investigated, see figure C.7. As the figure shows, there is a clear overlap between the cropping patterns of the three groups. Thus, it does not seem that there is a definite relationship between a specific cropping pattern compositions and the robustness of an ACP. Rather, robust ACPs are cropping patterns that come from different regions of the domain of cropping patterns.

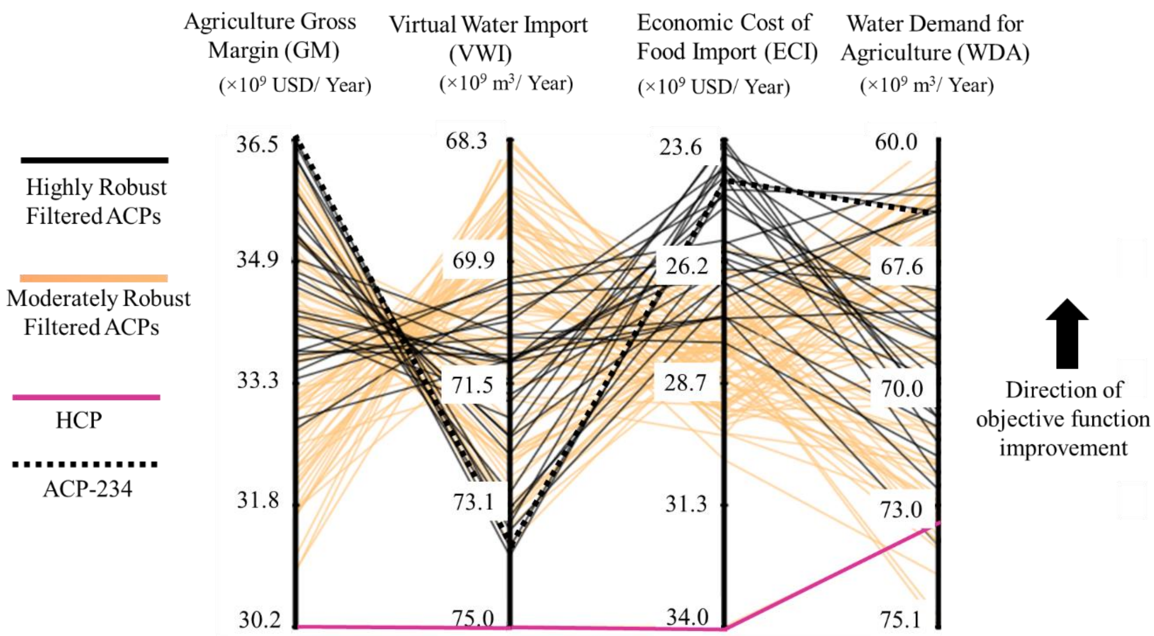

Figure 3.8: The objective functions evaluated for the period between 2014-2050 for the robust two groups of filtered ACPs (i.e., highly, and moderately robust ACPs) and the HCP. Each objective function is expressed as the mean across the 12 future scenarios. Axes value increase from top to bottom except for the first axis (i.e., GM).

3.5.2.3 Future Planning Decisions

Policymakers can use the ACPAR framework, proposed in this study, for crop pattern planning based on two major criteria: (i) their preference structure regarding the objective functions and (ii) the consideration of future uncertainty by selecting robust ACPs that performs well under the widest range of scenarios. For example, the ECI seems to have been the main decision factor in Egypt (Figure 3.5), as inferred from the HCP. If this situation continues in the future, Figure 3.8 can be used to select one of the ACPs from the two robust groups while considering this preference of low ECI. ACP-234 is one of the possible selections under this criterion. This ACP is characterized by a low ECI value of 24.4 billion USD/year compared with the HCP's 34.0 billion USD/ year if it continues in the future. Moreover, ACP-234 has a GM that is higher than the HCP by 6.3 billion USD/ year. Besides these economic gains, this ACP could also save water as it has WDA value that is lower than that of the HCP by 8.0×10^9 m^3/year, and the VWI also could be decreased by 1.2×10^9 m^3/year. More importantly, this ACP belongs to the highly robust ACPs group (group 1 in figure 3.8), meaning that its superiority over the HCP in the four objective functions is maintained for at least 70% of the future scenarios, reflecting higher chances of being superior, should the future come in different forms. The major changes required to shift the HCP to ACP-234 are a significant increase in the cultivated areas of wheat, fodder, and non-food from 19%, 15%, and 6% in the HCP to 26%, 22%, and 10%, while reducing fruits, maize, and pulses from 9%, 16%, and 4% to 6%, 10%, and 1% (Table 3.2).

Table 3.2: The cropping patterns of a possible selection for future implementation and the HCP expressed as a ratio of each crop area to the total cultivatable land available.

CP Name	Wheat	Fodder	Pulses	Roots	Spices	Nuts	Rice	Maize	Other Cereals	Fruits	Vegetables	Non-food	Oil crops	Sugar cane
HCP	0.19	0.15	0.04	0.03	0.01	0.01	0.10	0.16	0.04	0.09	0.08	0.06	0.02	0.02
ACP-234	0.26	0.22	0.01	0.01	0.00	0.00	0.07	0.10	0.04	0.06	0.09	0.10	0.02	0.02

3.6 Discussion

Some of the ACPs that we analyzed reveal crop compositions that might not be acceptable to farmers and policymakers, e.g., eliminating particular crops as shown in Tables 3 and C.8. Sudden and significant changes like this could lead to local socioeconomic costs to small farmers and industries that rely on these crops. Some of the crops also have multi-dimensional benefits, such as rice cultivation in the Nile delta of Egypt, which is important for reducing seawater intrusion and balancing soil salinity. Sudden changes to rice areas could lead to severe environmental problems. Other crops would have an irreversibility problem; for example, some fruit trees, once their area is reduced, cannot easily increase again because it takes years to grow and become fully productive. In addition, shifting cropping patterns could seriously affect the nutritional health of the population. In developing countries, making imported crops affordable and accessible might be challenging. Accordingly, maintaining a certain level of diversity in the cropping pattern is necessary to make diverse food finding its way to small markets, and to preserve the dietary intake of broader range of the population more balanced and healthier. Moreover, cropping patterns that are selected today should be favored if they are adaptive or flexibly accept changes over time with the least negative impacts (e.g., socioeconomic, environmental). Thus, while selecting ACPs, it is important to consider how an ACP would be easily evolving from the existing cropping pattern, and also how easy it accepts multiple changes over time. In our study, the generated ACPs met all of the objective functions and the filtering criteria that we selected a priori. However, this multitude of other considerations can be incorporated by setting cropping area constraints within the NWFT model or by adding additional filtering criteria within the ACPAR framework, both of which are easily implementable.

In the current formulation of ACPAR, we kept the cultivated ratio of each crop constant over the entire simulation period within a particular scenario. Another possible approach is to allow for periodic changes in the pattern, e.g., every five years, in response to changing conditions. The ACPAR framework can be re-run every five years with new conditions as a way to use the proposed framework for dynamic decision-making, and to reduce the uncertainty of long-term planning decisions.

In this study, there was less emphasis on the spatial representations related to cropping pattern distribution, variations of input variables, and model outcomes. In particular, variables like crop water requirements and crop prices were aggregated as national average values. When there is a shortage in the water supply for agriculture, it was considered as a uniform water deficit that impacts all crops. In reality, this shortage might only impact specific crops, depending on the season, crop type, and the availability of water from different sources, but mainly the crops cultivated at the most downstream part of the water system are known to be impacted the most. Another implication of spatial aggregation is that ACPAR would not be able to provide decision-makers with spatial information about cropping pattern changes but only changes at the national level. In a previous study, we showed that such aggregations and assumptions have an ignorable impact on the accuracy of our model results regarding the annual national agriculture water demand and the national production of each crop (Abdelkader et al., 2018). Accordingly, for this study, we trust that this issue has insignificant impact on the calculated national objective functions of Egypt. However, this concern remains valid, especially if ACPAR is applied to other countries that have significant spatial variability in model variables and outcomes. In such cases, it is crucial to modify the ACPAR framework to incorporate more explicit spatial representations.

The filtering criteria used in this study included the coefficient of variation of the GM and ECI to maintain ACPs with relatively more stable GM and ECI over the simulation period. One disadvantage of this formulation of stability is that it might penalize both the high and low values of GM and ECI. The use of this formulation did not affect the filtering outcomes for this case study, as the filtered ACPs were significantly dependent on other filtering criteria (i.e., NFSS and NFAR). However, we acknowledge the limitation of this formulation and recommend for similar studies an alternative formulation that only penalizes ACPs that have deviations from the mean (i.e., period average) toward undesired directions (e.g., low GM, and high ECI).

In this paper, we set the objective functions to match with the stated targets of our study, which were to provide cropping patterns that can enhance the water and food security states of Egypt, while increasing the economic benefits. Our selection of the objective functions also allowed for establishing a connection between the global food trade dynamics and the national water management decisions. More specifically, the link between the changes of global food prices and national water management within the agriculture sector, to meet the set objectives through changing cropping patterns, is a key contribution of this work. We acknowledge that there is no single way to set the objective functions, but different forms could be used to express the same targets. For example, the GM, ECI, and WDA might be combined to form an overall societal utility objective that can be maximized. The objective function of VWI was minimized to secure better food self-sufficiency conditions and reduce Egypt's burden on the global water resources. Such a criterion shows its importance in circumstances of a disconnected world; the Covid-19 pandemic of 2020 is an example. However, it might be argued that Egypt can import its food from only water rich countries. Accordingly, this objective function can be replaced with an explicit food security metric. The evaluation measures of robustness and mean of objective functions across scenarios could have been used within the objective functions rather than just evaluation and selection criteria. However, as the matter of selecting objective functions would always remain debatable, we acknowledge that the process should be performed by including various stakeholders that are interested in national cropping pattern planning (i.e., farmers, industries, etc.) in discussions about the determination of those objective functions and how they are formulated.

The government of Egypt is the major stakeholder targeted in this study, which is known to have policies to intervene periodically in the national cropping pattern by setting incentives and penalties to direct farmers to cultivate specific crops. This might not be valid for other countries where the government has no-intervention policy in shaping national cropping patterns. However, in such a case, the ACPAR can be modified, for example, to reflect the interest of stakeholders, rather than the government, that would benefit from the cropping pattern planning and has the control of changing it (e.g., farmers, industries).

As part of the future scenarios used in this study, a constant price-cost ratio was assumed for the estimation of the agriculture sector's gross margin in the future. Even though this is not an unrealistic assumption, it is an important assumption to keep in mind when analyzing and understanding the results derived from the ACPAR framework. The issue of predicting the local crop prices in Egypt in the future is also related to the previous point. We projected the local market price based on the global market price, which is a reasonable assumption given that Egypt is moving fast towards free-market mechanisms (Joya, 2017). However, another option in future studies is to develop a (or use an existing) computable general equilibrium (CGE) model for Egypt that links supply, demand, and prices (MWRI, 2001), noting that CGE models also contain several assumptions about the market mechanisms and consumer behavior and, in turn, the stationarity of such relationships in the future might be questionable (Arthur, 1999).

Finally, one should note the importance of the outcomes presented by this study for integrated water resources management in Egypt. Under scenarios featuring shortages of Nile River water flowing into Egypt, cropping pattern changes can reduce the amount of water needed for agriculture significantly. This reduction can be even more than the governmental municipal water demand reduction plans. Egypt's most optimistic future scenario assumes a reduction in the future water demand for municipal uses by only 5.0×10^9 m^3/ year, while ACPAR proposed cropping patterns that can reduce the future demand for irrigation by amounts that exceed this number (see Figure 3.8). However, reducing irrigation water demands will come with the tradeoffs of increasing the cost of food imports or reducing food self-sufficiency. ACPAR was able to avoid such consequences by introducing robust ACPs that outperform the HCP in these objective functions, while reducing irrigation water demands, for wide future conditions. Abdelkader et al. (2018) presented a quantitative analysis of the sensitivity of Egypt's food gap to the scenario of reduced water availability. This scenario of reduced national water availability is critical for Egypt's consideration and should receive special attention in light of the heated negotiations within the Eastern Nile Basin regarding the potential consequences of the Grand Ethiopian Renaissance Dam (GERD). The GERD is expected to negatively affect Egypt's annual water supply, especially during recurring drought periods in the Eastern Nile Basin.

3.7 Conclusions

In arid regions, water security cannot be separated from food security as the requirements of agricultural crop production make the agriculture sector the major water consumer. Any decrease in crop production leads to a decrease in the national gross margin of the agriculture sector, decline in food self-sufficiency, and increase in the economic cost of food imports. Therefore, efficient management of agricultural water has a multitude of socioeconomic implications, and thus is of high priority. However, such management must take into account the physical and socioeconomic considerations of both water and food security. In this study, a framework for the generation and assessment of alternative cropping patterns in arid regions

(ACPAR) was developed. ACPAR is an optimization-simulation framework that was introduced to assist decision makers in comprehensive planning for agriculture by changing cropping patterns while considering the impacts on important national variables, such as the water demand for agriculture (WDA), agriculture gross margin (GM), economic costs of import (ECI), and virtual water (food) imports (VWI). Egypt was considered a representative case of arid regions to apply the framework, generate a large number of alternative cropping patterns (ACPs), and investigate the tradeoffs among different objectives. The national fertilizer application rate, desired percent of national food self-sufficiency, and inter-annual variability of the GM and ECI were considered as additional criteria with threshold values that can be set by decision makers to filter the generated ACPs.

The ACPAR framework uses the NWFT model, which simulates water resources availability, competing uses, agricultural crop production and consumption, and the food trade of Egypt. The framework was implemented for the baseline period (1986-2013) as well as under future uncertainty represented by different scenarios up to 2050. Twelve combinations of national water and socioeconomic target scenarios and global projections of food prices subject to different shared socioeconomic pathways (SSPs) were considered. The results show that the thematic tradeoff that exists, when performing the cropping pattern planning in Egypt, is that minimizing the economic costs of food import and maximizing food self-sufficiency come at the cost of increasing agricultural water use and lowering the gross margin of the agriculture sector. In the baseline period, however, Egypt's historical cropping pattern (HCP) implied preferences to minimize the ECI and maximize the food self-sufficiency. In the future, the previously adopted policies of increasing total cultivated land area and improving the yields of different crops might not be enough, most likely Egypt would need to increase the area allocated for wheat cultivation. This action increases the water demand of agriculture and reduces the agricultural gross margin, which would require other cropping pattern changes, such as reducing the areas of water-intensive, less profitable crops (e.g., other cereals), and increasing the areas of water-saving, highly profitable crops (e.g., vegetables). This type of changes to the HCP should be applied carefully as our results show that the performance of ACPs is highly dependent on the combination of cropping pattern changes performed. Small differences between cropping patterns could result in deteriorations or improvements of the objective functions relative to the HCP. The ACPAR framework helps determine robust cropping patterns that can outperform the

HCP in all objective functions under wide future conditions.

Using frameworks, like ACPAR, that consider conflicting multi-objectives helps to minimize possible negative consequences of planning decisions. In addition, considering future and its uncertainty in cropping pattern planning proved to be significant, as this helps in finding cropping patterns that can perform well under a wide range of conditions. Tradeoffs are easily quantifiable using the ACPAR framework, which connects national water resource management to global food production, prices, and trade dynamics.

3.8 Acknowledgment

The authors acknowledge the financial support of the Natural Sciences and Engineering Research Council (NSERC) of Canada through the NSERC-DG grant # 403047. Author Abdelkader also acknowledges the University of Saskatchewan's devolved scholarship fund. Data used in this study are referenced in this chapter with links to allow readers access to them. The sources of data used in this study are as follows: FAOSTAT (http://www.fao.org/faostat/en/#data), Water footprint (https://waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/), and the International Food Policy Research Institute (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/XEZXT4

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Chapter 4 Future pathways of water, energy, and food in the Eastern Nile Basin

This chapter is a manuscript submitted to a peer reviewed journal. The content of this chapter is a modified version of this article submitted for possible publication, modifications to make it consistent with the format and body of the thesis.

Authors Contributions and The Contribution of This Chapter to The Overall Study

The following are the contributions from the different authors of this (chapter) manuscript. A. Abdelkader contributed to the conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing - original draft, and visualization. A. Elshorbagy contributed to the conceptualization, writing - review & editing, and supervision, M. Elshamy contributed to writing- review & editing, and H. Wheater contributed to writing- review & editing.

This chapter address the second objective of this thesis, this includes quantifying the value-added from planning and managing of water and food sectors within a multi-sectoral approach that adds the energy sector to those two and considers them as one integrated system. This also investigates the benefits of regional WEF assessments in improving water-food-energy conditions, as an approach to addressing the problem of limited and conflicted shared water resources. The work adds to the huge body of literature of similar nature that was performed for the Eastern Nile basin, as it considers evaluating future WEF conditions under a wide range of development plans. Moreover, it considers, for the first time, the uncertainty in WEF conditions under multiple social and climate change scenarios, and performs the analysis on regional scale with equal importance for each country in the region to highlight states that could lead to WEF planning trade-offs or synergies.

4.1 Abstract

The Eastern Nile Basin (ENB) countries of Egypt, Sudan, South Sudan, and Ethiopia are subject to pronounced water, energy, and food (WEF) insecurity problems. There is a need to manage the WEF nexus to meet rapidly increasing demands, but this is extremely challenging due to resource scarcity and climate change. If countries that rely on shared transboundary water resources have contradictory WEF plans, that could diminish the expected outcomes, both nationally and regionally. Egypt as the downstream Nile country is concerned about ongoing and future developments upstream, which could exacerbate Egypt's water scarcity and affect its ability to meet its WEF objectives. In this context, we introduce a multi-model WEF framework that simulates the ENB's water resources, food production, and hydropower generation systems. The models were calibrated and validated for the period 1983-2016, then utilized to project a wide range of future development plans, up to 2050, using four performance measures to evaluate the WEF nexus. A thematic pathway for regional development that showed high potential for mutual benefits was identified. Results indicate that the ENB countries could be nearly food self-sufficient before 2050 and generate an additional 42000 GWh/yr of hydropower, with minimal impacts on Egypt's water scarcity problems. The WEF planning outcomes for the region are sensitive to climate change, but, if social drivers can be managed (e.g., by lowered population growth rates) despite the difficulties involved, climate change impacts on WEF security could be less severe.

4.2 Introduction

Pressures on global water, energy, and food (WEF) systems are rapidly expanding. WEF demands are highly increasing, driven by population and socioeconomic growth. However, increasing the WEF supply is challenged by resource scarcity (Beck and Walker, 2013). Climate change exacerbates the problem, as it may increase demand and reduce supply in several regions (Hanjra and Qureshi, 2010). This gains more importance, knowing that WEF resources and sectors are interrelated in what is known as the WEF nexus (Cai et al., 2018; Wu et al., 2021). The region of the Eastern Nile Basin (ENB) is one where the ability to meet its growing WEF demands is increasingly challenging, with possible climate change leading to increasing concerns among the region's countries about future WEF conditions.

The ENB in north-eastern Africa encompasses parts of Egypt, Sudan, South Sudan, and Ethiopia, with a total area of 1.8 million km^2 (Figure 4.1). The characteristics of the region's WEF systems differ among the four countries. The Nile River is the main river system that connects the four countries and sustains the livelihood of more than 50% of their populations. The Nile has two main sources, the equatorial lakes, which contribute 15% to its mean annual flow, and the Ethiopian high lands, which contribute the remaining 85%. Ethiopia is the ENB's water richest country, as it has the highest annual precipitation and 12 major river basins, three of which contribute to the Nile (i.e., Blue Nile, Atbara, and Sobat; Figure 4.1). South Sudan and Sudan receive considerable precipitation but have no major perennial rivers except for the Nile and its tributaries. Although there is a relative higher availability of water in Sudan, South Sudan, and Ethiopia, there is a significant accessibility problem, especially for municipal uses, due to poverty and the absence of necessary infrastructure. Egypt is the water-poorest country in the ENB with negligible rainfall; the country is 97% dependent on the Nile River flow for its water uses. Over the past 60 years, the Egyptian population, as well as that of the rest of the basin, has grown by four-fold while the country's renewable water resources from the Nile have not changed, hence the country suffers severe water scarcity (Mekonnen and Hoekstra, 2016).

The rainfall in Ethiopia, Sudan, and South Sudan allows them to produce most of their food from rainfed agriculture, while Egyptian food production almost solely depends on irrigated agriculture. In the last 40 years, Egypt has boosted its food production by adopting new technologies (i.e., fertilizers, soil enhancements, pesticides, and using highly productive strains of seeds, etc..) that have significantly increased crop yields (FAO, 2021). However, Ethiopia, Sudan, and South Sudan mainly produce their food from rainfed agriculture, with much lower crop yields, as this type of agriculture lacks access to technology and is mainly performed on small-scale farms owned by poor farmers (Namara et al., 2008). Currently, Egypt's crop yield is twice that of the three other ENB countries (FAO, 2021). With all the improvements that Egypt has made, food production is still hindered by water scarcity, and insufficient and declining fertile land area. Food production is insufficient to meet the growing demand, which creates a pronounced food gap (i.e., shortage of local production to meet national food demand; Abdelkader et al., 2018). The rest of ENB is not doing better, however, their food gaps can be attributed to the lack of use of technologies to enhance crop yields, in addition to natural climate variability (Rockström et al., 2010) affecting their rainfed agriculture. Egypt fills its food gap by importing food from the global market, while the low purchasing power of the three other countries does not always allow this to happen. Portions of the population are left with unfulfilled food demands, resulting in malnutrition, and sometimes famines (Mera, 2018).

There is large potential for energy production in the basin countries, with a significant reserve of natural gas in Egypt, considerable oil reserves in South Sudan, and several opportunities for renewable energy in each of the basin's countries. However, among the various sources of energy, hydropower generation, especially in Ethiopia, is the major source that is directly tied in a nexus with the water and food sectors in the ENB region. Currently, Egypt is the only country that has energy production that exceeds its demand, with the surplus exported; 100% of its population has had access to electricity since 2016. Notably, Egyptian electricity is mainly generated from fossil fuel. Hydropower constitutes only 8% of the national electricity production with very limited potential for expansion (MOEE, 2021). The three other basin countries lack the capital and investments necessary for the production and distribution of energy, which leads to a significant energy deficit. South Sudan is the largest sufferer, with only 7% of its population having access to electricity, followed by 48% and 54% for Ethiopia and Sudan, respectively (World Bank, 2019).

There is clearly an immense need to improve the WEF conditions for the less fortunate portion of the 260 million people living in the region, but also for the projected 170 million increase in population by 2050 (United Nations, 2022). However, development plans to address WEF shortages can be problematic because of their dependence on scarce resources (e.g., water), which can lead to undesired trade-offs between sectors, either in the same country or across the basin. A contemporary example is the large hydropower dam (i.e., Grand Ethiopian Renaissance Dam; GERD) under construction on the major upstream tributary of the Nile (i.e., the Blue Nile; Figure 4.1). The GERD has triggered political tensions between Egypt and Sudan on one side and Ethiopia on the other side. In the future, the situation may worsen, given uncoordinated plans to build further dams and withdraw more water from the shared water resources in the basin, leading to more potential conflicts. Accordingly, the overarching objective of this study is to aid future WEF planning by identifying development pathways that could lead to common benefits and reduce the potential for conflicts among the ENB countries.

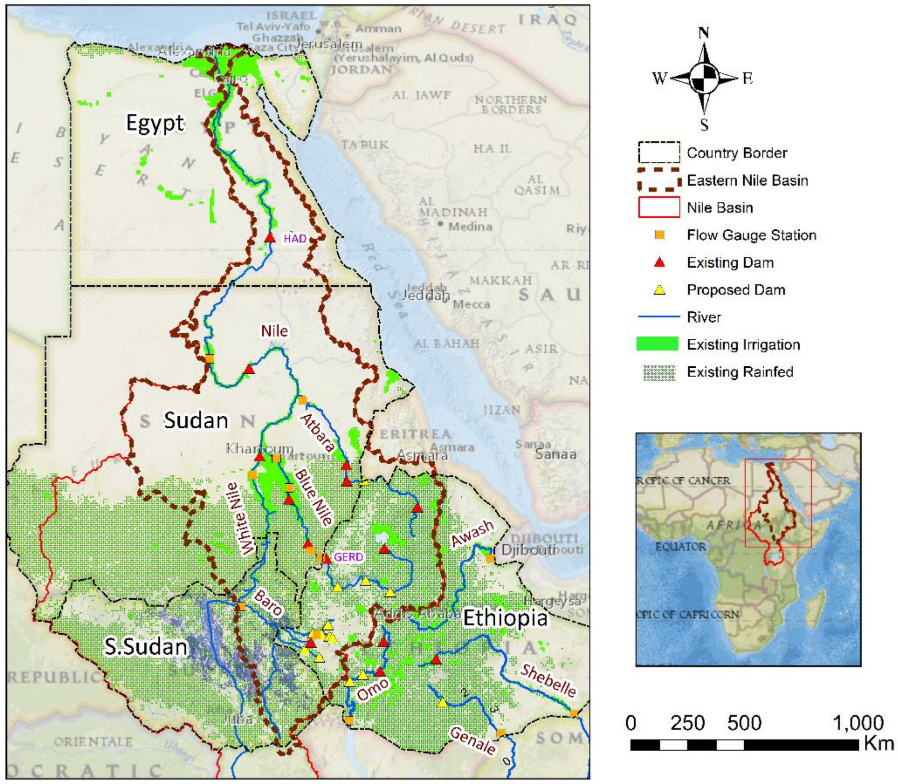


Figure 4.1: The study area of the Eastern Nile Basin (ENB) countries.

4.3 Relevance of WEF Nexus Concept to the Eastern Nile Basin

WEF nexus is particularly important in regions such as the ENB, with shared resources between countries, where attempts by individual countries to maximize their benefits may result in conflicts that are complex to resolve (Bernauer, 2002; D'Odorico et al., 2018). The advantage of the WEF nexus paradigm is that it does not require all solutions to align solely with the planning objectives of a single sector/country. Instead, it encourages broader planning concepts, such as equitable trade-offs between the WEF sectors and synergistic thinking, promoting shared benefits and cooperation rather than conflict (Cai et al., 2018; Al-Saidi and Hefny, 2018). The WEF nexus was conceptualized to address global issues, but more effort is required to scale its understanding to generate implementable regional and national planning methods (Wu et al., 2021; Benson et al., 2015). To this end, it is important to provide policymakers with future WEF pathways, highlighting synergies and trade-offs.

In projecting future WEF pathways, it is essential to consider the uncertainty of unknown future WEF drivers. In particular, climate variables are significant drivers of all three WEF sectors. Climate change has been extensively studied for the ENB, where there is consensus among climate models over future temperature increases, which are consistent also with observations (Mohamed and El-Mahdy, 2021). Projected precipitation changes were perceived to have major differences in projected magnitude and direction of change among climate models (Elshamy et al., 2009). However, more recent studies show that the majority of climate models project increasing precipitation (Alaminie et al., 2021; Liersch et al., 2018). Climate uncertainty can be incorporated in WEF planning in the form of climate change scenarios generated from global or regional climate models (Wu et al., 2022). But also, it could be incorporated by generating synthetic climate time series that feature potential climate conditions (Culley et al., 2019).

Several studies have aimed at understanding the complexities and possible future changes in the ENB WEF systems. However, most focused on the water-energy system, especially the impacts of filling and operating the GERD on water and hydropower in the Nile basin (Digna et al., 2018; Wheeler et al., 2016; Basheer et al., 2018). Only a few studies have considered the water-food systems. In particular, Siderius et al. (2016) indicated that Sudan, South Sudan, and Ethiopia can meet all their food demands by 2025 through the intensification and expansion of rainfed agriculture. This conclusion was also valid for 2050, except for Ethiopia, which might be constrained by the availability of suitable land (Ayyad and Khalifa, 2021). Multsch et al. (2017) showed that improving irrigation efficiency of the ENB might not completely enable the ENB countries to meet their water demands, nonetheless, it would significantly reduce stresses on the Nile system.

Among studies that have considered an integrated analysis of the WEF systems, Allam and Eltahir (2019) identified trade-offs between water supply for food production, hydropower generation in the upper Blue Nile basin in Ethiopia, and the various demands of downstream countries. Elsayed et al. (2020) projected Egypt's WEF conditions until 2080, indicating that the long-term operation of the GERD could reduce Egypt's food production and hydropower generation by 4% and 7%, respectively.

In the above-mentioned studies, various tools and methods were used, however, all depend on one of two approaches, namely: the optimization-based approach or the scenario-based approach, while a few studies combined both (Allam and Eltahir, 2019). The former approach is advantageous in identifying the trade-offs that face decision-makers in WEF systems planning and helps in minimizing them. However, there is a common misperception that the solutions found are "optimal" or "best" solutions. Moreover, those tools do not generally consider how the system will transform from its current state to the future state required to reach the suggested "optimal" solutions. On the other hand, tools that use the scenario approach are free of such misperceptions as they do not usually search for the "best" outcomes of the WEF systems, rather, they are used to evaluate the system performance under a wide range of plausible changes to the system drivers. In both approaches, decision-makers need to be well-informed about the underlying assumptions and limitations, so they can avoid misleading decisions. Significant social, environmental, and political dimensions that govern the planning decisions of WEF systems are difficult to represent mathematically and are often overlooked.

In the above, various limitations related to the projected future changes of WEF conditions can be identified. Notably, most studies were "single-project-centered", where the impacts of a single WEF development project (e.g., GERD) were the focus. Long-term future conditions (e.g., to 2050) were identified based on this single project, ignoring the fact that the long-term needs and plans of WEF sectors in the region might necessitate further development to meet the growing demands. The scale of the study area was another issue, as most studies considered small-scale (e.g., sub-basin) WEF changes (Basheer and Elagib, 2019; and Allam and Eltahir, 2019). Thus, impacts beyond the boundaries of the sub-basin under consideration were neglected, resulting in limited spatial analysis, ignoring impacts on other basin countries. We argue that in a transboundary river basin, such as the ENB, it is necessary to analyze long-term WEF developments at the regional scale, which could be significant in revealing the possibilities to reduce conflicts and reach common benefits in the region as a whole.

Most studies have underestimated the significance of rainfall in the ENB region, overlooking its important role in rainfed agriculture and food production. Siderius et al. (2016) indicated the potential to solve the persistent food gaps in the ENB region through enhanced rainfed rather than irrigated agriculture. Hence, it is important to include rainfed agriculture systems and their possible future changes when projecting future WEF conditions. Finally, in almost all studies, there was a lack of proper consideration of future uncertainty; important WEF variables like water, food, and energy demands were assumed fixed or assumed to change under a very limited range of variations (Basheer et al., 2018; Elsayed et al., 2020). More importantly, none of the reviewed studies considered the impacts of climate change on the three WEF sectors at the national and basin scales. Given the observed trend of increasing temperature, the possibilities of precipitation changes, and the fact that climate variables are major drivers of the WEF systems, it is important to consider climate change and quantify its impacts on future WEF conditions in the ENB.

To address the above-mentioned limitations, this study aims to investigate a wide spectrum of long-term projected conditions for the WEF nexus for the ENB at national and regional scales. The WEF nexus assessment framework (WEFNAF), introduced in this study, integrates the significant rainfed agricultural sector into the food security of the region and considers a wide range of development plans up to the year 2050. Multiple combinations of developments are considered, including building up to 16 dams and improving rainfed and irrigated agriculture, while addressing the future uncertainty of the major WEF drivers (i.e., climate change and socio-economic drivers).

4.4 Methodology

The water-energy-food nexus assessment framework (WEFNAF) contains two simulation models: (1) a SWAT-based hydrological model and (2) a WEF nexus model. The hydrological model requires four major inputs of climate, topography, landcover, and soil data and uses them to generate river streamflow, which is used to drive the second model. The WEF nexus model was built using a system dynamics simulation environment to simulate national demand and supply of water and food and to estimate national hydropower production in each ENB country. For this purpose, the model incorporates a component to simulate the ENB’s surface water resources system, in which the daily streamflow generated from the hydrological model is used as a boundary condition for simulating the river and reservoir network. Operational rules are the major input used to simulate reservoir operation and hydropower production at each reservoir location. Water demands were calculated within the model based on climatic and socioeconomic drivers, at respective river reaches, and water is supplied by prioritizing municipal, then industrial, and lastly irrigation uses. Moreover, the WEF nexus model incorporates a component that simulates the crop production for both irrigated and rainfed agriculture. The ENB was divided into small agriculture calculation units (ACUs), and in each unit, a daily soil water balance was performed based on antecedent soil moisture, irrigation supply for irrigated areas, precipitation, and potential evapotranspiration. Accordingly, crop yields were adjusted for water stress conditions and multiplied by crop cultivated land areas to estimate the production of each crop. Additionally, food demand was estimated within the model based on relevant socioeconomic drivers. The model requires economic inputs of prices and production costs for crops and hydropower, such that the economic evaluation of agriculture and hydropower production can be determined.

WEFNAF incorporates four performance measures used to assess the WEF conditions of each country, namely renewable water use, reliable hydropower generation, food gap, and the combined gross margin of agriculture and hydropower (i.e., the difference between the revenue and the variable production costs). The framework was set to run under historical and future conditions, in which the future runs can feature changes in (a) variables controlled by decision-makers (combined changes of those variables constitute future development plans); and (b) WEF drivers, which are those exogenous variables that have a significant impact on WEF conditions, but over which decision-makers have limited or no control (these includes climate and socioeconomic variables). Figure 4.2 shows the WEFNAF framework components as outlined above, while a more detailed explanation is provided in Appendix D.1.

Implementation of the WEFNAF framework includes four steps. The first is model validation for a historical period from 1983 to2016, in which the hydrological model was calibrated and validated using observed daily and monthly flow data at 13 gauge stations. Likewise, the WEF nexus model outputs were validated against observed data, which included reservoir water levels, water supply, hydropower generation, and food production. In the second step, the validated WEFNAF models were used to simulate a future reference scenario for the period 2017 to 2050, assuming no development plans were implemented, with future WEF drivers maintaining their historical patterns and values. In the third step, a wide range of possible development plans were investigated for the period 2017 to 2050 and assessed using the four WEF nexus performance measures. Accordingly, a group of development plans that resulted in relatively reduced trade-offs were identified and named *thematic development pathway*. In the fourth step, a single development plan from this thematic pathway was selected and analyzed under a wide range of possible changes in climate and socioeconomic driver for the period 2017 to 2050.

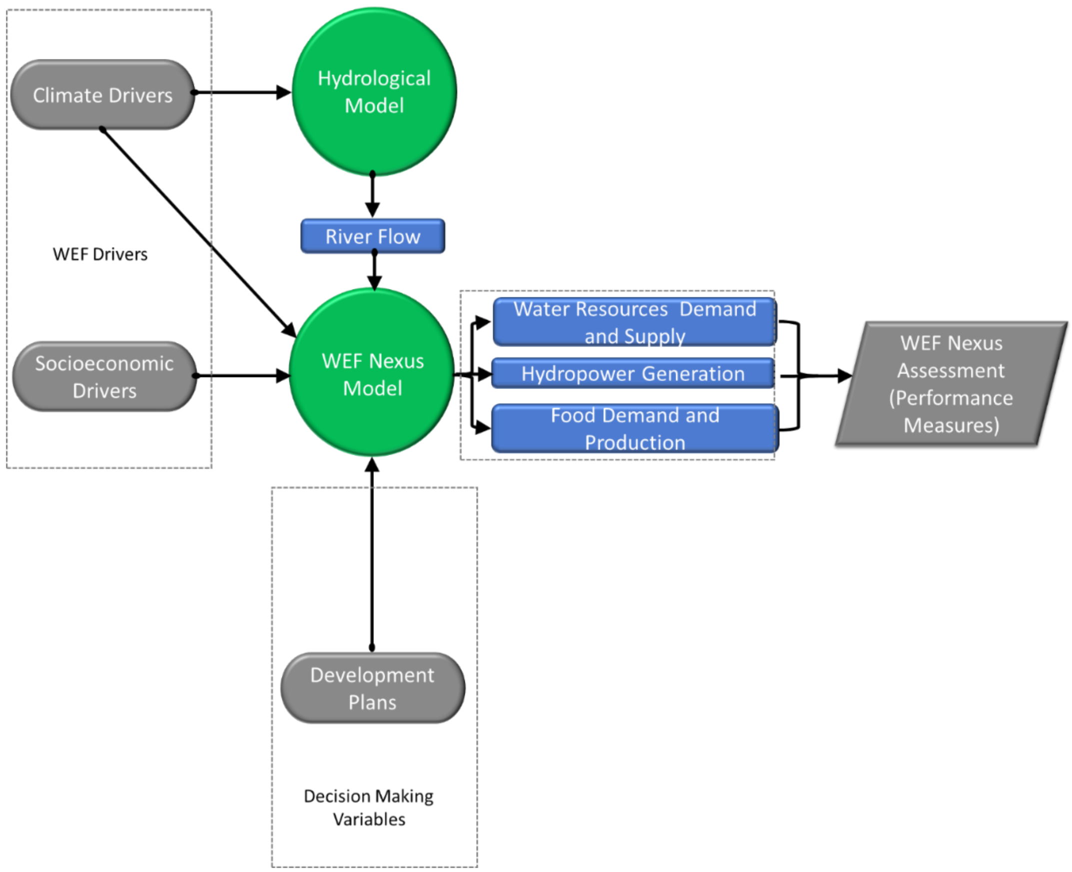


Figure 4.2: A schematic drawing for the major components of the WEFNAF framework

4.4.1 Data Sources

The hydrological model used in this study (SWAT; Arnold, 1994) was forced using daily precipitation and temperature. The precipitation data used are the climate hazards group infrared precipitation with station data (CHIRPS; Funk et al., 2015), while the temperature data were taken from the observational reanalysis hybrid temperature dataset (ORH; Sheffield et al., 2006). Notably, these two datasets showed high accuracy in representing daily precipitation and temperature timeseries within the study area (Gebrechorkos et al., 2018). The daily data for both variables are available for a common period between 1981 and 2016 in gridded format with a spatial resolution of 0.05° for CHIRPS and 0.25° for ORH. The hydrological model is semi-distributed and required ground elevation, soil, and landcover data, retrieved from NASA Shuttle Radar Topography Mission (SRTM; Rabus et al., 2003), International Soil Reference and Information Centre (ISRIC, 2012), and the European Space Agency (ESA, 2010), respectively. Observed streamflow time series data were compiled from NBI (2018).

In addition, the WEF nexus model required spatial data for soil available water capacity, retrieved from Dunne and Willmott (1996). The annual total irrigated and rainfed areas were compiled from NBI (2017) and FAO (2015a; 2016; 2021) reports. The partitioning of each crop area among the agriculture sub-sectors (i.e., irrigation and rainfed) was retrieved from ENTRO (2017). The spatial distribution of crop areas was estimated based on satellite data compiled from Portmann et al. (2010). Crop yields, food demand, production losses, food prices, and production cost data were compiled from FAO (2021). Operation of the GERD, which is under construction, was set based on an operation rule that fulfills the targeted annual hydropower generation (Wheeler et al., 2016). The operational data for other existing reservoirs were based on historical observed operation, while future reservoirs were set to operate based on rules that maximize hydropower generation for hydropower dams and minimize water shortages of future irrigation projects for irrigation dams, compiled from ENTRO (2020).

4.4.2 WEF Nexus Performance Measures

The modeled WEF nexus in each of the ENB countries was assessed using four performance measures that address the WEF issues of concern to decision-makers. These measures allow tracking and comparison of the nexus state under different development plans and possible driver changes and are intended to support the WEF nexus planning decisions.

The first measure is renewable water use (RWU; m^3/cap/yr), which is important to evaluate water scarcity in the study area, especially for Egypt. RWU is a modified version of the water stress index (Falkenmark 1989; Damkjaer and Taylor, 2017), calculated for a given country as the summation of water withdrawals from rivers and the proportion of the national green water potential (i.e., the portion of precipitation that is stored in soil and is abstractable by vegetation) used by crops, divided by the population of this country, as in Eq. 4.1. This formulation allows decision-makers to investigate the impact of variables such as population growth and water use efficiency on water use. When applied to a downstream country, it allows investigation of the compound impact of upstream climate change and water use on downstream water availability and stress.

$$\text{RWU}_c\ (\text{t}) = \frac{W_c\ (t) + (ETR_c\ (t\ ) * AR_c(t\ ) * 10)}{POP_c\ (t)} \tag{4.1}$$

where, $W_c\ (t)$ is the annual withdrawals from renewable river flow (m^3/yr), and $(ETR_c\ (t) *\ AR_c(t))$ is the annual green water available in a country c and year t, estimated as the multiplication of annual actual evapotranspiration averaged over crops cultivated in the rainfed system of this country ($ETR_c\ (t)$; mm/ yr), and the maximum potential land suitable for rainfed agriculture in year t ($AR_c(t)$ ha). The value of 10 is a unit conversion factor. $POP_c\ (t)$ is the population of a country c in a year t.

The second measure is the food gap (FG; %; Abdelkader et al., 2018), which is important for each of the countries in the study area, as almost all suffer from persistent food gaps. In this study, FG is calculated for each country as the percentage of the per capita food demand that is not met by the national food supply, as indicated in Eq. 4.2.

$$FG_c\ (\text{t}) = \frac{\sum_{i=1}^{n} DEM_{ci}(t) - SUP_{ci}(t)}{POP_c\ (t) * NED_c\ (\text{t})} \tag{4.2}$$

where, $DEM_{ci}(t)$ is the national demand for food product i consumed in a country c and year t expressed in energy units (Kcal/yr), $SUP_{ci}(t)$ is the national supply of the same food product (Kcal/yr). n is the total number of food products that have a supply deficit. The national supply of each product i is calculated within the model as its national production after subtracting production losses. NED_c (t) is the per capita nutritional energy demand (NED; kcal/cap/yr).

The third measure is the reliable annual hydropower generation (RHP; GWh/yr), estimated as the annual hydropower that could be generated in a country with a given level of reliability, in this study assumed as 80% (as explained in Appendix D.2). RHP is calculated as the generated annual hydropower that corresponds to a predetermined cumulative probability of exceedance (i.e., is exceeded for 80% of simulation period), as in Eq. 4.3. This measure is important especially for Ethiopia, which plans to depend on hydropower as the main source of future energy generation.

$$RHP_c(\text{t}) = \left(\sum_{j=1}^{m} HP_{cj}\ (t)\right)\{r\} \qquad , \text{r} = \text{P}\times(\text{T}+1) \tag{4.3}$$

Where, $HP_{cj}\ (t)$ is the annual hydropower generated (GWh/ Year) in a country c in a year t from a dam j, summed for the total number of dams in this country (i.e., m). $\{r\}$ is a notation for the rank of the RHP among the annual hydropower generated for all years of simulation, arranged from highest to lowest and is calculated as the multiplication of the probability of exceedance (i.e., P; 80%) and the number of years in the simulation period (T) plus one (according to Weibull plotting position; Gumbel, 1958).

The last measure is the combined gross margin of agriculture and hydropower (GM; USD/yr), which expresses the long-term net economic revenues from water usage in agriculture and hydropower for each country. As Eq. 4.4 shows, it was calculated as the summation of agriculture gross margin (AGM) and hydropower gross margin (HGM). The gross margin of any economic activity is calculated as the difference between the revenue and the variable production costs of this activity (Brink and McCarl, 1978; Abdelkader and Elshorbagy, 2021). AGM was calculated as the summation of the national production of crops (tonnes) multiplied by the net revenue of crop production (USD/ tonne), where the global market price was used for the portion of crops that is exported. HGM was calculated as the national generated hydropower (NHP; GWh/ yr) multiplied by the net revenue of hydropower generation, as represented in the equations provided in Appendix D.2. To estimate future GM, prices were assumed to continue growing at the rates observed in the historical period, also future cost to price ratios were assumed to be the same as historical values. This was applied for all future scenarios considered in this study, including the reference scenario.

$$GM_c(\text{t}) = AGM_c\ (t) + HGM_c\ (t) \tag{4.4}$$

4.4.3 WEF Nexus Reference Scenario

After validating the two models of the WEFNAF framework using historical model forcing variables from 1983 to 2016, the reference scenario was created by extending the values to the year 2050. However, it was assumed for this scenario that no WEF development plan is implemented, i.e., only dams that are currently under construction were assumed to be implemented and operational (i.e., GERD, Figure 4.1; Wheeler et al., 2016), and there was no expansion in the currently cultivated agricultural land, and no changes in current cropping patterns, crop yields, or irrigation efficiencies. Moreover, in this scenario it was assumed that WEF drivers continued as observed in their historical period. Socioeconomic WEF drivers of population growth rate, per-capita municipal water demand, and per-capita food demand were assumed to have their historical values (Table D.4). Likewise, climate WEF drivers of precipitation and temperature were assumed to follow their historical trends. This was achieved by applying a weather generator (Appendix D.2; Culley et al., 2019) to generate daily future precipitation time series until 2050, assuming no change in mean annual precipitation, and to generate temperature that follows the spatially varied historical rate of increase in annual mean temperature observed in the study area (Figure D.6d). The scenario thus represents a future reference state of the WEF nexus, which is important for comparing the changes due to development plans and/or WEF drivers.

4.4.4 WEF Nexus Development Plans

A WEF development plan is a set of changes to decision variables that might be adopted to increase the national supply of water, food, and hydropower energy. In this study, each WEF development plan constitutes nine decision variables that control the future WEF supply. Table 4.1 lists those variable and their values, while Table D.1 in Appendix D.3 provides additional details and includes sources of those values. As Table 4.1 shows, each decision variable is capped with country-specific limits. The rainfed agricultural land area expansion is limited by land suitability and rainfall availability. The region's potential expansion is estimated to be 127 million ha (Berry, 2015; Diao et al., 2012; Alemoyehu et al., 2020), which can be added to the 32 million ha of currently cultivated rainfed land areas in South Sudan, Sudan, and Ethiopia. The irrigated agriculture land area expansion is very limited, mainly due to the scarce river water resources available. Egypt, Sudan, and Ethiopia could add 0.9, 0.5, and 1.0 million ha, respectively, to their current irrigated land area of 6.6 million ha. Food supply could also increase significantly if crop yield technology is improved; in the ENB countries there is a significant crop yield gap, whereby Egypt's crop yields are twice those of the other three countries (Figure D.3 in Appendix D.4). In this study, the crop yields of Sudan, South Sudan, and Ethiopia were assumed to have the potential to match Egypt's current values, whereas Egypt's crop yields were assumed to increase with values that vary by crop, up to 30% for wheat and maize (Ayyad and Khalifa, 2021). The cropping pattern is also an important decision variable that can increase food production with no change in agricultural area or crop yield. We considered three possible cropping patterns: The historical cropping pattern (i.e., as in the reference scenario), an increased area allocated to cereals (i.e., cereal-shift) but a reduced area for cash crops, and an increased area of cash crops (i.e., cash crops-shift) but smaller area for cereals, as in Figure D.4.

The hydropower production of the ENB countries has a high potential for increase, especially for Ethiopia, which has several planned hydropower projects (Seleshi et al., 2014). The national hydropower generation target of Ethiopia was considered to increase by up to 42,000 GWh/yr, adding to the existing 10,000 GWh/yr (Table 4.1). Egypt, Sudan, and South Sudan have limited potential for increasing hydropower generation; thus, future hydropower generation increase in the three countries was ignored.

Increasing water resources availability is an important determinant to meet the future WEF supply. In this regard, Egypt has limited potential, thus, only 5.0×10^9 m^3/yr was added to its existing supply, mainly from wastewater and agricultural drainage water reuse, desalination, and deep groundwater withdrawals (MWRI, 2010). Ethiopia plans to face the temporal variability of river flows by enhancing river water availability for irrigation and hydropower by adding up to 16 dams to the river system with a storage potential of 239×10^9 m^3 (Seleshi et al., 2014; Table D.2). The four countries of the ENB could also enhance water availability by saving water usage within the irrigation sector as it is the major water user; irrigation efficiency could potentially increase from 63% in Egypt and 50% in Ethiopia, Sudan, and South Sudan to an idealized value of 90%.

To form a WEF development plan, each of the nine decision variables was changed from its existing value by increments of 0%, 25%, 50, or 100% of the limits explained above, except for the irrigation efficiency, which could increase to 65%, 75%, or 90%. The cropping pattern could be historical, cereal-shift, or cash crop-shift. The priority for spatial implementation of rainfed and irrigation expansion was given to spatial locations with the highest annual rainfall and annual river flow volumes. Likewise, the implementation of hydropower dams was spatially prioritized for rivers with higher annual flow volumes. Adding irrigation dams to the system was dependent on the irrigation expansion (i.e., magnitude of expansion and its spatial locations), while adding hydropower dams was dependent on the amount of hydropower generation increase and its spatial locations. Both types of dams were selected from the list in Table D.2. Based on these assumptions, all possible combinations of the decision variables of the four countries were considered. As stated in Table D.1, each of the four decision variables of the rainfed agriculture land area, irrigated agriculture land area, crop yield technology, water withdrawals from non- river sources, has four possible changes; while each of the three decision variables of cropping patterns, hydropower generation, and irrigation efficiency has three possible changes; whereas the remaining two decision variables of building irrigation dams and hydropower dams are dependent on other decision variables of irrigated agriculture land area and hydropower generation. This makes the total number of development plans generated in this study to be 4 raised to the power of 4, multiplied by 3 raised to the power of 3, resulting in 6,912 development plans that were simulated. A sample of the generated development plans is presented in Table D.3. Importantly, all changes in the decision variables were assumed to occur simultaneously in all the ENB countries to limit the computational burden of the modeling exercise. Moreover, decision-variable changes were assumed to occur at the beginning of the simulation (i.e., 2017), no transient or gradual change was assumed for development plans.

Table 4.1: Decision variables names, current values, and limits of change in each country

Country	WEF sector	Decision variable name	Current value/ State as in year 2016	Limits of increase/ change
Egypt	Food	Rainfed agriculture land area	0.04 million ha	-
		Irrigated agriculture land area	3.8 million ha	Add up to 0.9 million ha
		Crop yield technology	Highest crop yield in the ENB (Figure D.3)	Variant by crop but up to 30% increase for wheat and maize yield
		Cropping patterns	see Figure D.4	Shift between cereals, and cash crops within 10% of their historical cultivated areas (Figure D.4)
	Energy	Hydropower generation	8000 GWh/ year	-
	Water	Irrigation efficiency	63%	Increase up to 90%
		Water withdrawal from non-River sources	25.0 $\times 10^9$ m^3/year	Add up to 5.0 $\times 10^9$ m^3/year
		Irrigation dam(s)	Only High Aswan Dam (HAD) Exists	-
		Hydropower dam(s)	Only High Aswan Dam (HAD) Exists	-
Sudan	Food	Rainfed agriculture land area	15.5 million ha	Add up to 38 million ha
		Irrigated agriculture land area	1.8 million ha	Add up to 0.5 million ha
		Crop yield technology	Crop Yield values are half of that of Egypt on average (Figure D.3)	Increase up to match Egypt's crop yields (Figure D.3)
		Cropping patterns	Figure D.4	Shift between cereals, and cash crops within 10% of their historical cultivated areas (Figure D.4)
	Energy	Hydropower generation	10,000 GWh/ year	-
	Water	Irrigation efficiency	50%	Increase up to 90%
		Water from Non- River Sources	-	-
		Irrigation dam(s)	6 Dams exist on the Nile River and its tributaries (Figure D.1)	-
		Hydropower dam(s)	4 Dams exist on the Nile River and its tributaries (Figure D.1)	-
South-Sudan	Food	Rainfed agriculture land area	1.62 million ha	Add up to 54 million ha
		Irrigated agriculture land area	0.12 million ha	-
		Crop yield technology	Crop Yield values are half of that of Egypt on average (Figure D.3)	Increase up to match Egypt's crop yields (Figure D.3)
		Cropping patterns	Figure D.4	Shift between cereals, and cash crops within 10% of their historical cultivated areas (Figure D.4)
	Energy	Hydropower generation	-	-
	Water	Irrigation efficiency	50%	Increase up to 90%
		Water from Non- River Sources	-	-
		Irrigation dam(s)	-	-
		Hydropower dam(s)	-	-
Ethiopia	Food	Rainfed agriculture land area	15.0 million ha	Add up to more 35 million ha
		Irrigated agriculture land area	0.89 million ha	Add up to more 1.0 million ha
		Crop yield technology	Crop Yield values are half of that of Egypt on average (Figure D.3)	Increase up to match Egypt's crop yields (Figure D.3)
		Cropping patterns	Figure D.4	Shift between cereals, and cash crops within 10% of their historical cultivated areas (Figure D.4)
	Energy	Hydropower generation	10,000 GWh/ year	Add up to 42,000 GWh/year
	Water	Irrigation efficiency	50%	Increase up to 90%
		Water from Non- River Sources	-	-
		Irrigation dam(s)	5 dams exist on different rivers (Figure D.1)	Add up to 9 dams on different rivers (Figure D.1 and Table D.2)
		Hydropower dam(s)	7 dams exist on different rivers (Figure D.1)	Add up to 14 dams on different rivers (Figure D.1 and Table D.2)

4.4.5 Changes in WEF Drivers

WEF nexus drivers are variables with limited or no control by decision-makers but can cause significant changes to future WEF demand and supply. These include three socio-economic drivers, population growth rate, per capita nutritional energy demand, and per capita municipal water demand, which are the major demand drivers considered in this study. These, implicitly reflect changes in economic status (e.g., GDP increase), and when added to climate variables (precipitation and temperature) form a set of five nexus drivers that influence both demand and supply sides of the WEF nexus.

The current population growth rates in the ENB are among the highest in the world with 2.0%, 2.5%, 2.3%, and 2.8% for Egypt, Sudan, South Sudan, and Ethiopia, respectively. The future rate of each country was assumed to change to one of three values of 3%, 2%, or 1%, which cover the full range of the historical population growth rates in the region and those projected by the United Nations (2022) and World Bank (2023). The per capita nutritional energy demand (NED; Kcal /cap/day) varies greatly among the ENB countries (Figure D.5). Egypt's demand has increased significantly from 2000 Kcal/cap/day in 1960 to the current value of 3500 Kcal/cap/day. Comparing Egypt's NED with global values implies that it has very limited potential to increase (FAO, 2021), therefore, it was assumed that future values at the year 2050 can be one of 3800, 3500, or 3000 Kcal/cap/day. However, due to poverty and lack of food availability, Ethiopia, Sudan, and South Sudan have low NED, below the minimum human energy requirement of 2300 Kcal/cap/day (Tontisirin and de Haen, 2001) until recently. The future values for those three countries were assumed to approach Egypt's current value, thus, future values could be 3500, 3000, or remain at 2300 Kcal/cap/day. Egypt has relatively better socioeconomic conditions and water accessibility, with per capita municipal water demand of 115 m^3/yr (MWRI, 2010). Conversely, Sudan, South Sudan, and Ethiopia have much lower values of 25, 19, and 11 m^3/yr (NBI, 2017), respectively, and their future values were assumed to increase to approach that of Egypt, whereas Egypt's value was assumed to slightly increase to 130 m^3/yr; remain at its current value; or through policies and water pricing, decrease to 70 m^3/yr.

The three social drivers explained above were used to build three social driver change scenarios that were based on the level of stress they would cause to the water and food systems of the region. These are: high socio-economic growth scenario, with the highest demand for municipal water and food, hence the highest stress to the water and food system; moderate; and low socio-economic scenario, as explained in Table D.4 in Appendix D.7.

The climate of the ENB countries is characterized by high spatiotemporal variability. The highest precipitation falls on the highlands of Ethiopia and the western part of South Sudan with long-term mean annual values that reach 2200 mm/yr. This value drops gradually moving north and reaches nearly zero in Egypt (Figure D.6c in Appendix D.7). The hottest temperatures are observed across southern Egypt, Sudan, and South Sudan; milder temperatures exist along the Egyptian northern region and Ethiopian highlands (Figure D.6a and D.6b). Based on our analysis of the ORH ENB temperature dataset, the basin countries' mean annual temperature has been increasing at a rate that spatially varies between 0.005 to 0.04 °C/yr (Figure D.6d), with minor areas showing a declining or zero trend. In this study, the future daily climate time series was generated using a daily weather generator (Appendix D.2; Culley et al., 2019), covering the range of the projected values generated by the 21 general circulation models that ran under the full range of representative concentration pathways, as included in the Coupled Model Intercomparison Project phase 6 (Eyring et al., 2016). The annual mean temperature was assumed to increase by between +0.5 and +4 °C by 2050, and long-term mean annual precipitation was assumed to change from between -10% and +30%. Within these ranges, the temperature was assumed to have five possible perturbations, while precipitation was assumed to have nine possible perturbations, as stated in Table D.4. All possible combinations of those five temperature changes, nine precipitation changes, and the three social drivers' future scenarios were generated, which resulted in a total of 135 drivers change combinations.

Importantly, all changes in the climate WEF drivers were assumed to occur in a spatially consistent way (e.g., if mean annual precipitation assumed to increase by 5%, this value was applied simultaneously at all locations within the ENB). Moreover, driver changes were assumed to occur at the beginning of the simulation (i.e., 2017), no transient or gradual change was assumed, except for the annual mean temperature changes that were assumed to occur gradually according to a linear trend until the year 2050.

4.5 Results

4.5.1 Modeling Framework Validation

The performance of the hydrological model in simulating historical daily river flows at 13 different flow gauge stations was assessed for the period 1983 to 2016. The model was calibrated and validated using Nash-Sutcliffe Efficiency (NSE) and Percent bias (PBIAS) and resulted in values between 60% and 91%, and -16% and +9%, for NSE and PBIAS, respectively over the whole period, details are provided in Appendix D8. These are considered acceptable for daily flow prediction, in light of previous studies in the region (Betrie et al., 2011; Mengistu et al., 2021).

The WEF model results were also evaluated against the best available information. There is a limited availability of reported annual water supply to different sectors in each country, the simulated water supply data are presented for the year 2016 in Figure 4.3a. Egypt's modeled water supply totaled 82 × 10^9 m^3/yr, of which 82% is supplied to irrigated agriculture, including animal feed production, 13% to municipal uses, and 2.5% to industrial uses. Egypt's water supply is mainly sourced from blue water sources (i.e., freshwater flows or surface and subsurface storage). This includes 55.5 × 10^9 m^3/yr from the Nile, 6.3 × 10^9 m^3/yr from shallow groundwater, 2.2 × 10^9 m^3/yr from deep groundwater, 16.0 × 10^9 m^3/yr from agricultural drainage reuse, and 0.3 × 10^9 m^3/yr from seawater desalination. Egypt's hyper-aridity does not allow for rainfed agriculture except in very limited areas on the north coast and Sinai (i.e., less than 1% of Egypt's cultivated land); in the WEF model 1.7 × 10^9 m^3/yr of green water was simulated for Egypt's agriculture. These simulated values for the Egyptian annual water supply were consistent with the values reported by governmental reports and other studies (MWRI, 2010; Allam and Allam, 2007).

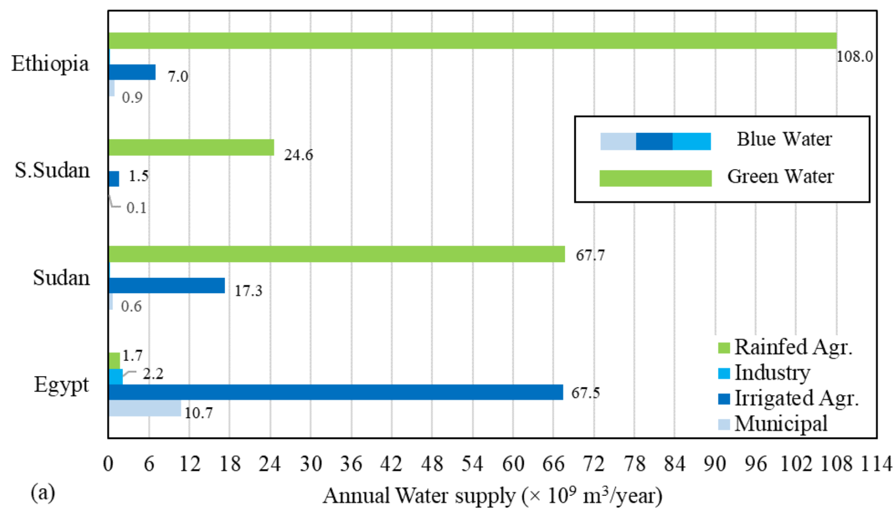
In contrast, most of the water use in Sudan, South Sudan, and Ethiopia is sourced from green water that contributes to rainfed crop agriculture, pasture, and other natural vegetation and forests. However, within the WEF model, the green water use was only quantified for rainfed crop agriculture. For Sudan, the modeled water use in 2016 was 85.6 × 10^9 m^3/yr, where 67.7 × 10^9 m^3/yr was green water used for rainfed agriculture. Blue water sources supplied 17.3 × 10^9 m^3/yr for irrigated agriculture, and 0.6 × 10^9 m^3/yr for municipal supply. In South Sudan, the modeled water use was 26.2 × 10^9 m^3/yr in 2016, with 24.6 × 10^9 m^3/yr of green water used for rainfed agriculture. Blue water supplied for irrigated agriculture and municipal sectors was 1.6 × 10^9

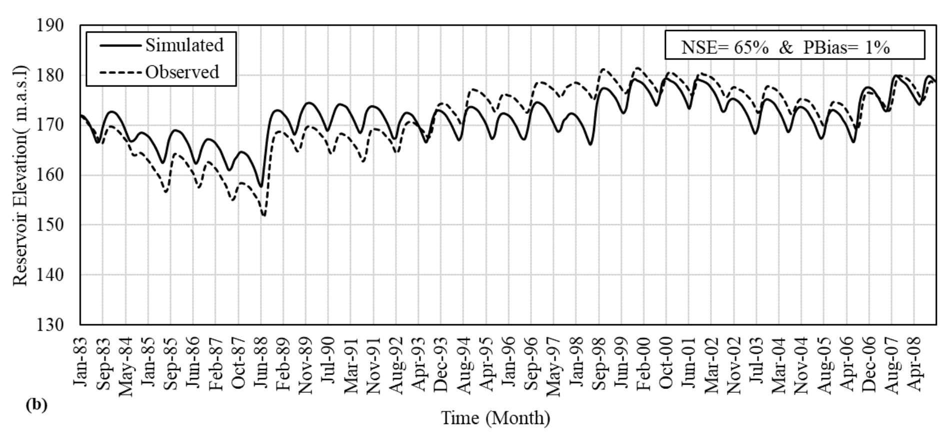
m^3/yr. Ethiopia's water use is the highest among the ENB countries with a modeled water use of 116.1× 10^9 m^3/yr, of which 108.0 × 10^9 m^3/yr are green water used for rainfed agriculture. Blue water supplied to municipal and irrigated agriculture sectors was 7.9 × 10^9 m^3/yr. For Sudan, South Sudan, and Ethiopia, the blue water supplied within the WEF model was assumed to occur entirely from river flows, where for Sudan and South Sudan the supply occurs from the Nile, while for Ethiopia the modeled blue water supplied from the Nile tributaries was 1.4 × 10^9 m^3/yr, and 6.5× 10^9 m^3/yr from the other rivers (Figure 4.1). The blue water supply simulated for Sudan, South Sudan, and Ethiopia (Figure D.8a) was comparable to values reported by FAO (2015a, 2015b, and 2016). The same was true for the green water use of the three countries, which was evaluated for the period 1996 to 2005 and found to be close to the values reported in Mekonnen and Hoekstra (2011).

In addition to water supply, the WEF model performance in simulating existing dams' operation was assessed. Figure 4.3b shows the comparison of observed and simulated monthly elevation of High Aswan Dam (HAD), which is considered satisfactory with NSE of 65% and PBIAS of 1%. The simulated flow at calibration stations were validated within the WEF model, daily inflow to HAD compared with observed data at Dongola station resulted in an NSE of 70% and PBIAS of 1%. Likewise, the inflow to Rosieres and outflow of Sennar Dams in Sudan were compared with observations and showed NSE of 86% and 82% and PBIAS of -4% and -10%, respectively, as discussed in Appendix D.8 and Table D.5. Because of limited data availability, the operation of the other dams in the study area (Figure D.1 in appendix D.1.2) was simulated using the long-term monthly mean reservoir elevation data extracted from other existing models and studies (ENTRO, 2020).

The annual hydropower generated from all dams in each country was also evaluated. As Figure 4.3c shows, the simulated hydropower matches well the reported average annual hydropower of each country. Ethiopia and Sudan built hydropower dams over the historical period, which explains the stepped increase in their hydropower generation. By the year 2009, the Merowe dam in Sudan and Tekeze dam in Ethiopia were operational, and since then, the three countries of Egypt, Sudan, and Ethiopia have generated comparable annual hydropower that ranges between 8,000 and 10,000 GWh/ yr.

The performance of the WEF model in simulating the national crop and animal agriculture production in the four countries of the study area was also assessed. Figure 4.4 shows the ranges of production for the period between 1983 and 2016. The crop production of the ENB countries is diverse with 21 crops and crop groups. Cereals are considered important strategic crops in the region, as they represent an affordable source of high nutritional energy. In 2016, Egypt produced 10 million tonnes of wheat, Sudan and South Sudan produced 7.6 million tonnes of sorghum, while Ethiopia produced 8 million tonnes of maize, 6 million tonnes of teff, and considerable production of wheat and sorghum. The WEF model simulated crop and animal production ranges that match well the data reported by FAO (Figure 4.4). Overall, the model shows good performance in simulating the historical water, food, and hydropower conditions of the study area and can be reliably used to project future WEF conditions.





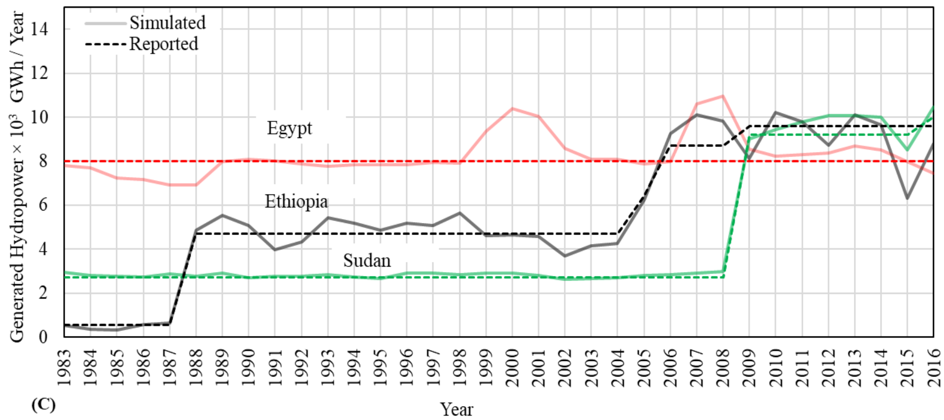


Figure 4.3: Evaluation of the ENB WEF model for (a) simulated blue and green water resources use for different sectors as in 2016, (b) High Aswan Dam Reservoir elevation, and (c) annual national hydropower generated in each country.

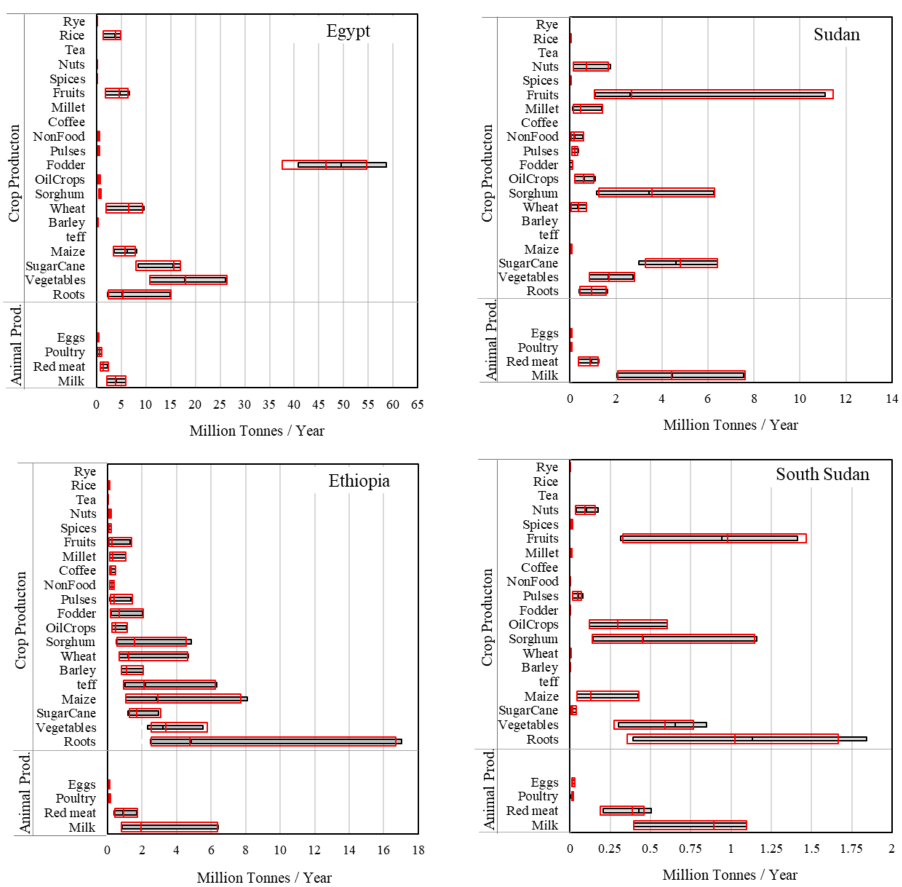


Figure 4.4**:** Evaluation of the ENB WEF model for agricultural production, the gray bars represent the range of annual national agricultural crop and animal production as simulated for

the period between 1983 and 2016, and the red bars are for the FAO reported production (FAO, 2021).

4.5.2 Reference Scenario Results

In this scenario, used as a reference for comparison, no WEF development occurs, except for projects under construction (i.e., GERD), and future WEF system drivers follow the observed patterns/trends of the historical period, as explained in section 4.1.1. The simulated renewable water use reflects the worsening water conditions in the region due to high population growth (Figure 4.5a), whereby 2016 values were reduced by a factor of 2 due to the doubled population by 2050. Egypt is the largest sufferer as its 2016 RWU of 650 m^3/cap/day is projected to drop to 332 m^3/cap/day in 2050. In contrast, South Sudan does not seem to be under any physical water stress; RWU drops from 30,000 m^3/cap/day in 2016 to 15,400 m^3/cap/day in 2050, while Sudan and Ethiopia are in between these two extremes with RWU reaching 2,010 and 1,392 m^3/cap/day in 2050, respectively. In the reference scenario it was assumed that temperature continued to increase according to the historical trend, however, this did not significantly impact crop water requirements and water stress impacts on crop yields; accordingly, food production under the reference scenario is insignificantly different from current production. However, the high population growth increases food demand, which results in a larger food gap, projected to grow significantly by 2050 (Figure 4.5b). Egypt and South Sudan could reach values of 60% in 2050, increasing from 40% in 2016, while Sudan and Ethiopia reach values of 40% and 50%, respectively. The availability of water and suitable arable land in Sudan, South Sudan, and Ethiopia reflects the fact that the food gap in the region could be reduced compared to those values reported for the reference scenario because it was assumed in this scenario that no action was taken by decision-makers.

Although the hydropower systems of Egypt and Sudan can produce comparable maximum annual hydropower production between 10,000 and 11,000 GWh/yr (Figure 4.5c), Sudan can achieve higher reliable hydropower generation (RHP) of 9,500 GWh/yr, compared to 7,700 GWh/yr for Egypt. This is due to the limited annual variation in hydropower production of Sudan under the reference scenario, as the country produces its hydropower energy from several small-scale dams that will benefit from the regulated flow releases of the GERD. Ethiopia’s hydropower production would be the largest in the region, after GERD is added to the system, with RHP of 22,800 GWh/yr.

The combined gross margin of agriculture and hydropower is projected to increase in the future; however, this is mainly due to the continued growth of prices at the rates observed in the historical period. Egypt, Sudan, and Ethiopia have comparable economic benefits from water use in agriculture and hydropower production, while the economic benefit for South Sudan is significantly less. Stemming from the current conditions and worsening future projections, decision-makers of the region are most likely to intervene to implement WEF development plans that aim to decrease the food gap, increase energy production and its reliability, increase the gross margin, and eradicate or diminish the worsening water stress conditions.

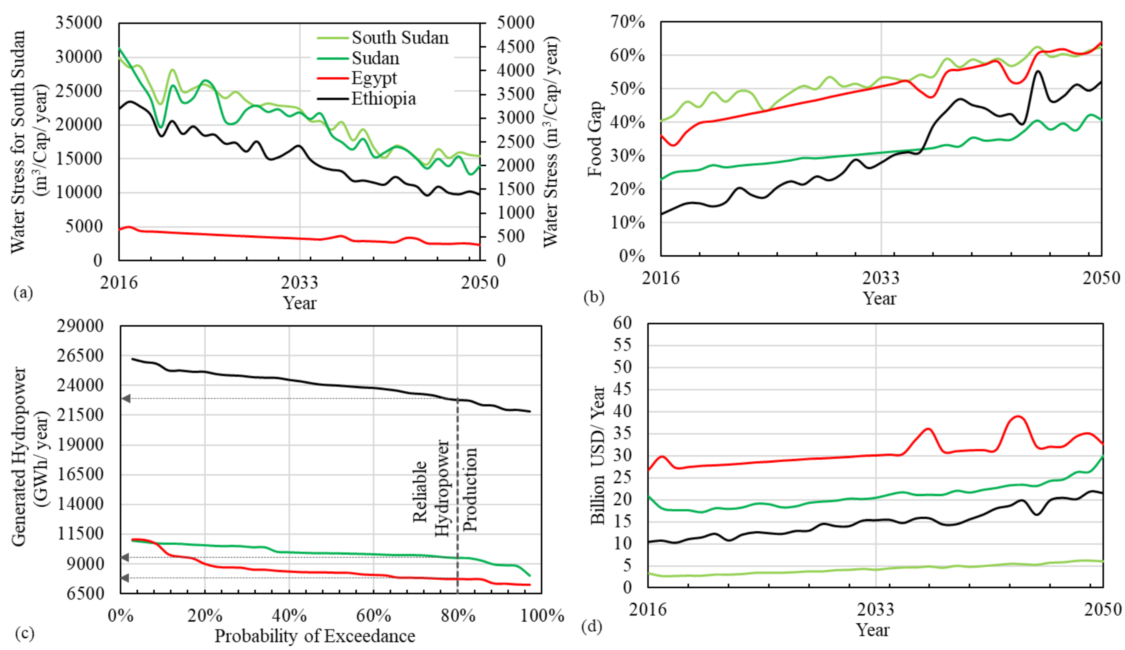


Figure 4.5: WEF nexus performance measures of (a) renewable water use (RWU; the left axis is for South Sudan and right axis for three other countries), (b) food gap (FG), (c) reliable hydropower generation (RHP), and (d) combined gross margin of agriculture and hydropower (GM), evaluated for the reference scenario

4.5.3 WEF Nexus Performance Under Development Plans

Results of the four WEF performance measures used to evaluate the 6,912 generated development plans for the period between 2016 and 2050 are shown in Figures 4.6, 4.7, 4.8, and 4.9. To enhance the readability of the figures, only the decision variables that significantly impact each of the performance measures were included.

4.5.3.1 Renewable Water Use

Under the studied ENB development plans, renewable water use is found to vary mainly due to irrigation. In particular, the two most sensitive decision variables are increasing irrigated area, which increases river withdrawals and RWU; and increasing irrigation efficiency, which reduces river water withdrawals and RWU. Notably, most withdrawal for irrigation occurs from the shared, scarce, and fully utilized water resources of the Nile. Accordingly, the changes to withdrawals and RWU upstream in the Nile have a trade-off with water availability, withdrawals, and RWU downstream. Figure 4.6 shows RWU changes in the four countries under the considered plans. The first two axes show the two major decision variables impacting RWU; the first axis has increments of 0%, 25%, 50%, and 100% for irrigated land expansion (i.e., Irrig. Expansion), in which 100% expansion corresponds to an additional irrigation area stated in Tables 4.1 and D.1. The second axis represents irrigation efficiency, set to increase to three possible values as explained in Tables 4.1 and D.1. Axes from three to five indicate RWU values for South Sudan, Sudan, and Ethiopia, respectively. The sixth axis indicates the Nile River flow upstream of the High Aswan dam (HAD) corresponding to each plan, which indicates the shared Nile water resources that arrive at the Egyptian border and indirectly reflects the water withdrawals that occurred upstream. Egypt's RWU is represented on the last axis. Importantly, the changes in the decision variables for each development plan are assumed to occur simultaneously in all the ENB countries (e.g., a plan with 100% irrigation expansion, means that 100% of the potential area in each country was expanded).

Development plans were divided into clusters based on their resulting RWU for the four countries and Nile flow upstream of the HAD, clusters of interest are colored in blue, green, and red in Figure 4.6, while the results for the rest of the 6,912 development plans are indicated in grey color. A major cluster with the highest improvement in irrigation efficiency (90%) but no change in the irrigated areas from their current values (0%; blue lines in Figure 4.6) leads to reduced river water withdrawals in South Sudan, Sudan, and Ethiopia, hence, reducing RWU relative to the reference scenario (the solid black line in Figure 4.6). However, this enhances the Nile flows that arrive in Egypt and leads to the maximum enhancement for water availability and the RWU of Egypt. In contrast, the red cluster, which represents the highest expansion of irrigated areas (100%) but the least improvement in irrigation efficiency, 65%, results in the highest RWU for Sudan and Ethiopia relative to the reference scenario, but the least Nile flow to Egypt, reducing its RWU, and resulting in the most severe water stress conditions for the country. Interestingly, the green cluster indicates that maximized irrigation efficiency could balance these negative impacts of upstream irrigation expansion on the water stress of the downstream countries. As Figure 4.6 shows, Egypt's RWU retains the level of the reference scenario when the irrigation potential of the upstream countries is fully exploited simultaneously with an improved irrigation efficiency reaching 90%.

Importantly, the relatively high RWU values for the three countries of South Sudan, Sudan, and Ethiopia indicate that they will not suffer significant water stress when compared to Egypt. RWU values for those three countries remain high under the full range of the considered irrigation expansion and irrigation efficiency changes, as the lowest values reported for 2050 were 15364, 1933, and 1378 m^3/cap/yr for South Sudan, Sudan, and Ethiopia, respectively. In contrast, Egypt's RWU is projected to be low (i.e., 334 m^3/cap/yr) in 2050, mainly due to high population growth, and some of the development plans that withdraw Nile water in the upstream countries will further exacerbate this water stress with RWU values as low as 322 m^3/cap/yr

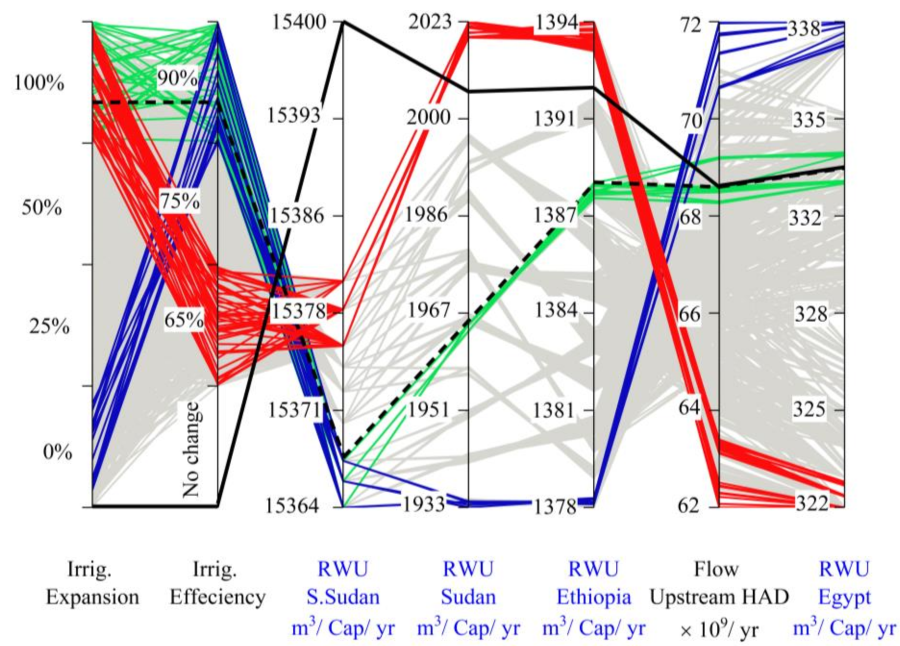


Figure 4.6: Parallel coordinate plot for the WEF system performance measure of renewable water use (RWU), reported for the year 2050, for Egypt, Sudan, South Sudan, and Ethiopia under the 6,912 studied development plans. Only major decision variables affecting RWU are included in the figure. Line colors represent clusters of development plans that have close performance measure values and have close values for the Nile flow upstream HAD. Performance measures are identified by blue color to differentiate them from the decision variables and the Nile flow axes. The solid black line represents the reference scenario, while the dotted black line represents a selected development plan (SDP) for further analysis under drivers change.

4.5.3.2 Reliable Hydropower generation

In the studied development plans, it was assumed that hydropower generation increase by building new dams would only occur in Ethiopia; no hydropower dams would be built in South Sudan, Sudan, or Egypt due to the flatter topography and consequent negligible potential in those three countries. The first axis in Figure 4.7 refers to the increase in hydropower generation in Ethiopia, while the second reflects the Nile flow upstream HAD. The third to the sixth axes indicate the reliable hydropower generation (RHP) of Sudan, Ethiopia, and Egypt, respectively. South Sudan does not have significant hydropower generation and was excluded from this figure for simplicity.

Figure 4.7 shows that the RHP of each country is dependent on the combination of the decision to increase hydropower generation in Ethiopia, and other development decisions that rely on Nile water withdrawals, e.g., expansion of irrigated area. Interestingly, Sudan's RHP is better than that of the reference scenario (i.e., 9,500 GWh/yr, the black solid line) under all development plans; up to an additional 800 GWh/ yr could be achieved. This is attributed to the more regulated flows that occur under all development plans, due to adding more dams upstream in Ethiopia. However, the magnitude of this increase would be lower when the hydropower development in Ethiopia is combined with more water withdrawals from the Nile in Ethiopia and Sudan (red cluster). The RHP of Ethiopia changes mainly due to the increased hydropower generation from additional hydropower dams. Under the highest increase in hydropower generation (i.e., all considered hydropower dams are built), RHP can reach 50,300 GWh/yr, 220% higher than the reference scenario. However, other internal development decisions in Ethiopia that result in withdrawing more water from the Nile would marginally decrease the RHP, which can be observed by comparing the red and green lines in Figure 4.7, maximized withdrawals from the Nile (lowest flow at HAD; red lines) result in slightly lower RHP. Egypt's RHP would be changed mainly based on the upstream withdrawals from the Nile, higher upstream withdrawals (i.e., lower flow upstream HAD) would result in reduction of the RHP, with the lowest value of 6,000 GWh/yr occurring under the highest upstream withdrawals, compared to 7,700 GWh/yr under the reference scenario.

A trade-off exists between irrigation development and the benefits of existing and expanded hydropower generation in the ENB countries. This can be seen by comparing the green and red clusters in Figure 4.7. In both clusters, it is assumed that all considered Ethiopian hydropower dams are built. When this is combined with no irrigation area expansion and maximum improvement of irrigation efficiency (i.e., the green cluster), the generated RHP is maximized for each of the ENB countries and totals 68,300 GWh/yr. However, when combined with maximized irrigation area expansion and minimal irrigation efficiency improvement, the generated RHP of the ENB would be lowered by 11% to be only 60,500 GWh/yr.

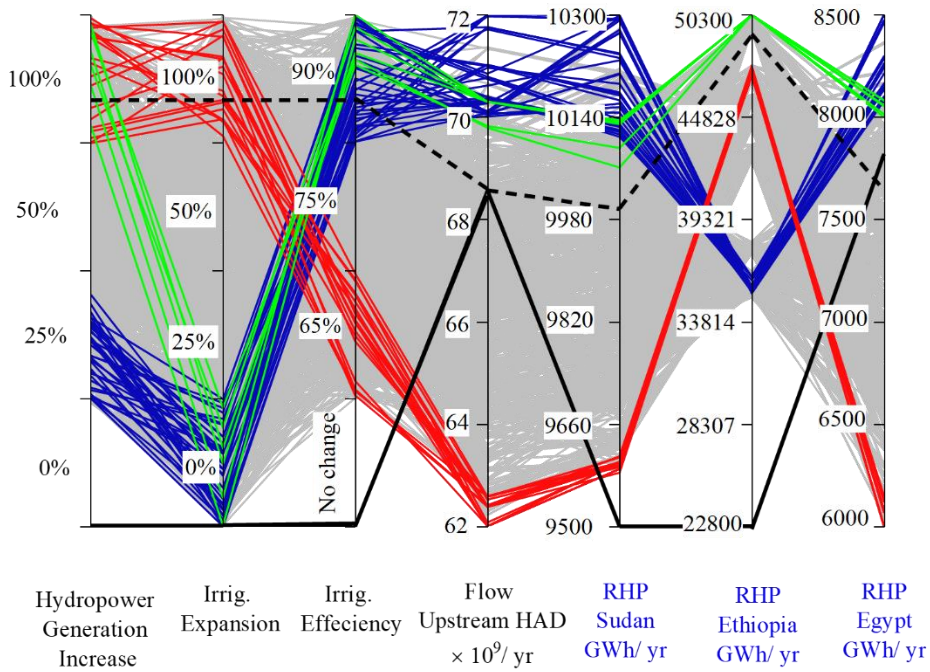


Figure 4.7: Parallel coordinate plots for the WEF systems performance measures of Reliable hydropower generation (RHP), for Egypt, Sudan, South Sudan, and Ethiopia under the 6,912 studied development plans. Only major decision variables affecting RHP are included in the figures. RHP is a summary hydropower production measure (i.e., 80% exceedance probability) for the whole period from 2017 to 2050. Line colors represent clusters of development plans that have close performance measure values and have close values for the Nile flow upstream HAD. Performance measures are identified by blue color to differentiate them from the decision variables and the Nile flow axes. The solid black line represents the reference scenario, while the dotted black line represents a selected development plan (SDP) for further analysis under drivers change.

4.5.3.3 Food Gap

The food gap (FG) of the ENB countries is sensitive to the combination of changes in decision variables that control food production (Figure 4.8). Due to the limited potential for expanding irrigated area, utilizing the full potential of irrigation expansion (i.e., red lines in

Figure 4.8) will not result in a significant change in the FG of South Sudan, Sudan, and Ethiopia compared to the reference scenario. Nonetheless, this irrigation expansion in the upstream countries, which occur with limited improvement to irrigation efficiency, as indicated by the red lines, will result in a significant reduction in the Nile flow upstream of HAD, diminishing Egypt's ability to reduce its FG. In such a case, even if Egypt expanded its irrigated area to the maximum potential, the FG would worsen compared to the reference scenario and increase from 60% in 2050 to up to 66%. Under this condition, if Egypt increased its maximum potential for water withdrawals from sources other than the Nile (i.e., as in Figure 4.8; non-river water withdrawal increases to 100%; equivalent to withdrawing an additional 5×10^9 m^3/yr), this would slightly lower the FG to be closer to the reference scenario with a value of 61% (i.e., the lower group of red lines on the last axes on Figure 4.8).

In contrast, the expansion of rainfed agriculture areas will significantly improve the FG of the ENB countries, especially if accompanied by enhancements in crop yields, switching cropping patterns toward cereal crops, and improving irrigation efficiency of existing irrigated lands to the maximum of 90% (i.e., blue lines in Figure 4.8). This can considerably lower the food gap of the three upstream countries while saving more of the Nile water flows to Egypt to be utilized to reduce its FG; under these conditions, FG values as low as 47% could be reached. Therefore, it is important to pay attention to the role of technology (irrigation efficiency and yield gap closure) in addressing water shortage and potential conflict in the ENB.

Under the full expansion of the rainfed and irrigated areas, the highest improvement of crop yield technology, shifting cropping patterns to allocate more areas to cereal crops, the FG improves significantly in comparison to the reference scenario for South Sudan, Sudan, and Ethiopia to achieve values of 4%, 12%, and 17%, by the year 2050, respectively (green lines in Figure 4.8). However, under this condition the Nile water that arrives in Egypt will be less than that for rainfed expansion only (the blue lines in Figure 4.8); Egypt's best FG value would be only 50%, as indicated by the green lines in Figure 4.8.

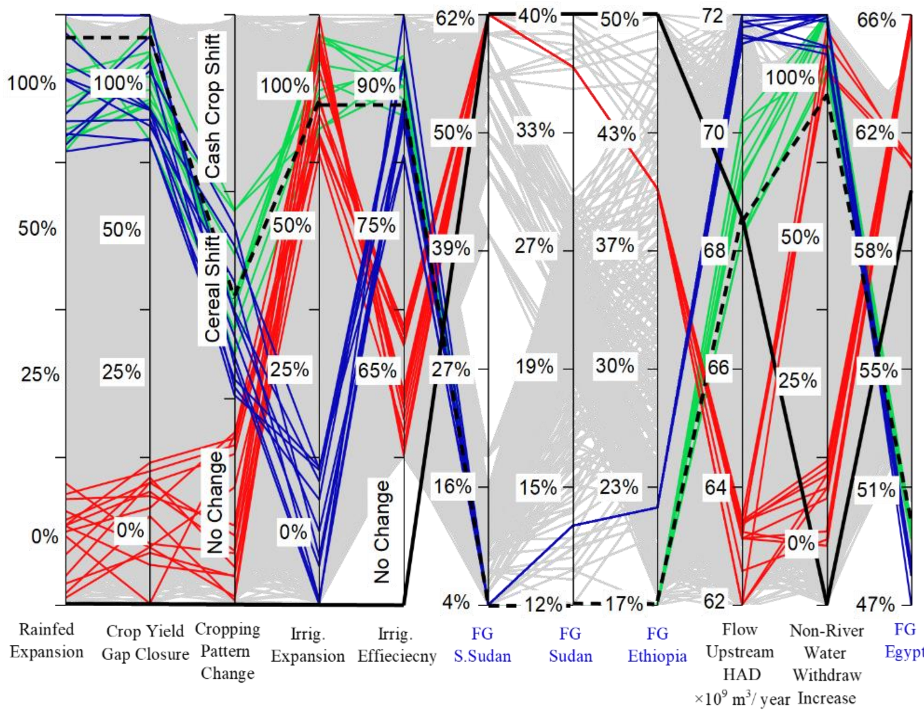


Figure 4.8 Parallel coordinate plot for the WEF systems performance measures of food gap (FG) reported for the year 2050 for Egypt, Sudan, South Sudan, and Ethiopia under the 6,912 studied development plans. Only major decision variables affecting FG are included in the figures. Line colors represent clusters of development plans that have close performance measure values and have close values for the Nile flow upstream HAD. Performance measures are identified by blue color to differentiate them from the decision variables and the Nile flow axes. The solid black line represents the reference scenario, while the dotted black line represents a selected development plan (SDP) for further analysis under drivers change.

4.5.3.4 Gross Margin of Agriculture and Hydropower

Increasing hydropower production will contribute to improving the socio-economic conditions in Ethiopia, however, the direct economic benefit from this increase will be small compared with the direct benefits of increasing agricultural production, mainly through rainfed expansion. The highest contribution hydropower can make to the Ethiopian GM is 2 billion USD/yr, whereas the agricultural production increase could add up to 106 billion USD/yr. The same observation applies to the other ENB countries, in which the major contribution to GM comes from agriculture. Notably, there are also some other indirect economic benefits that need to be quantified and included in such comparisons, electricity for example can drive industry and other economic sectors. The combined direct and indirect economic benefits could lead to different conclusions; however, this is out of the scope of this study.

Similar to FG, the most significant decision variables to increase GM in the ENB countries are rainfed area expansion and crop yield technology improvement, while Egypt's GM is based on irrigated agriculture, thus, the flow that arrives upstream HAD is an important indicator for the country. As Figure 4.9 shows, under the highest expansion of the rainfed agricultural areas, and with the full closure of the yield gap, these two decision variables, combined with cropping pattern shift to increase the area allocated to cash crops, the GM of South Sudan, Sudan, and Ethiopia can reach 166, 89, and 107 billion USD/yr (blue lines in Figure 4.9), which is 27, 3, and 5 times the GM with no agricultural development case (i.e. the reference scenario; solid black line in Figure 4.9). Under these conditions, the Nile flow upstream of the HAD allows Egypt to achieve GM values of 44 billion USD/yr or higher. Increasing the irrigated area only without expanding rainfed, with no significant change in irrigation efficiency, nor change to the cropping patterns, and without improving the crop yield technology will result in the least improvement to the GM of the ENB countries. This will also reduce the Nile flow that arrives in Egypt, and result in GM lower than the reference scenario (as indicated by the red lines versus the solid black line in Figure 4.9).

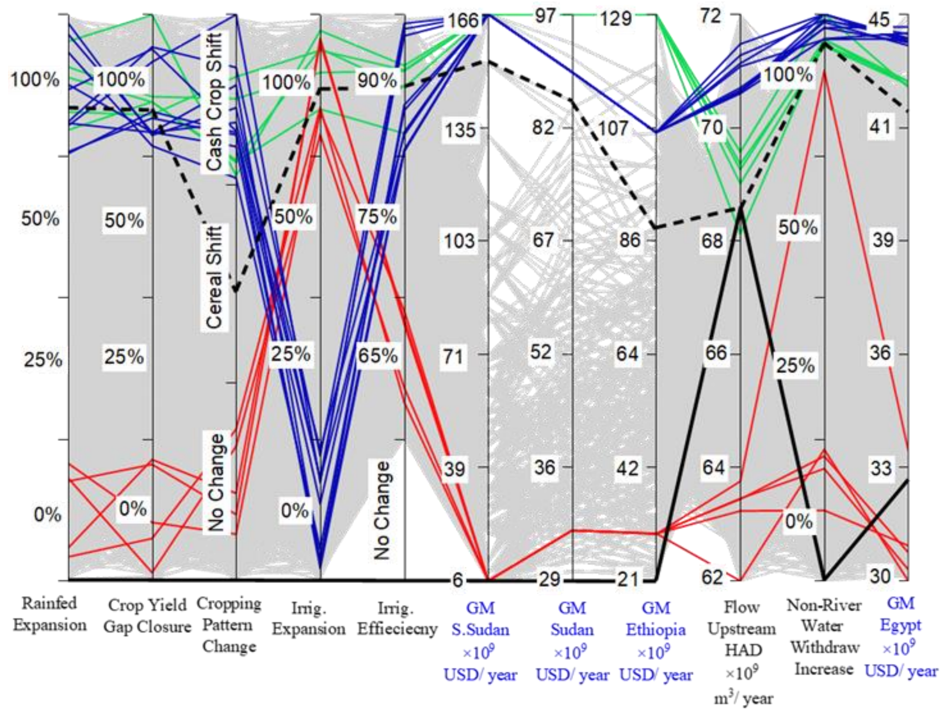


Figure 4.9: Parallel coordinate plots for the Gross Margin of Agriculture and Hydropower (GM) reported for the year 2050, for Egypt, Sudan, South Sudan, and Ethiopia under the 6,912 studied development plans. Only major decision variables affecting GM are included in the figures. Line colors represent clusters of development plans that have close performance measure values and have close values for the Nile flow upstream HAD. Performance measure names are identified by blue color to differentiate them from the decision variables and the Nile flow axes. A solid black line represents the reference scenario, while a dotted black line represents a selected development plan (SDP) for further analysis under drivers change.

4.5.4 The Selected WEF Development Plan

Development decisions in the water, food, and energy sectors in each of the ENB countries could result in trade-offs, but also synergies. These occur among the sectors of the same country but are more pronounced across sectors of different countries. A major synergy occurs in the energy sectors of Ethiopia and Sudan, in which the increase of Ethiopian hydropower generation by adding new hydropower dams to the Nile River system results in more regulated Nile flows, and consequently higher hydropower generation from existing

Sudanese dams (as indicated in Figure 4.7). The major trade-off across the ENB countries is associated with development plans that rely on increasing water withdrawals from the shared water resources of the Nile. More specifically, plans in South Sudan, Sudan, and Ethiopia that lead to increased withdrawals from the Nile (e.g., irrigation) reduce Nile water availability for Egypt and affect the performance of its WEF sectors. As Figures 4.6, 4.7, 4.8, and 4.9 show, under the studied development plans, the Nile mean annual flow upstream of the HAD can drop by 10%, compared to the reference scenario, and consequently, Egypt's RWU, FG, RHP, and GM will significantly deteriorate (red lines on the figures), whereas internal Egyptian planning decisions will be much less effective in improving the WEF sectors' performance.

It is clearly prudent to adopt development plans that reduce this major trade-off between upstream development and the negative consequences on Egypt. A thematic pathway would be to acknowledge Egypt's water scarcity problem when pursuing WEF development in the upstream countries. The goal would be to minimize additional Nile water withdrawals, while achieving enhanced WEF conditions. To this end, the potential of rainfed agriculture should be prioritized over irrigation for food production and enhancing the economy. The use of technology could play an important role in enhancing crop yields and closing the food gap. Irrigation efficiency improvement in existing and future projects is very important to guarantee that upstream irrigation expansion does not significantly reduce Nile water availability for Egypt, although it might not fully counterbalance the increase in demand as shown by Multsch et al. (2017). Hydropower growth through building new dams upstream might be doable, as long as downstream operational concerns are addressed (Wheeler et al., 2020), especially under prolonged drought and flood conditions. Following this, one of the studied development plans was selected for further analysis under a wide range of change in WEF exogenous drivers.

Although the selected development plan (thereafter SDP) may not necessarily represent optimal development for the ENB, it has some superior features as indicated by black dotted lines on Figures 4.6, 4.7, 4.8, and 4.9. The SDP significantly reduces the food gap for all ENB countries; FG values drop to 4%, 12%, 17%, and 50% compared with 62%, 40%, 50%, and 60% under the reference scenario for South Sudan, Sudan, Ethiopia, and Egypt, respectively. Gross margins for the four countries are significantly improved, with South Sudan, Sudan, Ethiopia, and Egypt having values of 154, 86, 88, and 41 billion USD/yr, which are 26, 3, 4, and 1.3 times the reference scenario values. The SDP shows high hydropower generation for Ethiopia and

Sudan with RHP of 50,000 GWh/yr and 9,985 GWh/yr, respectively. Importantly, this SDP does not exacerbate water problems for Egypt, as the same levels of Nile flows and water stress conditions are maintained as in the reference scenario. To achieve this good performance, the SDP assumes that the rainfed agricultural area is expanded to the maximum potential in South Sudan, Sudan, and Ethiopia, by adding 54 million ha, 38 million ha, and 35 million ha, respectively. Concurrently, crop yield should be improved to close the yield gap in the ENB countries. Additionally, cropping patterns need a shift to allocate more area to cereal crops. Irrigation was assumed to expand to the maximum potential with additional 0.5, 0.9, and 1 million ha added to the irrigated lands of Sudan, Egypt, and Ethiopia, respectively. The total number of 14 hydropower dams stated in Table D.2 were assumed to be implemented, and importantly, the maximum improvement of irrigation efficiency to reach an idealized value of 90% was assumed to occur in all countries, such that the mean annual Nile flows that arrives at Egypt remains at the same value as in the reference scenario. In addition, Egypt was assumed to utilize its maximum potential of withdrawing 5×10^9 m^3/yr from sources other than the Nile.

4.5.5 The Selected WEF Development Plan under Changing Conditions

As discussed in the previous section, the selected development plan (SDP) has good values for all performance measures, when evaluated under the assumption that socio-economic and climate drivers continued/trended as observed in their historical period (i.e., no driver change). However, under the full range of plausible projections for those socio-economic and climate drivers, the performance measures of the ENB would significantly vary.

In each country, performance measures of the SDP are worsened under the high socio-economic scenario compared with the case of no driver change, as indicated within the dotted boxes on Figures 4.10 and 4.11. This is expected, as the higher population growth rate of 3% would increase the level of competition over river water resources and stress the WEF systems. More per capita municipal water demand, as assumed under this scenario, will increase water withdrawals, however, due to the high population growth, the overall impact will be worsened RWU. The higher population growth combined with higher per capita food demand will increase national food demand, thus, worsen the FG. This scenario leads to higher river withdrawals for municipal supply and less river water is left for hydropower and irrigation, which result in reduced RHP and GM. Contrarily, as indicated by comparing the green and orange points within the dotted boxes on Figures 4.10 and 4.11, in each country, the low socio-economic scenario that features mild population growth rate of 1% resulted in less stress on river water resources, and thus, WEF performance measures are improved compared to the case of no driver change.

In addition to these changes caused by socio-economic scenarios, the studied climate driver changes resulted in significant impacts on the WEF performance measures of the SDP (Figures 4.10 and 4.11). Higher mean annual precipitation enhances both blue and green water availability and allows for more withdrawals for different uses, which improves the RWU and boosts food production leading to better FG values. This also increases the flow arriving to the river system, keeping the reservoir elevations at high levels and increasing the turbine water releases, thus, having a compound increasing effect on RHP. This enhanced hydropower and agriculture production leads to significant improvements in the GM of each of the ENB countries. However, the assumed increases in the annual mean temperature by an additional +0.5 °C to +4 °C by the year 2050 will marginally worsen the WEF performance measures. Higher temperatures increase evapotranspiration and reduce blue and green water availability but also increase water demand, which reduces the RWU, FG, RHP, and GM, as shown by Figures 4.10 and 4.11. Importantly, temperature increases could lead to heat stress, which may impact vegetation biophysical processes. This was not considered in our model and may cause additional reductions to crop production and GM and increases FG.

In the three countries of Ethiopia, Sudan, and South Sudan, FG seems to be more sensitive to precipitation reductions than precipitation increases. This is attributed to the fact that a major part of food production comes from rainfed agriculture, which is dependent on soil water availability (i.e., green water). There is a threshold of the mean annual precipitation increase after which the soil water availability is enhanced to the level that minimizes water stress for crop production (i.e., soil water availability approaches crop potential evapotranspiration), leading to maximized food production, any higher precipitation will not considerably impact crop production. Notably, the increased precipitation might also reflect increased flooding risks, which may cause damage to vegetations and reduce crop production, however, this was not considered in the model.

Remarkably, under all drivers of change combinations, the RWU of Ethiopia, Sudan, and South Sudan is still relatively good and does not reflect water stress conditions as severe as for

Egypt. Under the most extreme combination of driver change, i.e. the highest population growth of 3%, the largest reduction to mean annual precipitation of -10%, and the highest increase in annual mean temperature of +4 °C, the RWU would be 1,180, 1,614, and 10,886 m^3/cap/yr, for Ethiopia, Sudan, and South Sudan, respectively, which is 7 to 72 times Egypt's value of 150 m^3/cap/yr, as Figures 4.10 a, b, c, and d show.

Population growth rate is a major driver for improving the region's food conditions. Under the lowest growth rate of 1%, the food gap would significantly improve, values as low as 20%, 9%, 5%, and 2% could be reached in Egypt, Ethiopia, Sudan, and South Sudan, respectively. Importantly, due to the large agricultural area cultivated under the SDP, these low values remained nearly unchanged under the full range of considered climate changes (i.e., green points on Figures 4.10 e, f, g, and h).

Importantly, the impacts of socio-economic and climate driver changes on the WEF performance measures are not constrained by country boundaries. Driver changes in the upstream countries of the ENB that impact the shared water resources of the Nile will cause extended impacts to the downstream countries. This is most obvious for Egypt, being the most downstream country with hyper-arid climate and high dependency on the Nile as the major source of all water uses. Figure D.9, in Appendix D.10, shows the combined impacts of driver changes in the upstream on the Nile flow that arrive at Egypt. These impacted Nile flow values combined with the internal driver changes of Egypt dictated the WEF performance measures indicated in Figure 4.10 d and h, and 4.11 d and h.

As Figures 4.10 and 4.11 imply, among the four countries of the ENB, Egypt's water, food, and economic conditions are the most sensitive to the considered internal and external driver changes. Even if the WEF development plans of the upstream countries are optimized, decision-makers should anticipate the fact that the outcomes of Egyptian WEF planning decisions would be surrounded by high uncertainty stemming from climate and socio-economic changes in the upstream countries and within Egypt.

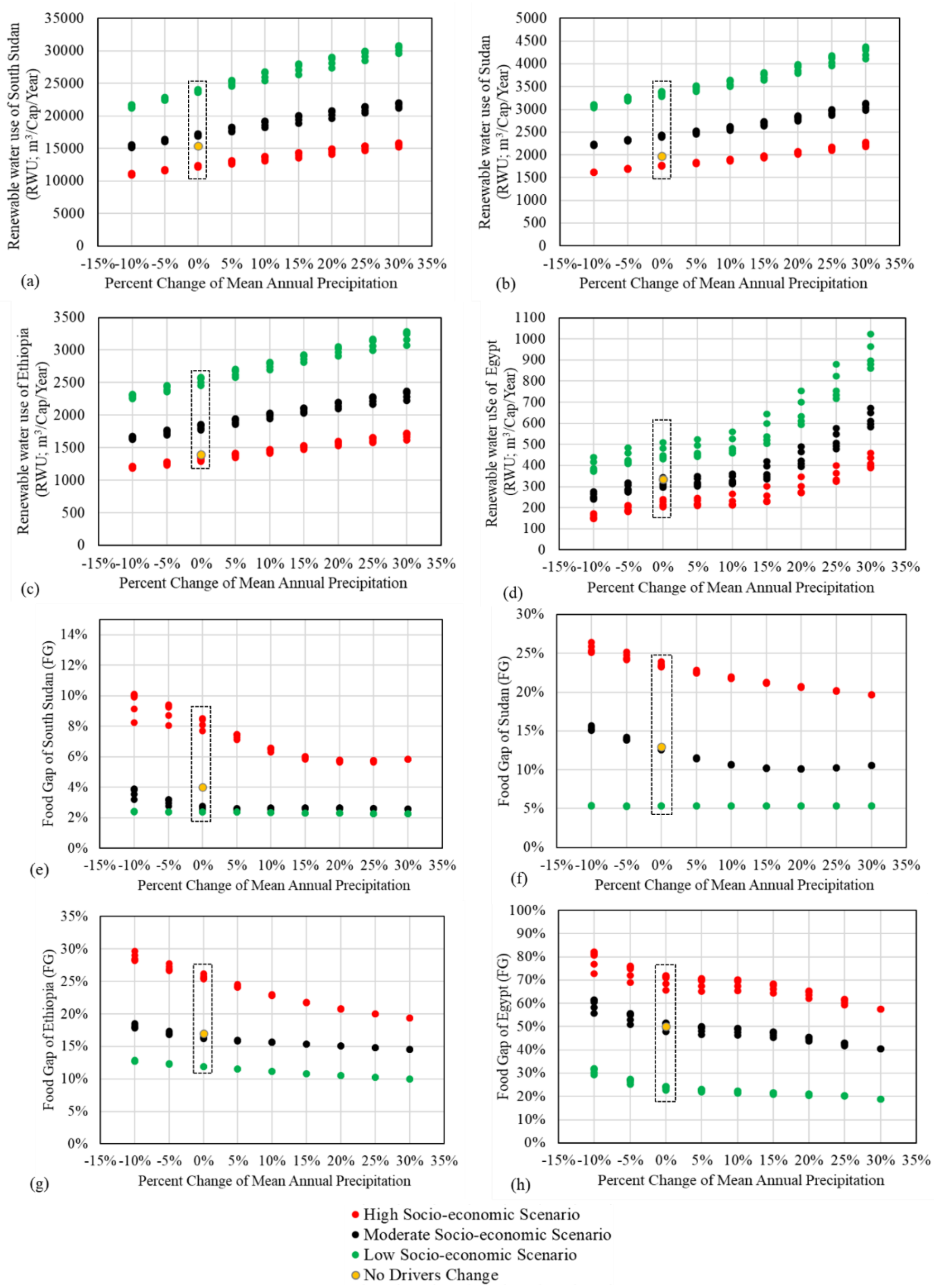


Figure 4.10: scatter plot for WEF nexus performance measures of renewable water use (RWU) for (a) South Sudan, (b) Sudan, (c) Ethiopia, and (d) Egypt; and food gap (FG) for (e) South Sudan, (f) Sudan, (g)Ethiopia, and (h) Egypt. Evaluated for the selected development plan (SDP) under different combinations of driver changes. The horizontal axis indicates the percent change of the mean annual precipitation, the vertical axis indicates the performance measure values. RWU and FG are reported for the year 2050. The orange point on the figures refers to evaluations

under no social nor climate drivers change, whereas point colors of green, black, and red, refer to one of the three socio-economic scenarios, as listed in Table D.4. At a given value for the percent change of mean annual precipitation, the vertical variations of the points with the same color are due to the different annual mean temperature changes. Points surrounded by a dotted box represent the performance measure values under social drivers change, but no mean annual precipitation change.

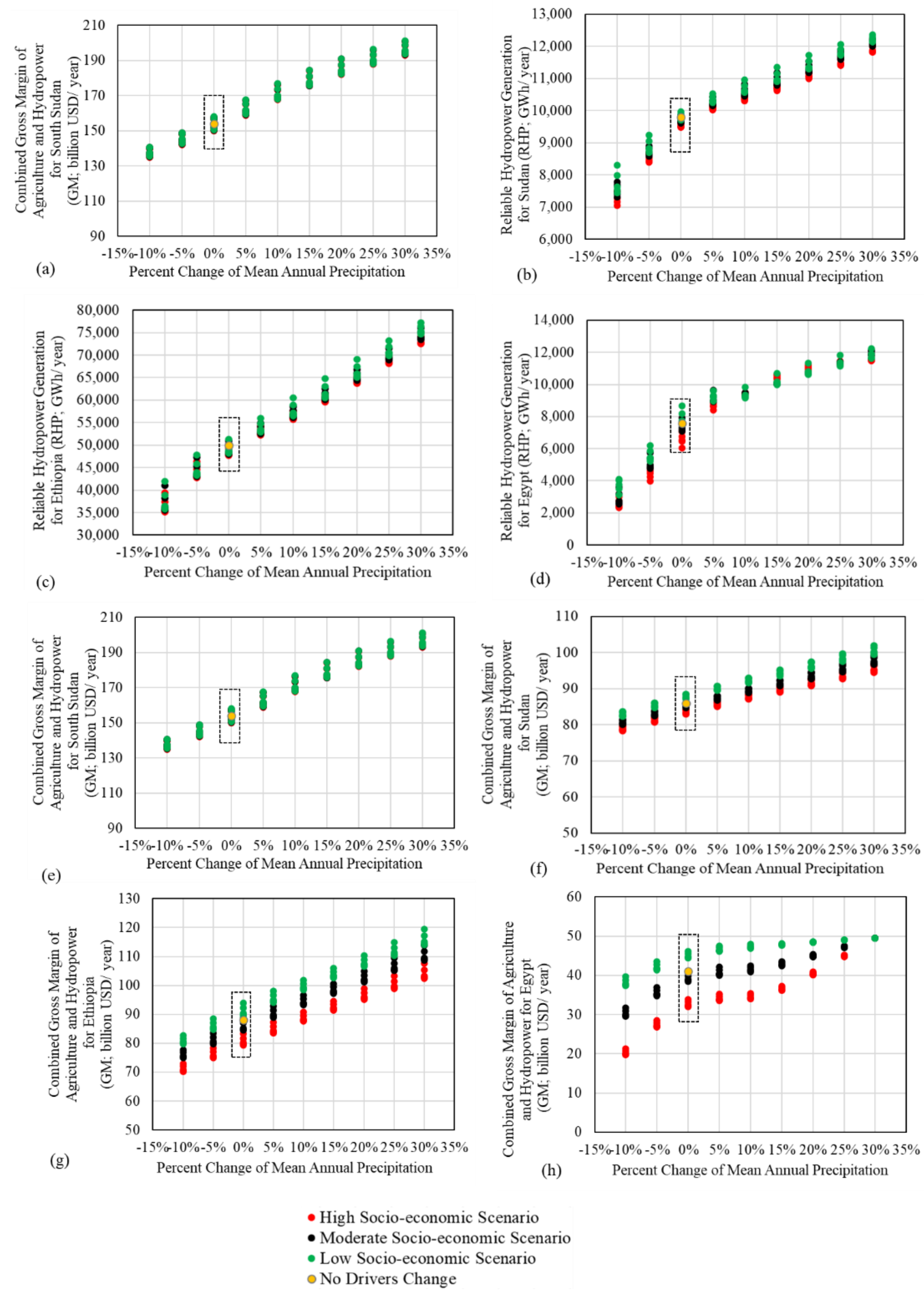


Figure 4.11*:* scatter plot for the WEF nexus performance measures of reliable hydropower generation (RHP)for (a) South Sudan, (b) Sudan, (c) Ethiopia, and (d) Egypt; and combined gross margin of agriculture and hydropower (GM) for (e) South Sudan, (f) Sudan, (g) Ethiopia, and (h) Egypt. Evaluated for the selected development plan (SDP) under different combinations of driver changes. The horizontal axis indicates the percent change of the mean annual precipitation, the vertical axis indicates the performance measure values. RHP estimation considers a summary measure (i.e., 80% exceedance probability) for the whole period between 2016 and 2050, while GM is reported for the year 2050. The orange point on the figures refers to evaluations under no social nor climate drivers change, whereas point colors of green, black, and red, refer to one of the three socio-economic scenarios, as listed in Table D.4. At a given value for the percent change of mean annual precipitation, the vertical variations of the points with the same color are due to the different annual mean temperature changes**.** Points surrounded by a dotted box represent the performance measure values under social drivers change, but no mean annual precipitation change.

4.6 Discussion of Limitations and Uncertainties

In this study, we explored the WEF nexus of the ENB countries under a wide range of plausible changes of socio-economic and climate drivers. The mean annual precipitation of the region was the driver that impacted the WEF nexus performance the most. However, there are specific climatic conditions that could critically stress the WEF nexus and were not explicitly considered in this study. Importantly, drought has severely impacted water and food systems of the ENB countries in the past and will likely reoccur in the future (Siam and Eltahir, 2017). Notably, under the SDP, discussed in this study, droughts are expected to cause less severe impacts on WEF performance measures compared to the case of no development (i.e., reference scenario). This is mainly due to the additional storage capacity of the planned reservoirs that would be added to the river system of the ENB and expected to act as a buffer that reduces the negative consequences of droughts (Wheeler et al., 2020; and Siam and Eltahir, 2017), subject to a basin agreement for reservoir filling and operation to ensure equitable benefit sharing. However, while this might benefit irrigated agriculture, rainfed agriculture, which is the major food production sector of the ENB, might not benefit from this increased storage and might be left susceptible to risks from climate variability. In such case, the huge benefits from expanding rainfed agriculture, as explored in this study, might be significantly reduced due to droughts. Accordingly, there is a need for explicit consideration of drought scenarios to quantify how drought characteristic changes might impact the WEF conditions, and specifically impact the rainfed agriculture, which is recommend for future research. A further impact of climate change that was not considered in this study is climate change-induced sea level rise, which will possibly submerge portions of the delta region in Egypt (Hereher, 2010), leading to risks of losing fertile land and expanding the food gap values estimated for Egypt.

For all the studied climate change scenarios, it was assumed that the percent change in mean annual precipitation and the change in annual mean temperature occur in a spatially uniform manner, which is a simplification that was made in accordance with the scope of this study. However, it is acknowledged that future climate change does not necessarily occur in a spatially uniform manner, some areas could change more than others. This simplification needs to be reviewed and explored in future research. It will be important to first test the sensitivity of the modelling outputs to such characteristic (i.e., spatial distribution of climate change). If this proves to be a sensitive characteristic, then it could be incorporated in the climate scenarios of such studies, possibly by using the weather generator to produce target spatial distributions.

For all considered development plans, it was assumed that the reservoirs added to the river system were filled to the full supply level at the beginning of future simulation period. This allowed for the exploration of the long-term impacts of development plans after reservoirs are added to the system and become operational but does not investigate the WEF nexus conditions during the filling period of the studied reservoirs. However, this has been extensively discussed for the case of GERD, where relatively longer periods of filling (i.e., 7 years or more) were found to cause significantly less impacts on the downstream countries, compared to shorter filling periods (i.e., 2- 6 years; Heggy et al., 2021; Elsayed et al., 2020; and Wheeler et al., 2020). Other than the GERD, there are 12 other dams, with a total storage capacity of 148×10^9 m^3 that have been considered in this study, to be built on the Nile, which is a huge storage compared to the annual flow of the Nile. When more of those reservoirs are filled concurrently and in shorter filling periods, sharp reductions of shared river flows are likely to occur, and hence, severe impacts on the WEF conditions would happen. Those reservoirs will thus require to be filled in a staged form and will likely require long time. It is important to study and assess the impacts of different scenarios of reservoir filling on the WEF performance measures of the ENB countries. Moreover, it is important to put the findings of such assessment in the context of the feasibility of adding such huge storage to the river system, which we recommend for future work.

Additionally, reservoir operation rules were assumed fixed for all the studied development plans and under all social and climate driver changes, which is a reasonable assumption in accordance with the objective of this study, and for the evaluation of the long-term values of the WEF nexus performance. However, reservoir operation rules are important decision variables that have been widely discussed for the case of the GERD (Basheer et al., 2018, Wheeler et al., 2016; and Wheeler et al., 2018). Ethiopian operational decisions of the GERD, which has a huge storage capacity, would affect the seasonality, magnitude, and timing of the Blue Nile flow that arrives to Sudan, which has a few reservoirs with small storage capacities. Sudanese operational concerns about the GERD release rates, which might be either too high and exceed the capacities of the small Sudanese dams with risks of dam overtopping and failures or be too low at critical times of water withdrawal with risks of water shortages need to be considered. Egypt's operational concerns are related to how the dam is operated under severe and prolonged droughts, as it can either amplify or dampen the drought impacts on Egypt. The GERD's, and possibly other planned Ethiopian dams', operational needs for Egypt and Sudan conflict with the operational needs of Ethiopia (i.e., maximize hydropower), thus, operational trade-offs exist. Ethiopia has plans to build up to 15 dams, of which 12 are on the Nile tributaries, with a total storage capacity of 148×10^9 m^3, which provides more control on the natural flow pattern, and in certain cases could result in conflicts with Egypt's and Sudan's operational needs. The operation of these reservoirs becomes a more critical variable and needs to be explored in future studies.

Due to limited data availability, the water resource system of the ENB countries was not fully represented in this study, as we considered only seven (Figure 4.1) out of the 12 rivers that originate in Ethiopia. However, the considered rivers' flows represent 95% of the flow of the 12 rivers. Moreover, for the same reasons, freshwater lakes and groundwater availability and usages were not considered for Sudan, South Sudan, and Ethiopia. The inclusion of these ignored water resources in the analysis might improve the WEF performance measures for those three countries, which we recommend for future research.

The energy production sector of the ENB countries was not fully represented in the model used in this study, only hydropower was considered. However, there are other sources of energy that currently exist and/or could be developed to produce more energy in the future. Relying on those other sources could result in additional trade-offs or synergies between the WEF sectors in one or more countries. For instance, expanding thermal energy generation as a major energy production source could result in additional water withdrawal from the river system for cooling purposes, which might limit water availability and result in additional trade-offs within the WEF nexus. Another example is expanding biofuel energy production, which will compete with the food production sector over water and land utilization. A possible improvement to the work presented in this study would be to consider the full energy production system (e.g., fossil fuel, thermal electricity stations, biofuels, solar system, wind turbines, etc.), and how the complete energy sector interacts with the water and food sectors of the ENB region.

Under the studied development plans, the full potential of rainfed agriculture area in the ENB countries was assumed to be utilized before 2050, although this may be unrealistic as it would require large investments, which may reduce the short-term economic gains of those expansions. A detailed cost-benefit analysis might be required to incorporate the capital costs required for such expansions and to evaluate net economic returns by 2050. The same requirement applies for the studied improvements of the irrigation and the hydropower sectors (Cervigni et al., 2015).

Despite all the limitations stated above, this study was able to determine and quantify the trade-offs and the possible future pathways of the WEF development planning process for the ENB countries. Although there are some conflicting pathways, we introduced a thematic pathway of development, which showed good WEF nexus performance for all ENB countries. Moreover, the study of development plans under a wide range of driver changes revealed the high sensitivity of the WEF system to these changes. Accordingly, future WEF planning approaches may need to not only consider such thematic pathways of development, but also consider development plans that could be robust and perform well under wide driver changes (Abdelkader and Elshorbagy, 2021). The WEFNAF framework introduced in this study allowed us to generate and assess WEF plans, but more importantly, this framework includes a rich database of thousands of plans that can be assessed by policymakers and used for any future WEF negotiations among the ENB countries.

Although each of the ENB countries has a food gap, some countries still have a considerable production surplus in one or more crops that could be exported. In the formulation of the ENB WEF model, it was assumed that any crop with production surplus was traded with the global market, with no priority given to food trade among the four countries of the ENB. However, if such intra-regional trade is prioritized, the food gaps reported in this study could reach much lower values. In the studied development plans, Sudan and South Sudan had the largest crop surpluses that could be utilized to reduce Egypt's and Ethiopia's food gaps. For instance, in the year 2050, under the selected development plan and the reference WEF drivers' values, the food gap was projected to be 50% and 17% for Egypt and Ethiopia, respectively (Figure 4.8). Egypt's and Ethiopia's major crop deficits were in cereal crops. Egypt also had a considerable deficit in sugar crops. These deficits can be filled by the surplus of the same crops that are produced in Sudan and South Sudan, resulting in much lower food gap values of 10% and 5% for Egypt and Ethiopia, respectively. Moreover, if this intra-region trade prioritization was combined with a regional cropping pattern planning that target diminishing the food gap of the region as a whole, lower food gap values could have been reached for Egypt and Ethiopia, while Sudan and South Sudan would completely close their food gaps.

4.7 Conclusions

A modeling framework that simulates the water resources demand and supply, food production, and hydropower generation of the Eastern Nile Basin (ENB) countries was introduced. The framework models were validated for a historical period, then used to generate a wide range of plausible future water, energy, and food (WEF) development plans up to 2050. Results indicated that increased water withdrawals upstream (i.e., Ethiopia, Sudan, and South Sudan) would reduce Nile water arriving at Egypt, and due to Egypt's high dependency on the Nile River, this will result in exacerbating Egypt's water scarcity problem, widening its food gap, and reducing its economic benefit from agriculture. Accordingly, a thematic WEF development pathway that aims to reduce this major trade-off among the region's countries was identified.

In this pathway, the neglected potential of rainfed agriculture sector was considered as a critical component for future development and should be prioritized over irrigation to enhance food production and improve the economy without stressing the shared water resources of the

Nile. Accordingly, more land areas were proposed to be utilized for rainfed agriculture, but more importantly, the reliance on technology would be instrumental as significant improvements in crop yields will be necessary to boost food production and enhance the economy. Moreover, as the upstream countries do not have the physical water scarcity problem of Egypt, it is proposed that they can limit their Nile water resource withdrawals to help Egypt minimize its water scarcity. To this end, upstream irrigation land expansion could be minimized or pursued with a commensurate irrigation efficiency enhancement, such that the total upstream withdrawals from the Nile do not significantly change from the existing conditions. Building new hydropower dams in the upstream countries would significantly increase the energy production, but importantly, coordination would be needed to address the downstream operational concerns.

However, the analysis of such pathway under social and climate drivers' changes revealed the high sensitivity of the WEF development outcomes of the ENB countries to future changes in the upstream mean annual precipitation, especially for Egypt, which would be the largest sufferer with increased water scarcity. The compound changes of some major socio-economic drivers, like population growth rates, per capita municipal water demands, and per capita nutritional energy demands were found to significantly impact WEF nexus conditions. Such impacts are not limited to the country where those socio-economic changes originate but often extends beyond the country's boundaries to impact other countries in the basin. Therefore, these drivers could be considered as key tools to face climate change impacts on WEF nexus. Under low population growth rates, moderate per capita municipal water demands, and moderate per capita nutritional energy demands, the climate change impacts were found to be much less severe.

The current WEF development path in the Eastern Nile Basin is characterized by unilateralism and claims of sovereignty in utilizing the shared water resources, and political tension is on the rise among the region's countries. In this study, we introduced an alternate development pathway (i.e., thematic pathway) that demonstrates that all ENB countries can achieve significantly improved WEF conditions with minimal trade-offs and conflicts. This represents a great opportunity for cooperation and coordinated development that could create long-lasting political stability in the region. Cooperation might include knowledge sharing and directing investments to achieve technological advancements to improve crop yields and irrigation efficiencies. Another important aspect is to reach agreements that guarantee consensual dam building, high coordination and cooperation on dam operation, and information sharing among the ENB countries to allow for managing the consequences of social and climatic driver changes in the region.

4.8 Acknowledgment

Abdelkader, A. acknowledges the devolved scholarship of the University of Saskatchewan granted to support his PhD studies. Elshorbagy, A. acknowledges the financial support to this research from the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Discovery Grant Program (# RGPIN-2019-04590).

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Chapter 5 Summary and Conclusions

5.1 Summary and Conclusions

This thesis developed a framework for the assessment and improvement of water and food security and used it in three different applications, each of which is presented as an independent scientific article (a thesis chapter). The first article (***Chapter 2***) introduces the national water, food, and trade (NWFT) modeling framework. The framework comprises a local model for simulating water and food supply and demand in Egypt, side by side with a global model for virtual water (food) trade related to imports and exports of crops and animal products. The second article (***Chapter 3***) extends the NWFT framework to a multi-objective simulation-optimization framework suitable for the generation, analysis, and assessment of alternative cropping patterns in arid regions (ACPAR). This modified framework takes into consideration the dynamics and changes of global food conditions (production, consumption, and trade) while planning for national water and food security. ACPAR and the NWFT framework together address the first objective of this thesis. The third article (***Chapter 4***) modifies the NWFT framework to address the second objective of the thesis, increasing the number of sectors from only the water and food sectors to include the energy sector. The model was configured for a regional study area broader than Egypt that includes the four Eastern Nile Basin (ENB) countries. This modified NWFT framework, called the water, energy, and food (WEF) nexus assessment framework (WEFNAF), simulates the ENB's water, food, and hydropower sectors. WEFNAF was used to project future WEF conditions with the aim of identifying less conflicting development paths for the region.

The NWFT modelling framework presented in ***Chapter 2*** was developed with the understanding that virtual water traded worldwide in the form of food and other products makes water a global resource, and that national water-food analysis and management should not only include the real water resources within the country but also the import and export of water in virtual form. Using the NWFT framework, the water-food nexus in Egypt was investigated and modelled in a system dynamics simulation environment. Four future scenarios of Egypt's socioeconomic and water conditions were assessed up to the year 2050; all showed Egypt struggling with growing food and water gaps. However, some scenarios were determined to be more optimistic than others, but those scenarios need significant investments to expand sea water desalination, incorporate the use of fossil groundwater, improve irrigation and municipal water use efficiencies, slow the rate of population growth, and secure additional amounts of the Nile water flowing from upstream countries. The sensitivity analysis showed Egypt's high population growth rate is a major factor driving the country's water and food gaps to alarming levels. The global virtual water trade model within the NWFT framework considered all countries combined into nine regions while maintaining Egypt as an explicit node. Five scenarios were used to project Egypt's imports of virtual water (food) up to 2050, constructed based on the shared socioeconomic pathways (SSPs). Egypt’s 2050 food imports were projected to increase by an average of 200% compared to 2021 values. Similar import trends for food were projected by both the global and national models, which together illustrate the growing food and water gaps in Egypt and strengthen the validity of both models. However, the global trade model projected greater food import by Egypt than the national model. The NWFT modelling framework can be simply expanded to include other sectors, such as energy, and it can be applied to other countries. Analyzing water in both its real and virtual forms can help quantify the relationship between water and food (and possibly energy) and inform decision-making by policy makers in individual sectors.

The ACPAR, presented in ***Chapter 3***, is an optimization-simulation framework that was developed based on the NWFT framework to help decision-makers in comprehensive planning for food and water security by altering cropping patterns while considering the effects on significant national variables, such as the water demand for agriculture (WDA), agriculture gross margin (GM), economic costs of import (ECI), and virtual water (food) imports (VWI). The framework was applied to Egypt as a case study, with a wide number of alternative cropping patterns (ACPs) produced and the tradeoffs among various objectives analyzed for a baseline period (1983 to 2013) as well as for future scenarios up to 2050. Twelve combinations of national water and socioeconomic target scenarios and global projections of food prices, subject to different shared socioeconomic pathways (SSPs) and climate change, were considered. The results show the major tradeoff that exists when performing cropping pattern planning in Egypt is that minimizing the economic costs of food imports and maximizing food self-sufficiency come at the cost of increasing agricultural water use and lowering the GM of the agriculture sector. In the baseline period, however, Egypt's historical cropping pattern (HCP) implied preferences related to minimizing the cost of imports and maximizing food self-sufficiency. In the future, the previously adopted policies of increasing total cultivated land area and improving the yields of different crops might not be enough. Egypt will likely need to increase the area allocated for wheat cultivation. This action increases the water demand of agriculture and reduces the agricultural GM, which would require other cropping pattern changes, such as reducing the areas of water-intensive, less profitable crops (e.g., other cereals) and increasing the areas of water-saving, highly profitable crops (e.g., vegetables). These type of changes to the HCP should be applied carefully as the performance of ACPs is highly dependent on the combination of cropping pattern changes. Small differences between cropping patterns could result in deteriorations or improvements of the objective functions relative to the HCP. The ACPAR framework helps to determine robust cropping patterns that can outperform the HCP in all objective functions under a wide range of future conditions, which is one of the advantages of ACPAR. The study also demonstrates that planning and management of water and food are inseparable in arid regions such as Egypt.

The WEFNAF, presented in ***Chapter 4***, is a modeling framework that simulates the water, food, and hydropower sectors of the ENB countries. The framework was used to project and investigate a wide range of plausible future WEF development plans up to the year 2050. Each development plan comprises a combination of changes to nine decision variables that feature enhancements of water, food, and hydropower sectors. In total, 6,912 development plans were composed and assessed under four performance measures. Accordingly, a thematic pathway of development that showed less conflicting performance measure values was identified and analyzed under changes in climate and social drivers. Increased irrigation withdrawals in the upstream countries (i.e., Sudan, South Sudan, and Ethiopia) would reduce Nile water arriving at Egypt and, due to Egypt's large dependence on the Nile River, exacerbate Egypt's water scarcity problem, widen its food gap, and reduce the economic benefit from agriculture. Nonetheless, the thematic pathway indicated fewer tradeoffs among the WEF sectors across the ENB countries if the forgotten potential of rainfed agriculture is prioritized over irrigation to enhance food production and improve the economy without stressing the shared water resources of the Nile. Rainfed agricultural land could be increased but, more importantly, significant improvements in crop yields will be necessary to boost food production and enhance the economy. The upstream countries do not have the physical water scarcity problems that affect Egypt, and thus have the potential to limit their withdrawals of shared water resources to help Egypt minimize its water scarcity problem. To this end, upstream irrigation land expansion might be limited or pursued with a commensurate improvement in irrigation efficiency, such that the total upstream withdrawals from the Nile do not significantly change from existing conditions. Building new hydropower dams upstream will significantly increase energy production, but coordination is needed to address downstream operational concerns.

Under these conditions, a significantly smaller food gap could be realized, with the values for South Sudan, Sudan, Ethiopia, and Egypt dropping to 4, 12, 17, and 50% from reference values of 62, 40, 50, and 60% (i.e., if no further action is taken). The agricultural gross margin can also reach 26, 3, 4, and 1.3 times the values achievable under the reference scenario for South Sudan, Sudan, Ethiopia, and Egypt, respectively. Hydropower generation could significantly increase for Ethiopia and Sudan to reach 50,000 and 10,000 GWh/year, respectively. Importantly, this development in the upstream did not exacerbate water problems in Egypt, as pre-development Nile flows and water availability conditions were maintained.

The analysis of WEF development plans under climate change revealed the high sensitivity of the WEF development outcomes of the ENB countries to changes in mean annual precipitation. Under reductions of up to 10% of the mean annual precipitation of the basin's countries, Egypt would be the largest sufferer: increased water scarcity, up to 10% increases in its food gap, up to 70% reduction in its hydropower generation, and a 30% reduction in its agricultural GM. Interestingly, population growth rate is a very important driver that could reduce the impacts of climate change in the ENB. Under a low population growth rate of 1%, the demand for water and food would be lower, thus resulting in less stress on water and food systems. Under the full range of climate variations (−10% to 30% change in mean annual precipitation; increases in annual mean temperature of up to 4 °C by 2050), the food production system was able to maintain a stable and low food gap for all four countries with much less impact on Egypt's water scarcity problem. Importantly, these conclusions are based on development plans based on long-term changes in climate; short-term impacts resulting from climate variability are not explicitly represented in the reported mean values.

5.2 Study Significance and Contribution

The major contribution of this thesis is the NWFT modeling framework, and its three applications, to support planning for water and food security. This contribution can be considered on three levels: conceptual, policymaking, and technical.

5.2.1 Conceptual Contribution

The conceptual contribution is demonstrating that the nexus approach is not a research luxury but a practical necessity. ***Chapters 2**, **3***, and ***4*** show the value of planning and management of resources in a multi-centric approach. ***Chapter 4*** illustrates how international transboundary rivers are ill-characterized when considered as a mere water apportionment problem rather than a regional WEF nexus management problem.

5.2.2 Contribution to Policymaking

The contribution of this thesis to policymaking is addressing two policy-related issues. First, it fills a gap related to the global food (virtual water) trade studies and models that are criticized for being unable to attract potential policymakers, who usually make decisions on finer scales (e.g., national). In ***Chapter 2,*** this gap is addressed in the development of the NWFT framework, which includes a national water-food supply and demand model that runs side-by-side with a global virtual water trade model. This allows decision-makers at the national level to perform analyses that support water and food security under global and national scenarios, so they can compare and incorporate the global model results in national planning decisions. This gap is also addressed in ***Chapter 3*** in the configuration of ACPAR to establish a link between global food trade and food prices and national water-food planning decisions. This is significant because it allows decision-makers to plan for the impacts of changes and disturbances in global food markets on water-food security conditions in a country such as Egypt, which relies heavily on food imports.

The second contribution to policymaking is introduced in ***Chapter 4*** through the development of a rich database of thousands of development plans assessed under climate and social driver uncertainty. This database and the modeling results could support decision-makers in any future WEF negotiations among the ENB countries, and help achieving better outcomes for the WEF planning for the region as a whole.

5.2.3 Technical Contribution

The technical contribution of this thesis comprises four points, each represents an enhancement to the utility and accuracy of the developed framework, and its applications, compared to similar frameworks and models. The first technical contribution is represented in an improvement to the formulation of the global virtual water trade model component of the NWFT. As illustrated in ***Chapter 2***, the reviewed VWT models do not preserve the global virtual water trade balance, i.e., the sum of global VW exports from all countries is not equal to the sum of global imports, resulting in erroneous global VWT estimates. This was essentially due to the usage of two estimates for bilateral trade flux, by using different equations for export and import, this technical gap was addressed, and the global VWT balance is preserved in the NWFT framework, by using only one estimate to the bilateral trade flux based on the export equation (as explained in section 2.3).

The second technical contribution is an improvement to the design of planning objectives incorporated in ACPAR, as explained in ***Chapter 3***. There is a gap in existing models that perform water-food security planning, represented in considering the planning problem in a single objective or a bi-objective formulations, which might overlook significant tradeoffs, by including less objectives than needed. To address this point, ACPAR was built to incorporate a multi-objective formulation, which gives more flexibility the framework users to identify more conflicting objectives and quantify as much tradeoffs as needed.

The third technical contribution is represented in properly incorporating uncertainty within the work introduced in this thesis. In the review of existing models and frameworks that perform WEF planning, a common issue is that the analysis was only performed under historical conditions ignoring any future uncertainty, which limits the utility of such models in guiding future planning decisions. Moreover, few studies considered perfect-foresight future scenarios that cover limited space of the full domain of possible future conditions. This gap was addressed in ***Chapter 3***, as ACPAR incorporated a formal uncertainty assessment procedure that considered a wide range of future scenarios and used methods to help framework users select robust plans that provide optimal performance under wide a range of future conditions. The same gap was also addressed in the development of WEFNAF presented in ***Chapter 4***, which incorporated an explicit uncertainty assessment for WEF conditions under future climate and major social driver changes.

The fourth technical contribution is related to the scale of the study area that is considered when planning for WEF conditions in the ENB. As presented in ***Chapter 4***, previous WEF nexus studies focused extensively on small-scale study areas (e.g., sub-watershed scale). This small scale does not allow to evaluate impacts of WEF development beyond the limited boundaries of the study area, resulting in very limited spatial analysis of development, which compromise the model ability in revealing the different possibilities of reducing conflicts and reaching common benefits on national and regional scales. This gap was addressed in the development of WEFNAF, as the models were structured to allow for WEF assessments on small scales (e.g., watershed), as well as on national and regional scales. This gives more flexibility and utility for WEFNAF and makes it potentially a suitable tool to coordinate WEF planning between decision-makers on different levels.

5.3 Study Limitations

The proposed framework in this study demonstrates a good ability to realistically reproduce water, food, and hydropower generation systems for the study areas, as well as their interdependence. Nonetheless, some limitations affected the research results. Addressing such limitations could improve the accuracy and utility of the developed framework, along with its models.

For the NWFT framework, the international model of virtual water trade consists of linear regression equations that estimate virtual water trade flux between different regions. The parameters of such model were determined through regression analysis; however, a regression validation step was not performed before the model was used to project future scenarios, mainly due to the limited length of data available, which was nearly the minimum length needed for parameterizing regression models (i.e., 25 data points; Jenkins and Quintana-Ascencio, 2020). When more data become available, the model prediction reliability could be better tested and improved through a model validation exercise. Furthermore, the formulation of the international model of virtual water trade can be improved, either through the use of a many-country model, rather than a nine-region model, or by adding more conceptual components. The food production, water use, and food consumption components can be captured with finer levels of details for each region. Furthermore, The VWT is not limited to food, industrial products also use water (for cooling, processing, etc.), which is traded between countries. Therefore, there is a need to include VWT of industrial products in the trade component of the NWFT Model.

In the formulation of the ACPAR, less emphasis was placed on spatial representations related to cropping pattern distribution, variations of input variables, and model output. Variables such as crop water requirements and crop prices were aggregated as national average values. Any shortage in the water supply for agriculture was considered a uniform water deficit that impacts all crops. However, such a shortage might only impact specific crops cultivated in the most downstream part of the water system. Another implication of spatial aggregation is that the ACPAR framework cannot provide decision-makers with spatial information about cropping pattern changes, only changes at the national level. Moreover, as part of the future scenarios used in ACPAR, a constant price-cost ratio was assumed for the estimation of the agriculture sector's gross margin. Even though this is not an unrealistic assumption, it is important to keep in mind when analyzing and understanding the results derived from the ACPAR framework. Predicting future local crop prices in Egypt is another issue. Regression models linking global and local prices, developed for historical period, were used to project the future local market price based on future global price scenarios, which is a reasonable approach given that Egypt is moving fast towards free-market mechanisms. However, another option is to develop a (or use an existing) computable general equilibrium (CGE) model for Egypt that links supply, demand, and prices (Robinson et al., 2015; MWRI, 2001). Noting that CGE models also contain several assumptions about market mechanisms and consumer behavior and, in turn, the stationarity of such relationships in the future might be questionable (Arthur, 1999).

In configuring the WEFNAF for the ENB countries, reservoir operation rules for existing Ethiopian and Sudanese reservoirs were deduced from long-term mean monthly observed reservoir pool elevations, which is a reasonable assumption in accordance with the objective of this study and the evaluation of the long-term values of WEF performance measures. This limitation has a marginal impact on the accuracy of WEFNAF, but including detailed operation rules of the reservoirs would make WEFNAF even more realistic for various types of studies. Due to limited data availability, the water resource system of the ENB countries was not fully represented within the WEFNAF, as we considered only seven rivers (Figure 4.1) out of the 12 rivers that originate in Ethiopia. However, the considered rivers' flows represent 95% of the flow of the 12 rivers. Moreover, for the same reasons, freshwater lakes and groundwater availability and usages were not considered. The inclusion of these ignored water resources in the analysis might marginally improve the Ethiopian WEF performance measures.

5.4 Recommendations for Future Research

The results provided in this thesis are promising and the developed framework and its applications can contribute to decision-making to improve the water and food security for Egypt, as an exemplar arid country, and for ENB countries. Accordingly, the framework developed can be used in the future to investigate other research ideas or directions as follows.

The national model configured for Egypt's water-food nexus in the NWFT framework can be extended to include the Egyptian energy sector. The role of energy in the nexus is currently minimal due to the limited contribution of hydropower and the small amounts of cooling water used for thermal power, relative to other water uses, and the negligible use of Egyptian crops in bioenergy. Nonetheless, a considerable amount of energy is required as an input towards the water and food supply, mainly due to the use of fertilizers and machinery in agriculture and pumping systems in irrigation and water extraction. An increase in desalination and use of deep groundwater would also necessitate the need to include energy and study the tradeoffs of its uses related to industry, agriculture, and drinking water.

In the application of the NWFT framework and ACPAR, one of the objectives was to explore the interactions between the changes in the global food trade network and national water and food management decisions. In this thesis, the evolution of global food trade conditions was projected within the adopted IMPACT model assuming smooth evolution and transitions up to the year 2050 (***Chapter 2***). This was adequate to explore and represent the long-term dynamics and evolution of global trade; nonetheless, it does not account for shocks that might occur over different evolution trajectories. Given the consecutive shocks to which the global market was subjected over recent years (e.g., global crises in 2008, COVID-19 pandemic in 2020, and Ukrainian-Russian war in 2021), it might be also important to evaluate the impacts of these global shocks on the national WEF nexus and management decisions.

The results of WEFNAF for the ENB indicate considerable conflicts between the planning objectives of different WEF sectors in the region. This is more pronounced between sectors from different countries, in which WEF plans that depend on shared water resources in the upstream conflict with WEF plans of the downstream. To help reduce and mitigate these conflicts, an instrumental decision variable is the operation rules of existing and proposed dams. The use of adaptive and dynamic operation rules could help achieve optimal performance of the whole ENB WEF system and be utilized to balance the tradeoffs between different sectors/countries. Such adaptive operation rules were not tested in this thesis but is an important direction for future research.

Using the WEFNAF framework, the WEF sectors of the ENB countries were explored under a wide range of plausible changes of social and climate drivers. Among the considered drivers, the mean annual precipitation of the region impacted the WEF system performance the most. However, specific climatic conditions could critically stress the WEF sectors but were not explicitly considered in this study. Importantly, drought has severely impacted water and food systems of the ENB countries in the past and possibly will in the future. Explicit consideration of drought scenarios, to quantify how future drought characteristic changes might impact the WEF conditions under different development plans, is recommended for future research.

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National water, food, and trade modeling framework: The case of Egypt

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Publication: Science of The Total Environment

Publisher: Elsevier

Date: 15 October 2018

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ACPAR: A framework for linking national water and food security management with global conditions

Author: Ahmed Abdelkader,Amin Elshorbagy

Publication: Advances in Water Resources

Publisher: Elsevier

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Appendix B: Supplementary materials for Chapter 2

B.1 National water-food model of Egypt

This model characterizes the dynamic food-water supply and demand system at the national scale of Egypt and maintains water and food balances, taking into account the different uses of both food and water and the virtual water (VW) embodied in different crops and food products. The application of this model starts with a historical accounting period (1986-2013), then scenarios to represent the potential future alternatives based on assumptions set by the user. The model comprises three modules (sub-models), crop and animal production, Food and animal consumption, and Egypt's water resource system. These modules are described below in detail.

B.1.1 Crop and animal production module

The purpose of this module is to estimate the agriculture and animal production for crops and animal products produced in Egypt. The water required for this production process is estimated and checked against the water resources available for agriculture to prevent any water balance violation. This module is divided into two sub-modules Agriculture crop production, and Animal production sub-modules.

Agriculture crop production sub-module:

Here, the crop productivity (yield/feddan) is multiplied by the crop harvested area to obtain the annual crop production for total of 78 crops (72 food crops, 3 non-food crops, and 3 fodder crops). All crop data were downloaded from FAO (2017).

Animal production sub-module:

This sub-module calculates the quantity produced of major animal products in Egypt (i.e., meat, milk, eggs, and honey) for 12 livestock (i.e., buffalo, cattle, goat, sheep, camel, rabbit, chicken, duck, turkey, goose, pig, and bee). The data required to build this part include animal stock, off-take rates, milk/eggs/honey producing animal ratios, and animal productivity. These data were compiled and calculated based on data available in FAO (2017). Annual feed consumed by these animals was calculated because it is an important component to calculate the amount of water required for animal production and the food/feed balance, as in Egypt some grains are used to feed animals (e.g., wheat products) (FAO, 2015). Figure B.1 shows a schematic drawing that illustrates model calculations for animal products in the animal production component. The animal stock (population of live animals) was calculated every year based on a growth rate. The number of slaughtered animals was then calculated by multiplying the animal stock by annual off-take rate, and then, the meat production (tonne) was calculated by multiplying the meat productivity (kg/head) by the number of slaughtered animals for each livestock. In a similar process, the number of dairy animals and egg layers for chickens were separated from the animal stock, then multiplied by Milk/egg productivity (kg/head) to calculate the total annual production (tonne), noting that for honey the calculations was based on number of hives. In this process, and according to the available data, all animals were assumed to produce meat (except bee), milk was produced by (buffalo, cattle, goat, and sheep) and eggs were produced by chicken.

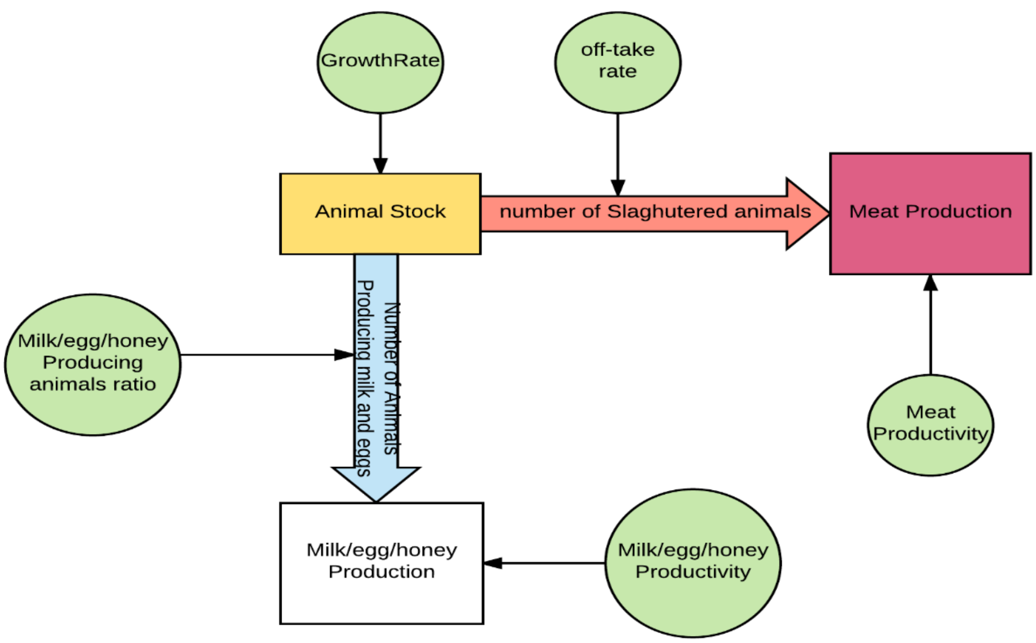

Figure B.1: Calculations flow in the animal production sub-module.

The annual feed consumed by these animals was then calculated as shown in Figure B.2. The animal stock was divided to three production systems: Fattening system (produces meat), Dairy system, and Egg layers system based on data available in FAO (2017). Feed quantities and composition vary depending on livestock type and also the production system for the same livestock. In Egypt, there is a shortage in detailed data of animal feeding, because the majority of animals are raised in a small-scale production system by farmers that feed their animals on diverse rations. However, the FAO reports (El-Nahrawy, 2011) and FAOSTAT (FAO, 2017) database provide estimations for the total amounts of feed consumed in Egypt, which were used in this study. The feed calculations require the knowledge of feed ration consumed per head for each livestock in each production system, which was calculated after making reasonable three assumptions: (1) the ration of both fattening and dairy ruminants is 80% roughages and 20% concentrates, while poultry in fattening and egg layers systems consumes only concentrates (El-Nahrawy, 2011), (2) the roughages only include Egyptian clover (Berseem), which is the major fodder crop in Egypt (El-Nahrawy, 2011), and that the concentrates is composed mainly of grains that are commonly consumed by humans as the FAOSTAT data show, and (3) concentrates were assumed to be entirely based on imported components. The calculation of feed per head was then made using the same approach as in (Mekonnen & Hoekstra, 2010) and the resulted feed ration was scaled by a factor range from (1-1.25) to match data available on FAOSTAT for Egypt. After that the total quantities of feed for each livestock in each production system was calculated by multiplying the number of animals by per head feed quantity (kg/head). Then, the total feed consumed in Egypt (National Feed) is calculated by summing the total roughage consumed and the total concentrates by different animals. The total amount of roughage (Berseem) was produced domestically in the historical period, but the model also calculates any gap and puts it as roughage import for any of the future scenarios.

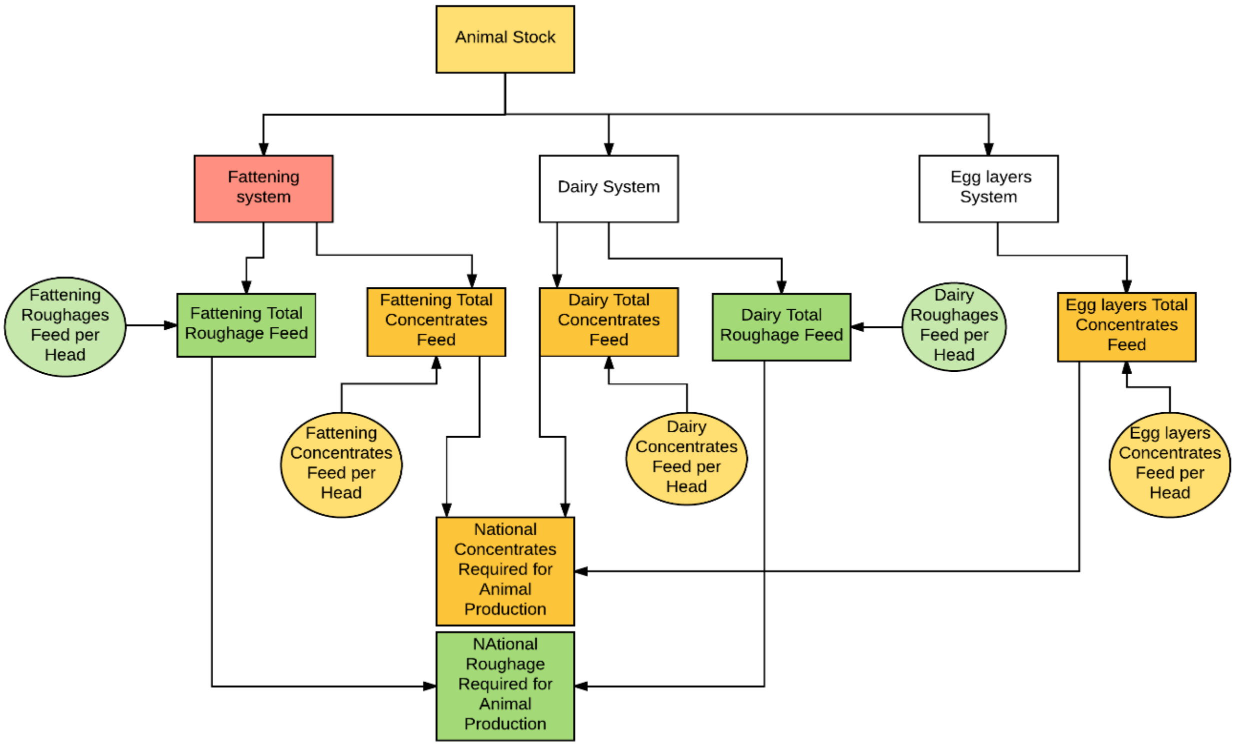

Figure B.2: Animal feed calculations in the animal production sub-module.

<u>Water required for agriculture and animal production calculations:</u>

The agricultural crop and animal production component was designed to calculate water required to produce crops and animal products – called water demand, then compare it with water available for agriculture and animal production as calculated in the water resources modeling component as "possible supply". If the demand is less than the possible supply, the extra water can be used to irrigate more lands, so the model increases the agriculture lands proportionally. When the demand is larger than the possible supply, it means that there is water shortage, and land productivity is adjusted to reduce productivity according to the following productivity function (equation 2.3 in the manuscript) (Doorenbos and Kassam, 1979). To calculate the amount of water required for agricultural production, each crop production is multiplied by the water footprint (WFP) of the crop and then, divided by agriculture irrigation efficiency, then summed up for all crops.

The calculation of water required for animal production includes two components: (1) water required to cultivate domestic feed (Berseem) and (2) water required for animal service and drinking water compiled from (Mekonnen & Hoekstra, 2010). Consequently, the water requirements were summed for all livestock to calculate the total water required for animal production. The summation of water required for agriculture and animal production is the water required for agriculture and animal production in the country.

B.1.2 Food and animal consumption module

In this module, the food consumption (kg/capita) was multiplied by the population of Egypt to calculate the national food consumption. The quantity of food supplied in a nation is larger than this national food consumed, mainly because of food waste/losses, but also for other parts used for seeds, feeding animals (in form of concentrates), and non-food uses. The FAOSTAT database includes food sheet balance that provides estimates for all these values and defines the Domestic Supply Quantity (DSQ) of certain product as the summation of all these items as equation B.1 shows.

$$DSQ = \text{Food} + \text{Feed} + \text{Seed} + \text{Non-food uses} + \text{Losses} \qquad (B.1)$$

The FAOSTAT data were used to calculate the percentage of Losses as Losses/ (national concentrates consumption + national food consumption), noting that the national concentrates consumption was calculated in the agricultural and animal production component, similarly for the percentage of Seeds and the percentage of Non-food uses. Then, to calculate the national losses (see Figure B.3) these percentages were multiplied by (national concentrates + national Food consumption), and similarly for national seeds and national Non-food uses. Finally, the summation of all previous values is the DSQ for each product. This calculation method allows for estimating the Losses, seeds, and Non-food uses for the future scenarios.

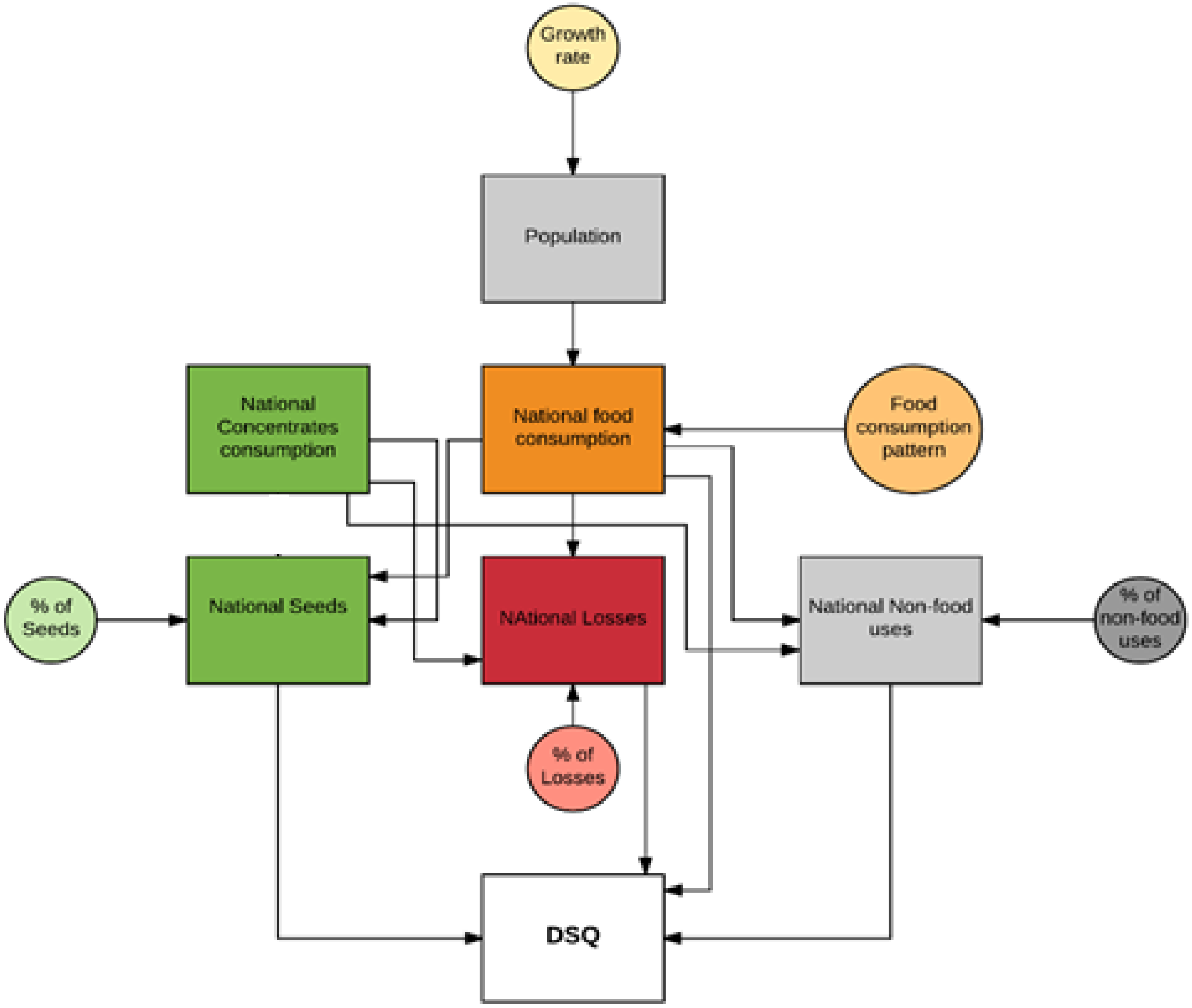

Figure B.3: Calculations of the Domestic Supply Quantity (DSQ) in the food and animal consumption module.

After estimating the DSQ, the imports and exports of each product were then calculated as the difference between DSQ and production quantity of the same product for 81 products that are either produced or consumed in Egypt. In this approach each product was assumed either imported or exported (export and import cannot take place together for the same product in the same year) Stock variations were not considered in the calculations and were assumed to be small at the model's annual temporal resolution.

The food gap is defined as the difference between the DSQ and the production for each product (if this difference is positive only), and thus, the national food gap is the summation of the gap values for all products. The water gap is defined as the water required to produce the food gap for each product domestically, and the national water gap is the summation for all products. Food self-sufficiency is the ratio between production and DSQ for each product and it can be larger than 1 for a product. The national food self-sufficiency is: $1 - \frac{national\ food\ gap}{DSQ}$. The National overall system water self-sufficiency is: $\frac{Water\ supplied\ for\ all\ uses}{water\ demand\ of\ all\ uses + national\ water\ gap}$

B.1.3 Egypt's water resources systems module

The water resources system in Egypt is quite unique, where almost all users and sectors rely on the Nile water, which is flowing into Egypt from the transboundary upper basin, shallow groundwater aquifer that is recharged mainly by the Nile water, and the irrigation system. Small amounts of water (less than 3%) are provided through rainfall harvesting and desalination of the sea water. Given the 90 $10^9\times$ m^3 (90 BCM) live storage size of the High Aswan Dam (HAD), it has been able to secure 55.5 $\times10^9$ m^3/y even though the annual inflows to Egypt has been historically varying from 30 to 120 $\times10^9$ m^3/y (MWRI, 2010).

The purpose of this module is to allocate water to three different water sectors: Municipal, Industrial, and Agricultural sectors. The water is being allocated through a water demand – supply process, considering the first priority for the municipal sector, followed by the industrial, then the agricultural sector.

The water demands of 1990, 2000, and 2010 were compiled from (Abu Zeid, 2007; Allam & Allam, 2007; MWRI, 2010), and linearly interpolated to estimate the annual demand time-series between 1986 -2013 for the three sectors.

Municipal Sector Water Demand:

The following equations were used to estimate the future demand.

GMD = NMD * PF / NE (B.2)

Where; GMD is the Gross per capita Municipal Demand, NMD is the Net per capita Municipal Demand, PF: Water Pricing Demand Reduction Factor, and NE is the Conveyance Network Efficiency. The NE was assumed to be 70% according to the MWRI (2010), and fixed for future scenarios, while changed in sensitivity analysis to see its effect on the food and water gaps. The PF was equal to 1 in 2013 (when the GMD was 114 m^3/cap/year), while decreased in scenarios linearly between 2013 and 2050 to reflect the reduction in demand when water prices increase. As an example, for the Critical scenario, this factor reached 0.697 in 2050 to match the GMD values expected by the MWRI in 2050 under the Critical scenario.

The National Municipal Water Demand (NMWD) = GMD * Population (B.3)

This amount was equal to 9.0×10^9 m^3/y in 2013 and 13.5×10^9 m^3/y in 2050 (for the Critical scenario).

Municipal Sector Water Supply:

The water is supplied to the Municipal Sector from multiple sources as Follows:

All water available through desalination, 15% of the total municipal demand is taken from shallow groundwater (MWRI, 2010), and finally the rest is withdrawn from the Nile River. The values of each source changed during the historical period but for example in 2010 the numbers were (0.2×10^9 m^3/y from desalination, 1.35×10^9 m^3/y from shallow GW, 7.45×10^9 m^3/y from the Nile River). For future scenarios, the supply from desalination was changed as specified in each scenario, and the supply of shallow GW was varying with the demand. The remaining part of the municipal future demand was withdrawn from the Nile River.

Industrial Sector Water Demand:

The future demand was estimated as mentioned in MWRI (2010) to increase by a specified annual growth rate according to each scenario (e.g., in the Critical scenario, the water demand increases by growth rate of 0.65%, so it will increase from 2.08 $\times 10^9$ m^3/y in 2013 to 3.1 $\times 10^9$ m^3/y in 2050). It should be noted that part of the water that is allocated to the municipal sector is used by the industry sector (MWRI, 2010), this amount was about 1.8 $\times 10^9$ m^3/y in 2010. But in the model this separation is not accounted for explicitly, which is the same approach indicated in the MWRI's Strategy 2050 (MWRI, 2010). So, the Municipal water in the model contains some water for industry.

Industrial Sector Water Supply:

Industry depends only on the Nile River for water supply.

Agriculture Sector Water Demand:

The water demand of crop agriculture and animal production sector was calculated as mentioned in Section B.1.1.

Agriculture Sector Water Supply:

Agriculture water supply is based on multiple sources as follows:
Nile River, shallow GW, Deep (fossil) GW, Rainfall harvesting, and Drainage and waste reuse.
Nile River: As mentioned before, the priority of water allocation is for municipal, industry, then agriculture. So, the remaining water after supplying the municipal and industry sectors, water is allocated for agriculture. Evaporation losses and navigation requirements are also accounted for as supplies from the Nile.

Water available for agriculture from Nile River = Water released from HAD – Evaporation – Municipal Supply portion from the Nile – Industrial Supply – Navigation requirements. (B.4)

Deep GW and Rainfall harvesting: Historical data were used as in Abu Zeid (2007); Allam and Allam, (2007); MWRI (2010), and linearly interpolated to estimate the annual supply time-series between 1986 -2013. For future scenarios, the values were increased linearly according to the planned values for each scenario up to year 2050.

Shallow GW: the remaining amount after supplying water to the municipal sector was supplied to agriculture. The total supply from shallow GW (to municipal and agriculture) in a year (*i*) was checked in order not to exceed the maximum yield (GWY_i), which was calculated as follows:

$$GWY_i = Maximum\ Yield\ in\ 2010 \times \frac{NRR_i}{AER_i} \quad \text{(B.5)}$$

Where, the *Maximum Yield of 2010* = 8.4 $\times 10^9$ m^3/y (MWRI, 2010), NRR_i is the Nile River water Ratio, AER_i is the Agriculture Irrigation Efficiency Ratio

$$NRR_i = \frac{Water\ available\ for\ agriculture\ from\ the\ Nile\ in\ year\ i}{Water\ available\ for\ agriculture\ from\ the\ Nile\ in\ 2010} \quad \text{(B.6)}$$

$$AER_i = \frac{Agriculture\ irrigation\ efficiency\ in\ year\ i}{Agriculture\ irrigation\ efficiency\ in\ 2010} \quad \text{(B.7)}$$

Drainage and wastewater reuse: To calculate the reuse from drainage and waste water, the following steps were carried out:

*Municipal waste water = (1- Municipal water consumption efficiency) * Water Allocated to Municipal sector* (B.8)

*Industry Waste Water = (1- Industry water consumption efficiency) * Water Allocated to Industrial sector* (B.9)

*Agriculture Drainage water = (1- Agriculture Irrigation efficiency) * Water Allocated to Agriculture before any reuse* (B.10)

Where, *Municipal water consumption efficiency = Municipal water Consumption / Municipal Supply*. In 2010, this ratio was = 1.8/7.2 = 25% (MWRI, 2010), and it was assumed to be constant in the historical period as well as in the future.

Industrial water consumption efficiency = Industrial Water Consumption / Industry Supply. In 2010, this ratio was = 1.4/3.8 = 37% (MWRI, 2010), and it was assumed to be constant in the historical period as well as in the future.

Water Allocated to Agriculture before any reuse = Water Available for Agriculture from Nile River + Deep GW + Rainfall harvesting + shallow GW supplied for Agriculture

The total amount of drainage water is the summation of agriculture drainage, municipal wastewater, and industrial wastewater. The drainage reuse ratio was varied between 10% in 1986 to 57% in 2013 to reflect the increased dependence on reuse. These estimates bring the reuse in 2010 to match the total reuse reported by the MWRI (2010) – 16×10^9 m^3/y. The MWRI attempts to limit the reuse ratio to a maximum of 60% of the drainage water. In the Critical scenario, the drainage reuse ratio increased to 61% in 2050).

Agriculture Irrigation Efficiency

Accurate values for the irrigation efficiency in Egypt were not available, however, Molle et al. (2013) found the efficiency to vary between 40% and 62%. In the NWF model, the demand for the agriculture sector and the total water resources available for agriculture were calculated. The demand was explained earlier, and the available water was calculated according to Equation (B.11):

Total water resources available for Agriculture = Water Available for Agriculture from Nile River + Deep GW + Rainfall Harvesting + shallow GW supplied for Agriculture + Waste and Drainage Water Reuse (B.11)

The Agriculture Irrigation Efficiency in the historical period was estimated in the model based on the calculated demand and the supplied water for agriculture, and it was found to have increased from 40% to 63% over the historical period (1986-2013).

Water Disposed to the sea

To estimate the water disposed to the sea, the overall water balance of the system considered as follows:

Water disposed to sea and northern lakes = independent water resources available (all sources except shallow GW and Reuse) - water consumed in the different sectors (B.12)

Where, independent water resources available is the summation of High Aswan Dam release, rainfall harvesting supply, desalination supply, and deep GW supply. The water consumed in the different sectors is the summation of municipal water consumption, industrial water consumption, agriculture water consumption, river navigation, and evaporation.

B.2 VWT model experiment (I) results

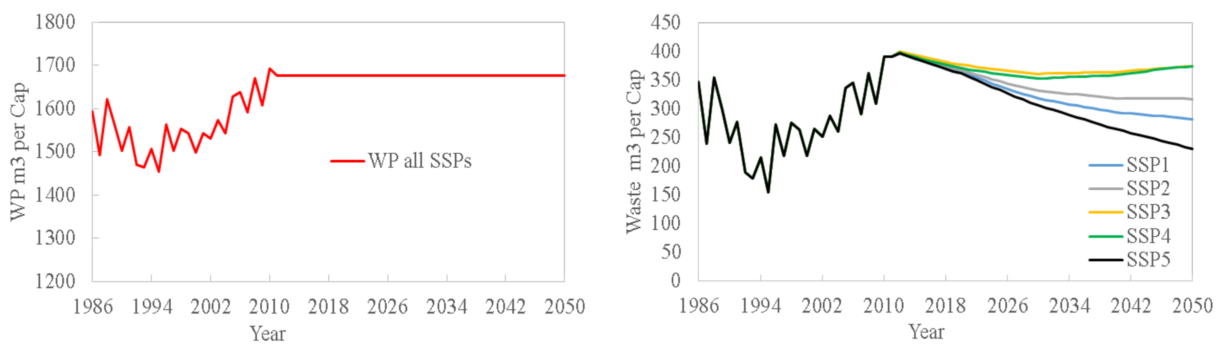

Figure B.4: WP per capita and waste per capita for Africa

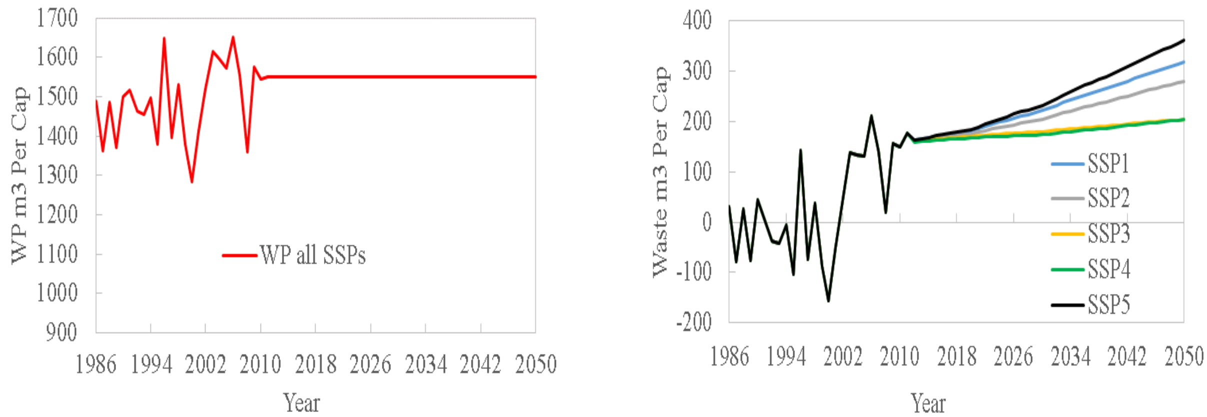

Figure B.5: WP per capita and waste per capita for Middle East and North Africa

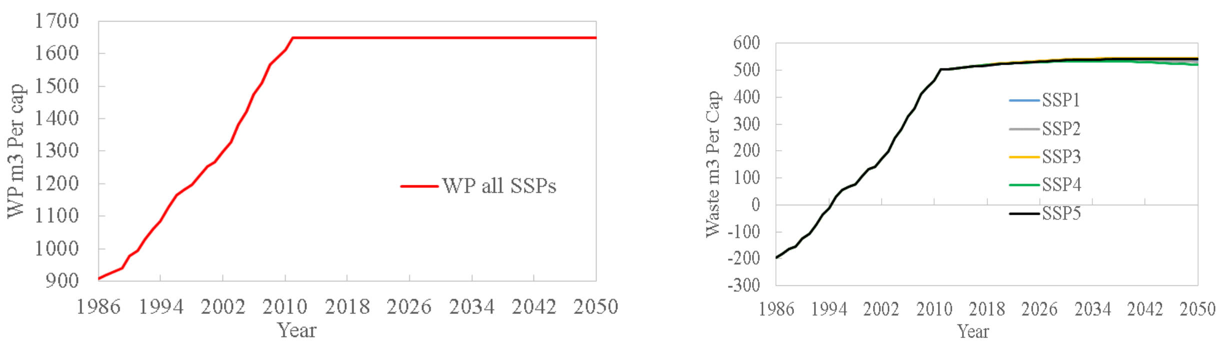

Figure B.6: WP per capita and waste per capita for East Asia

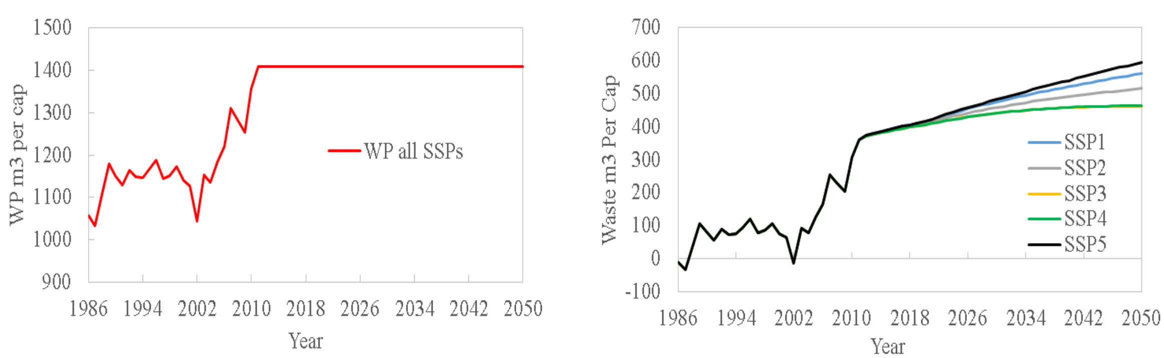

Figure B.7: WP per capita and waste per capita for South Asia

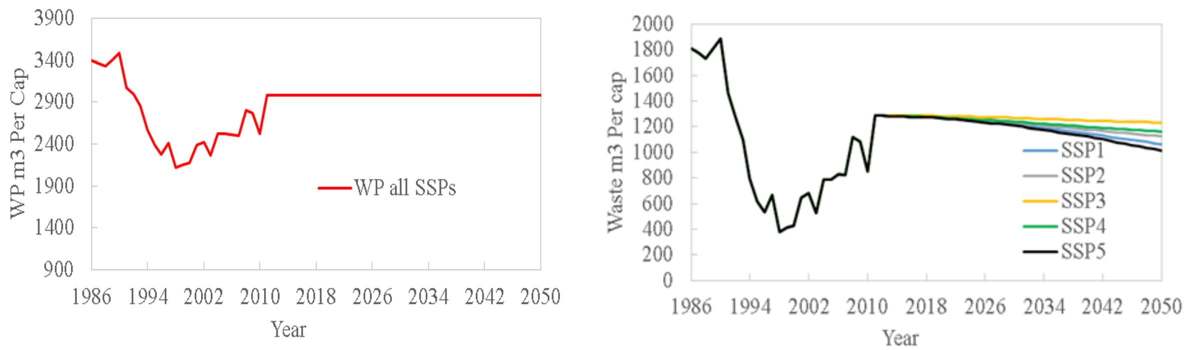

Figure B.8: WP per capita and waste per capita for East Europe and Central Asia

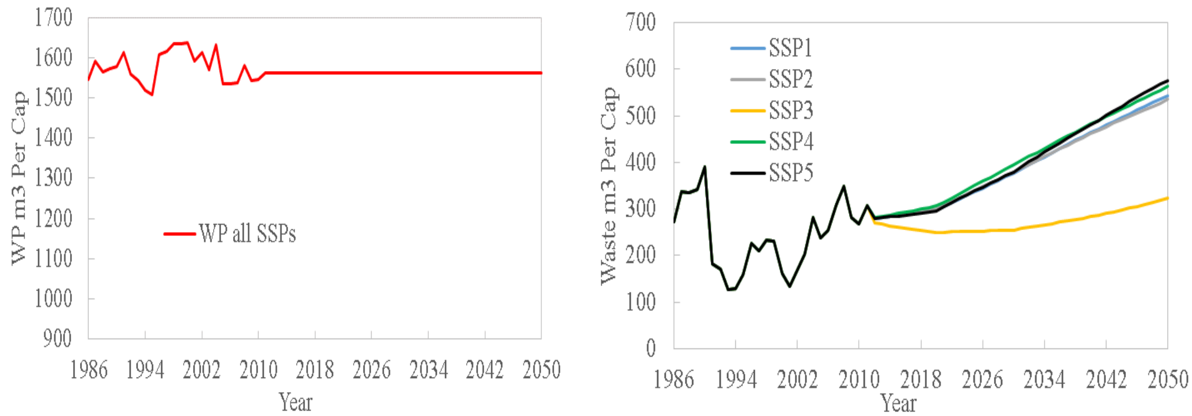

Figure B.9: WP per capita and waste per capita for Europe

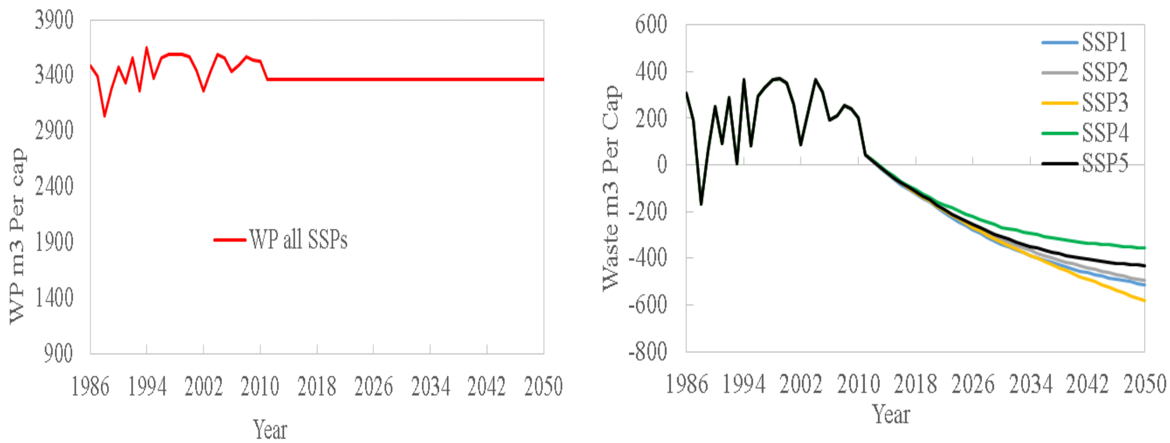

Figure B.10: WP per capita and waste per capita for North America

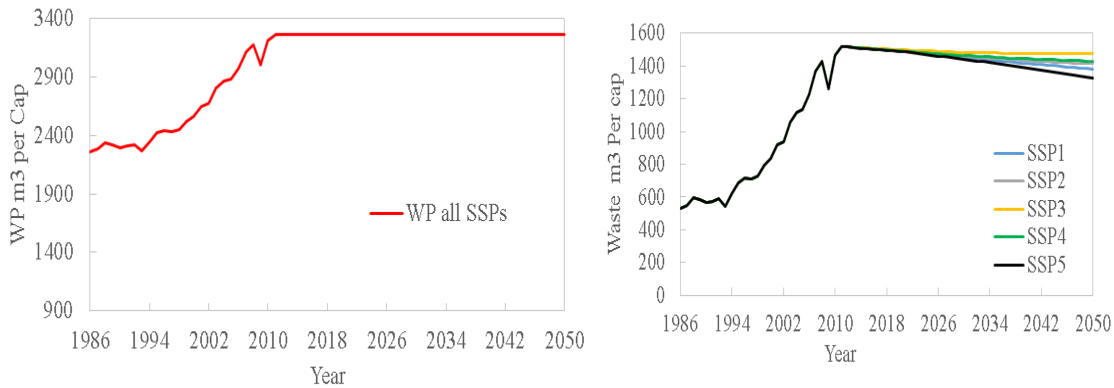

Figure B.11: WP per capita and waste per capita for Latin America

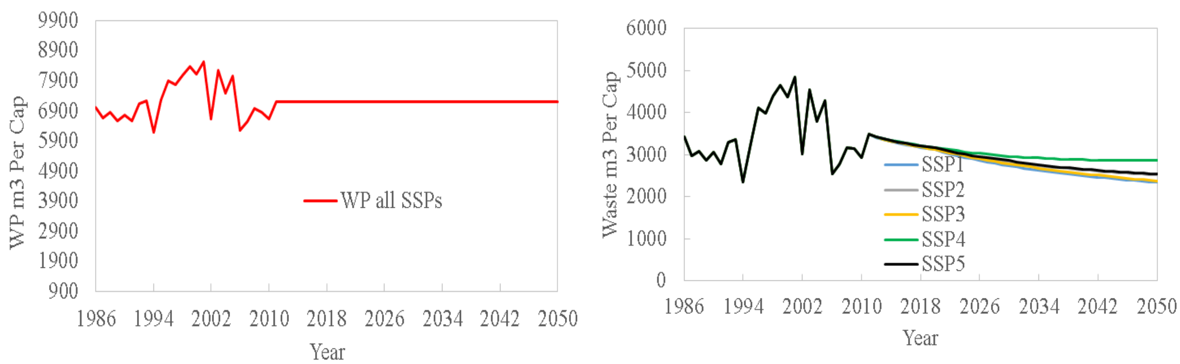

Figure B.12: WP per capita and waste per capita for Oceania

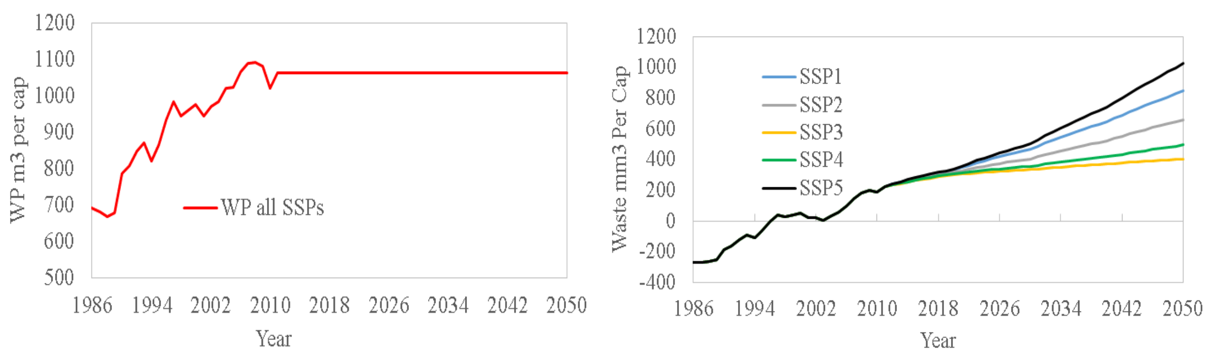

Figure B.13: WP per capita and waste per capita for Egypt

B.3 VWT model experiment (II) results

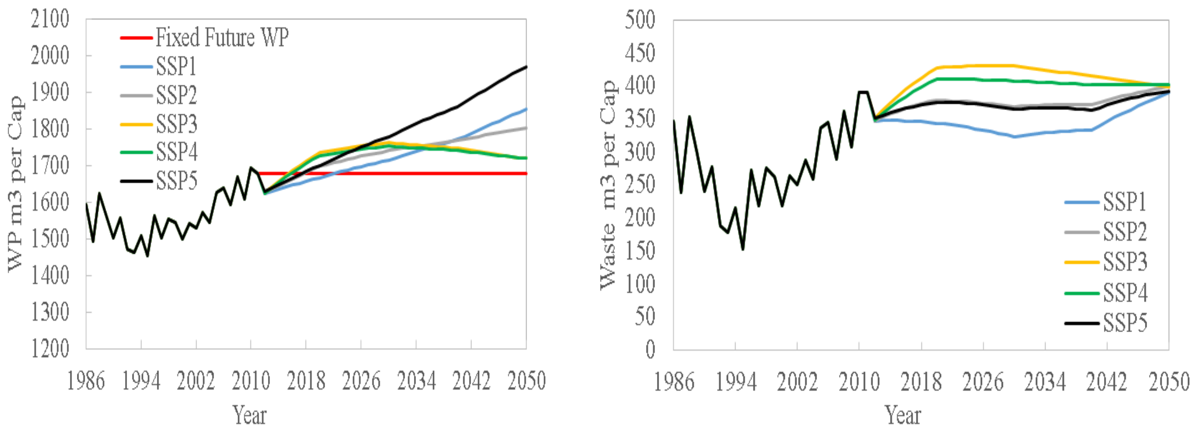

Figure B.14: WP per capita and waste per capita for Africa

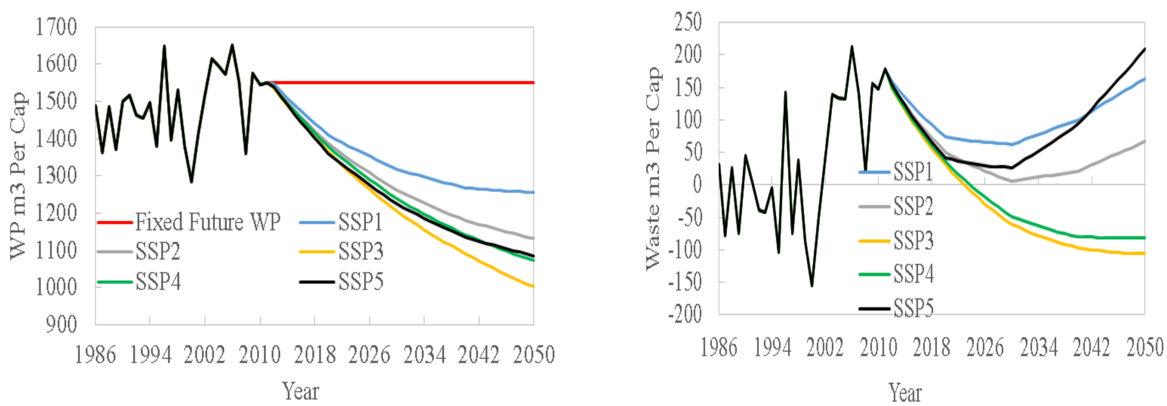

Figure B.15: WP per capita and waste per capita for Middle East and North Africa

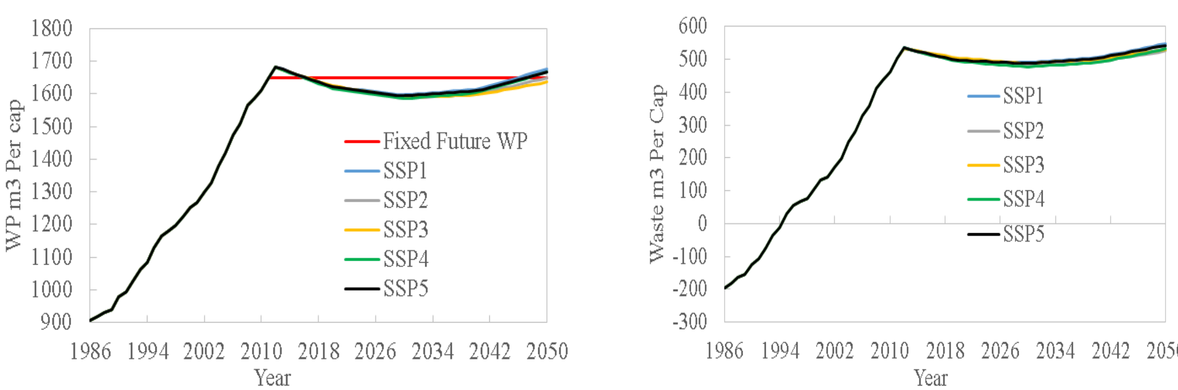

Figure B.16: WP per capita and waste per capita for East Asia

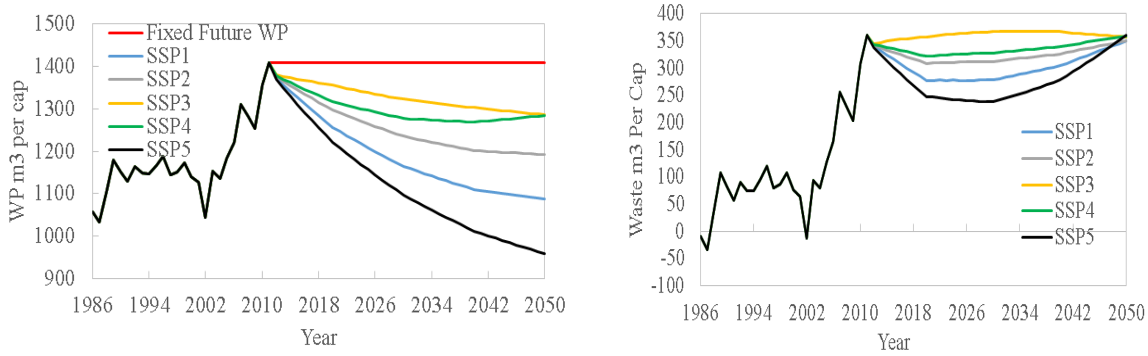

Figure B.17: WP per capita and waste per capita for South Asia

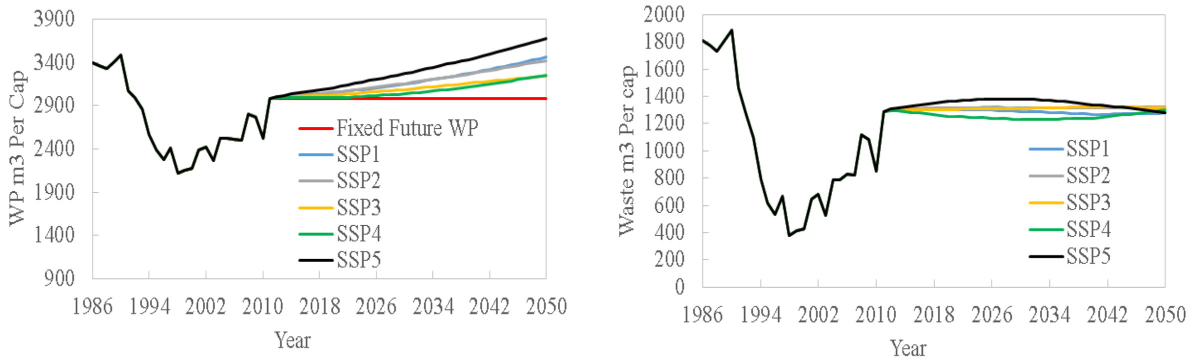

Figure B.18: WP per capita and waste per capita for East Europe and Central Asia

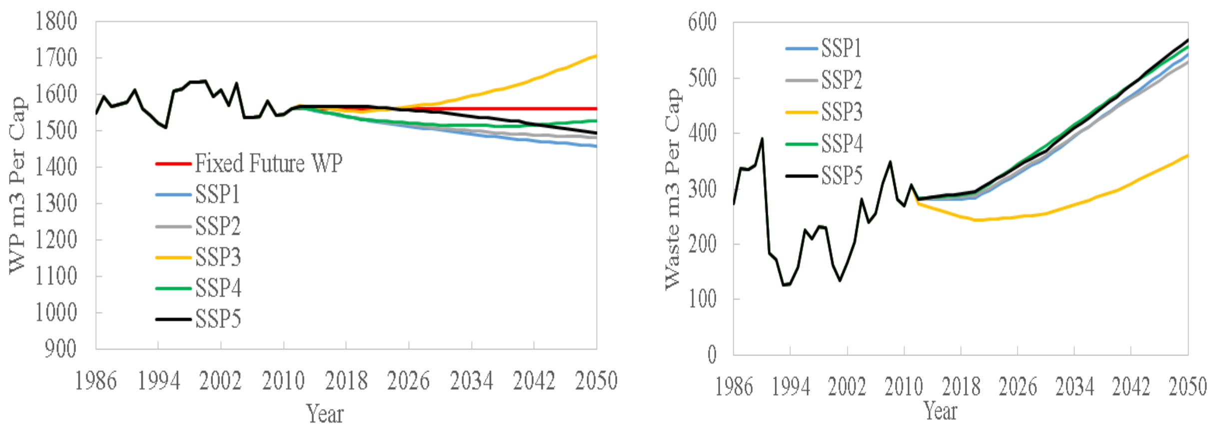

Figure B.19: WP per capita and waste per capita for Europe

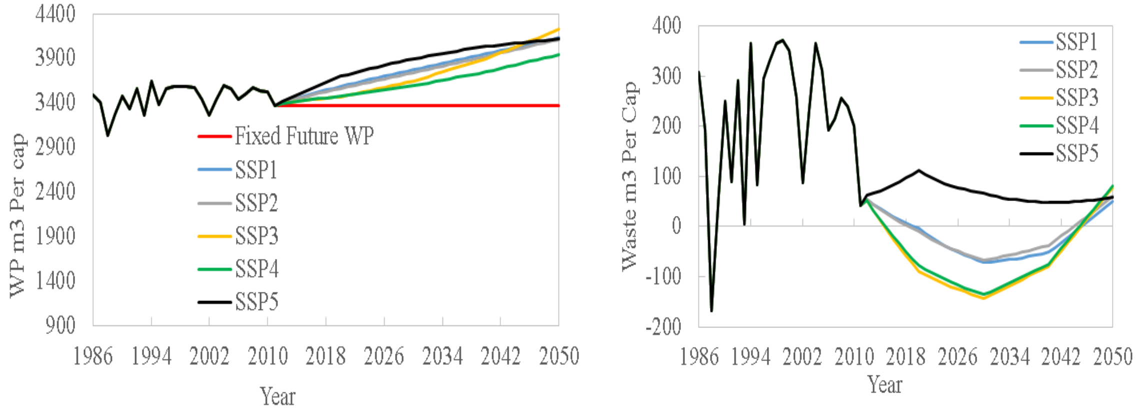

Figure B.20: WP per capita and waste per capita for North America

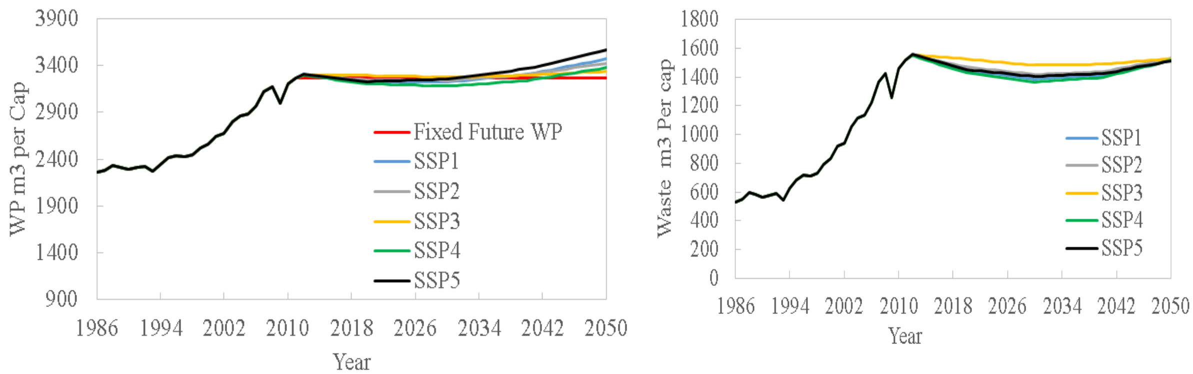

Figure B.21: WP per capita and waste per capita for Latin America

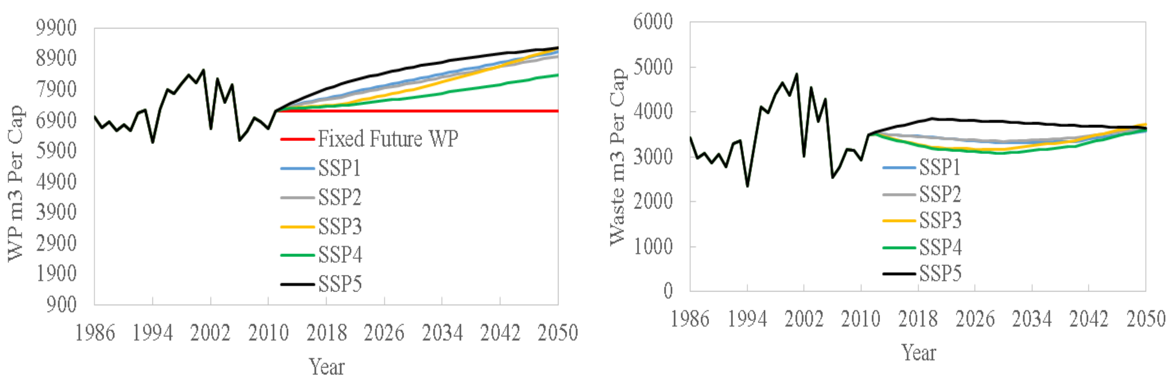

Figure B.22: WP per capita and waste per capita for Oceania

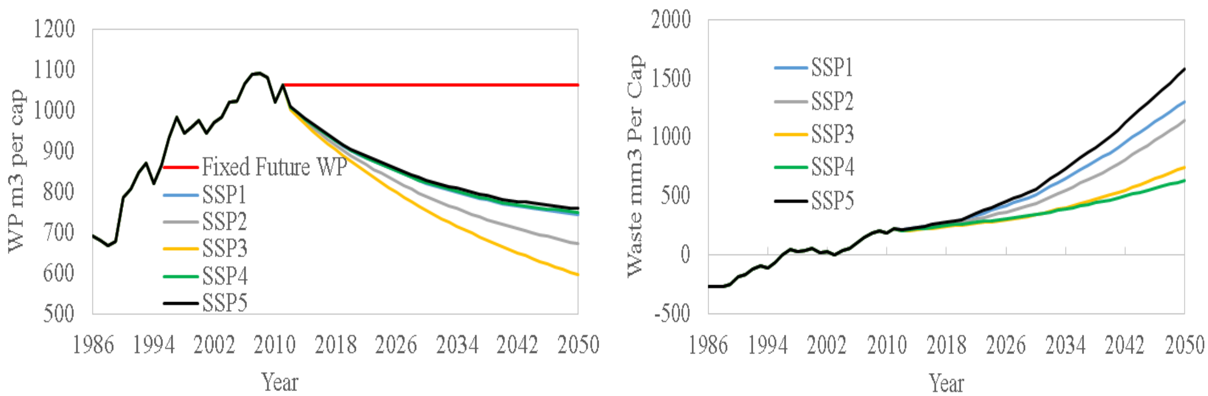

Figure B.23: WP per capita and waste per capita for Egypt

B.4 The regional distribution of Egypt's VW imports

Table B.1: The regional distribution of Egypt's VW imports in 2011 and projected in 2050 for all SSPs values in 10^9 m^3/y for Experiment I (fixed WP).

Region	2011	SSP1	SSP2	SSP3	SSP4	SSP5
AF	1	11	10	7	6	14
ME	1	2	2	1	1	2
EA	6	18	17	14	13	20
SA	2	5	4	4	3	5
CA	5	27	22	14	15	33
EU	4	9	9	7	7	10
NA	9	26	25	21	19	29
LA	1	8	7	5	4	10
OC	3	11	10	8	7	12
Total	**32**	**117**	**105**	**82**	**76**	**135**

Table B.2: The regional distribution of Egypt's VW imports in 2011 and projected in 2050 for all SSPs values in 10^9 m^3/y for Experiment II (varying WP and fixed Waste per capita).

Region	2011	SSP1	SSP2	SSP3	SSP4	SSP5
AF	1	20	21	17	11	24
ME	1	3	3	3	2	3
EA	6	21	21	19	15	23
SA	2	6	6	6	5	7
CA	5	72	77	69	38	83
EU	4	11	11	10	9	12
NA	9	38	40	39	27	41
LA	1	15	15	12	8	17
OC	3	19	21	20	13	21
Total	**32**	**206**	**215**	**197**	**128**	**232**

B.5 Water uses for different sectors for all scenarios

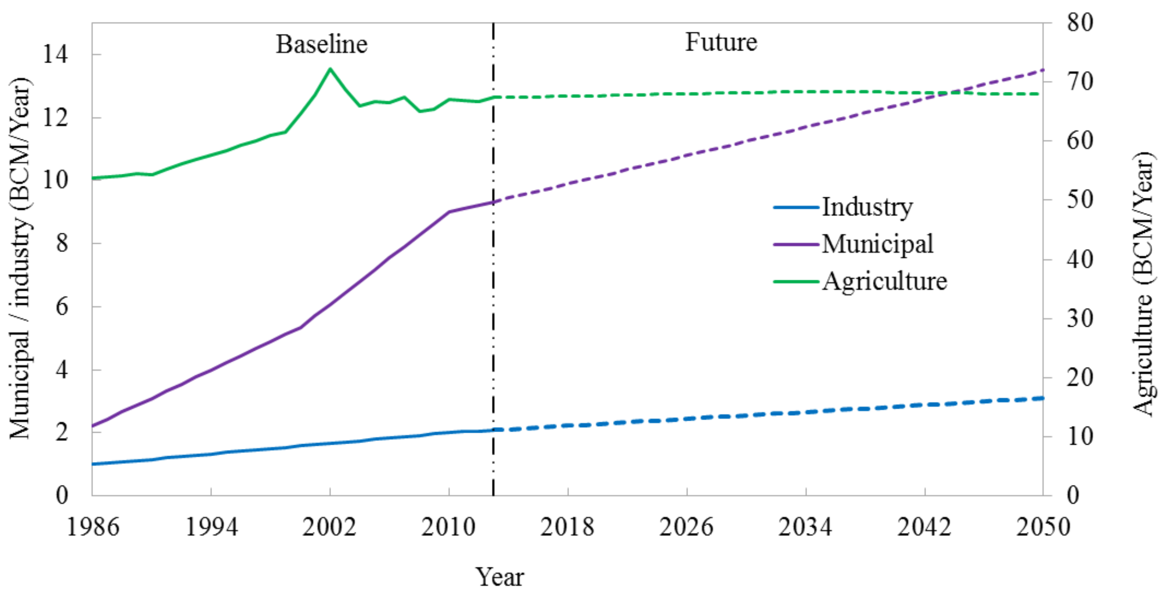

Figure B.24: Water Uses for different sectors for the Critical scenario

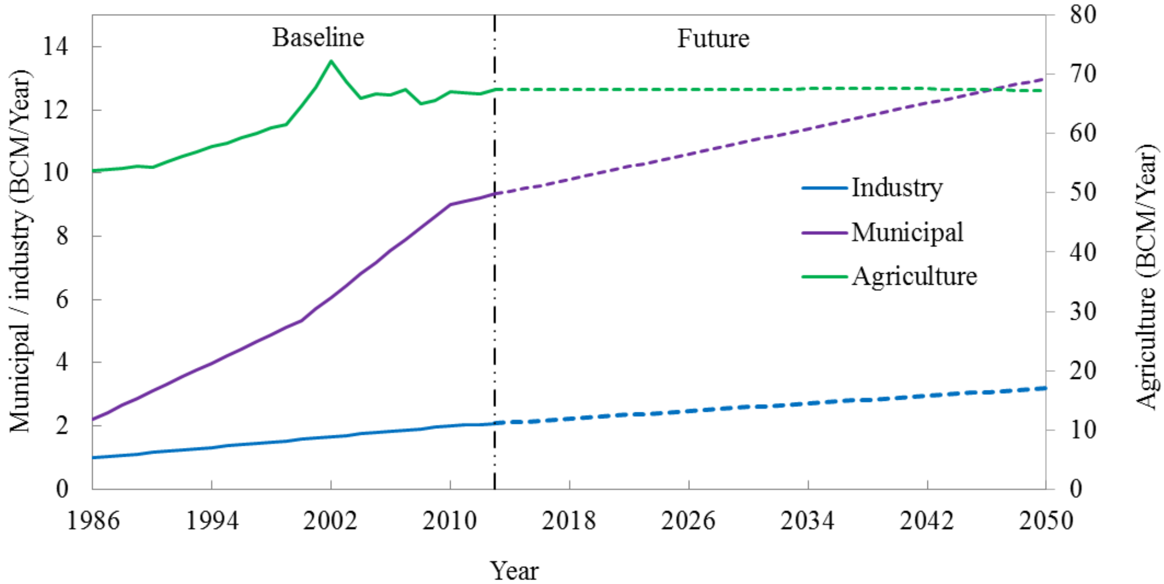

Figure B.25: Water Uses for different sectors for the Balanced scenario

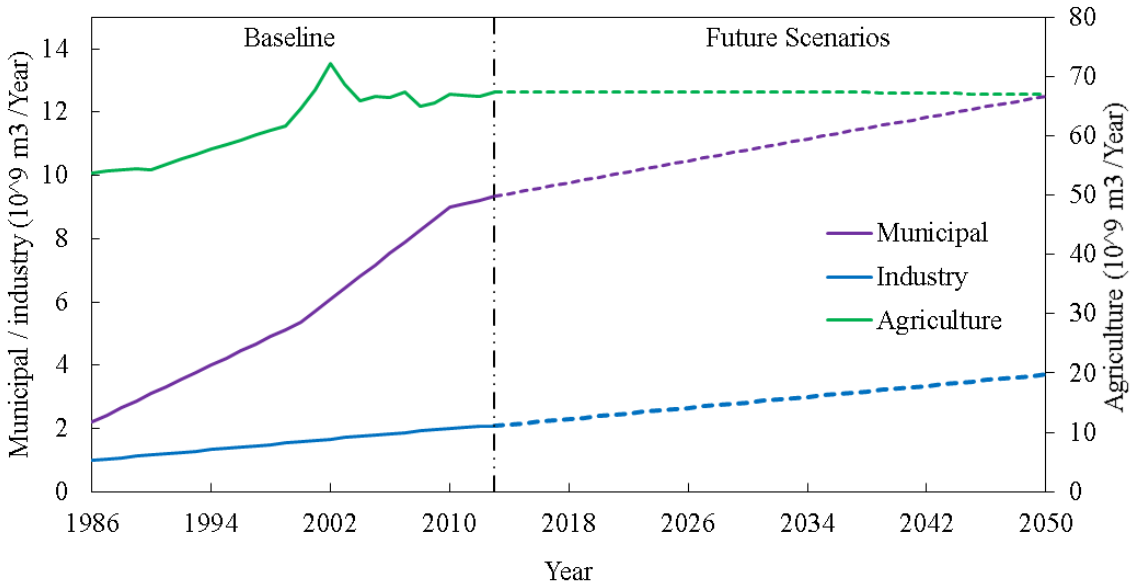

Figure B.26: Water Uses for different sectors for the Optimistic scenario

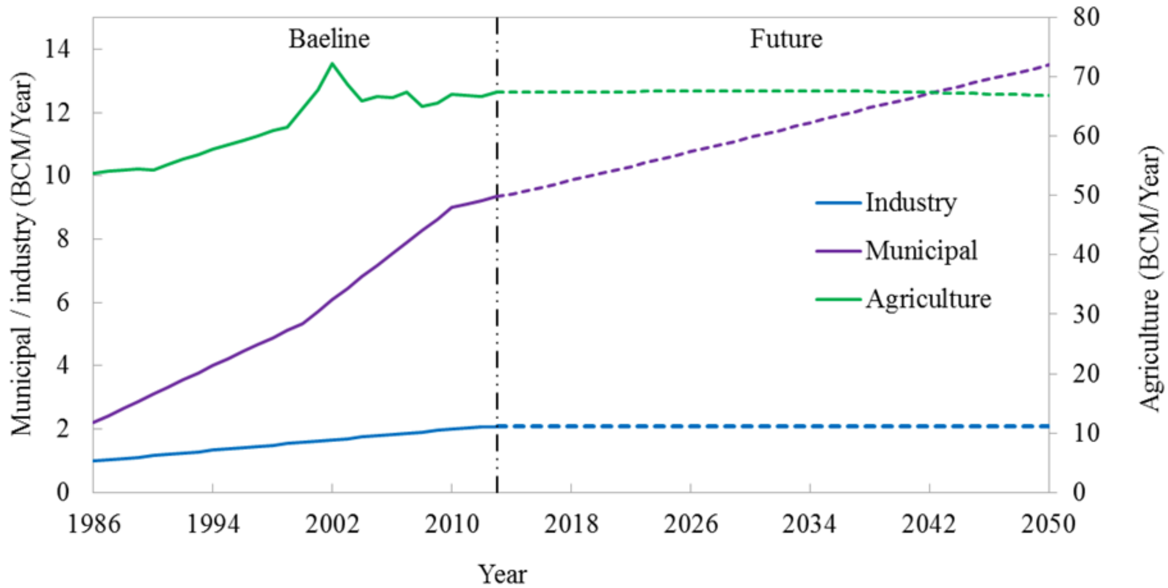

Figure B.27: Water Uses for different sectors for Reference scenario

B.6 Sensitivity analysis results

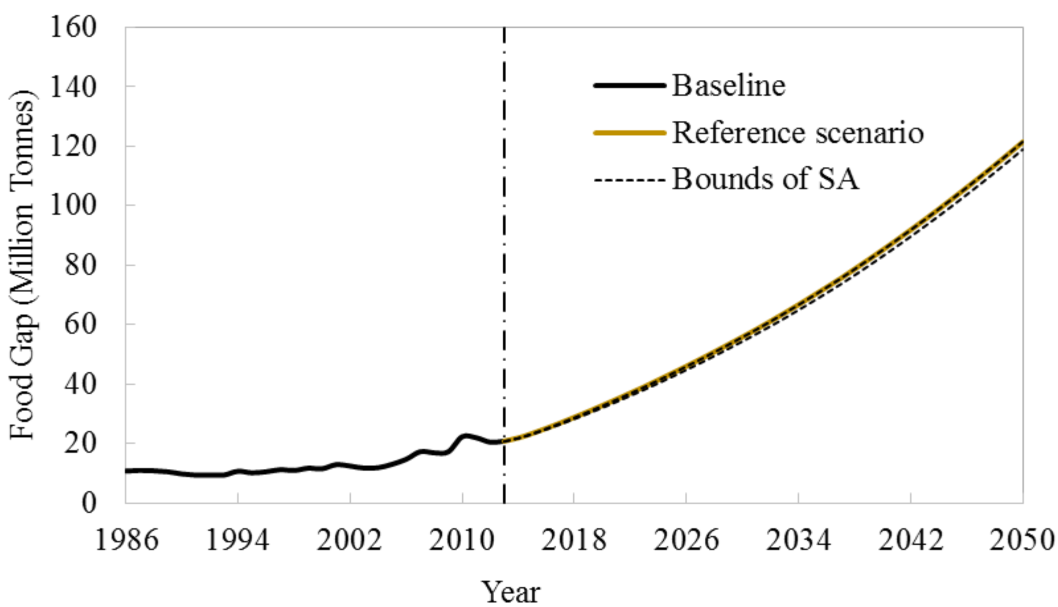

Figure B.28: Sensitivity analysis for agricultural land area, with other factors fixed as in the reference scenario.

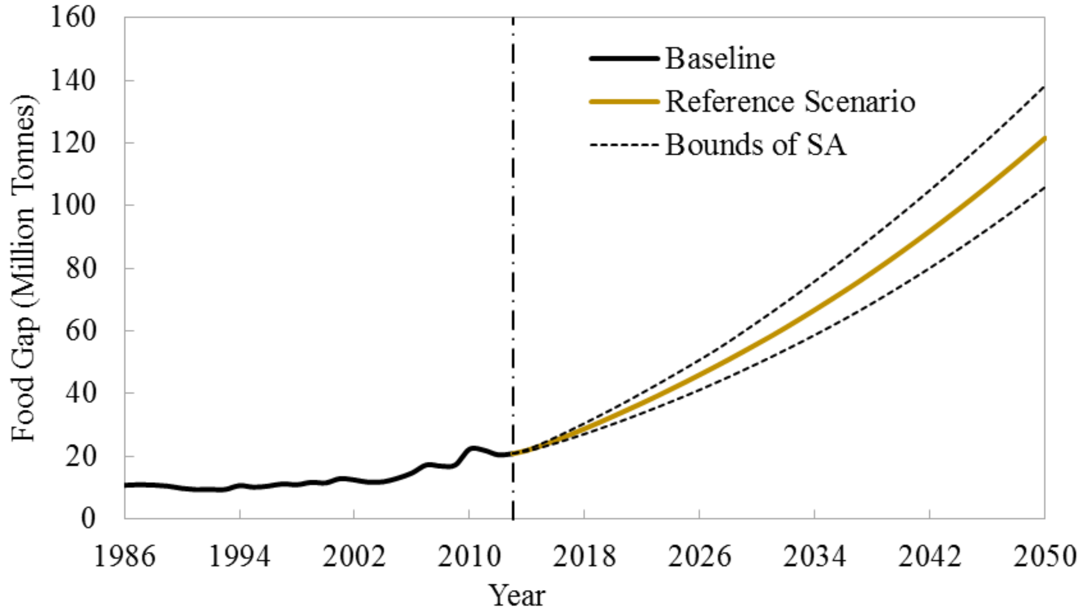

Figure B.29: Sensitivity analysis for the Nile Water, with other factors fixed as in the Reference scenario.

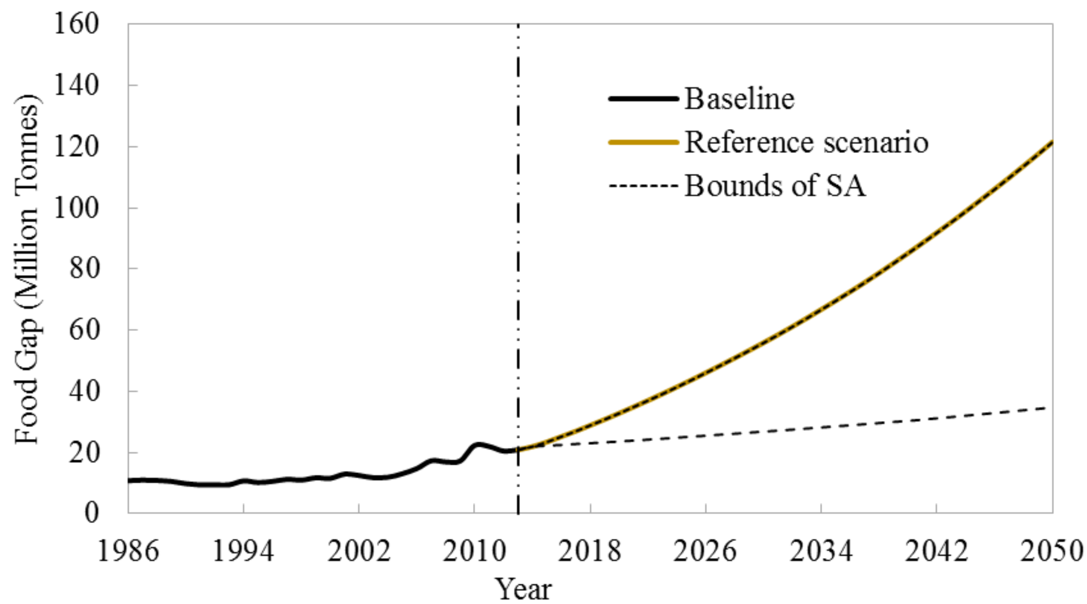

Figure B.30: Sensitivity analysis for population growth, with other factors fixed as in the Reference scenario.

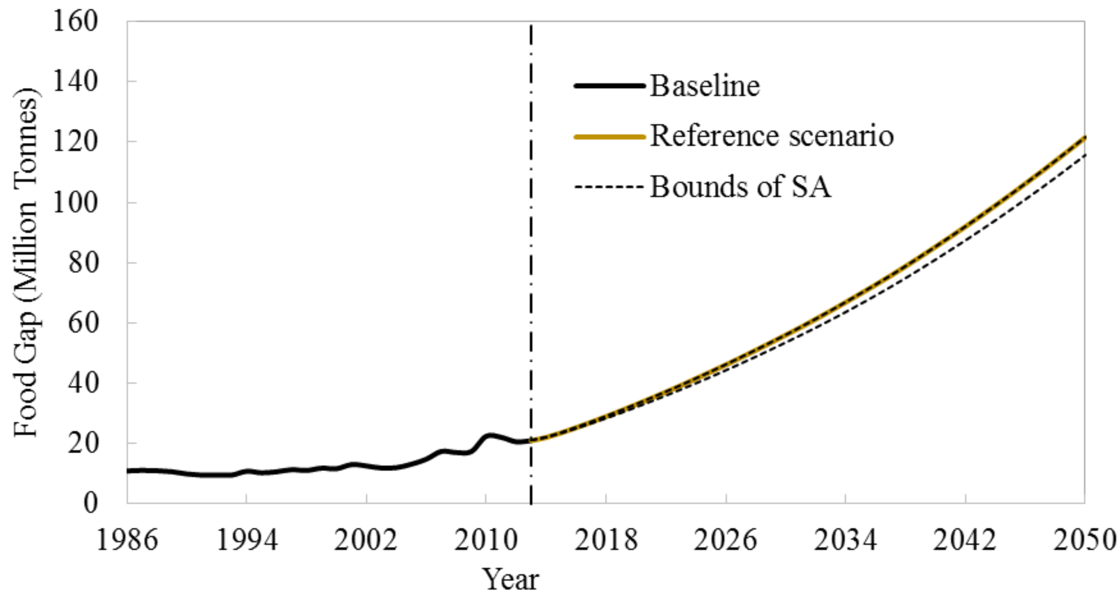

Figure B.31: Sensitivity Analysis for Desalination, with other factors fixed as in the Reference scenario.

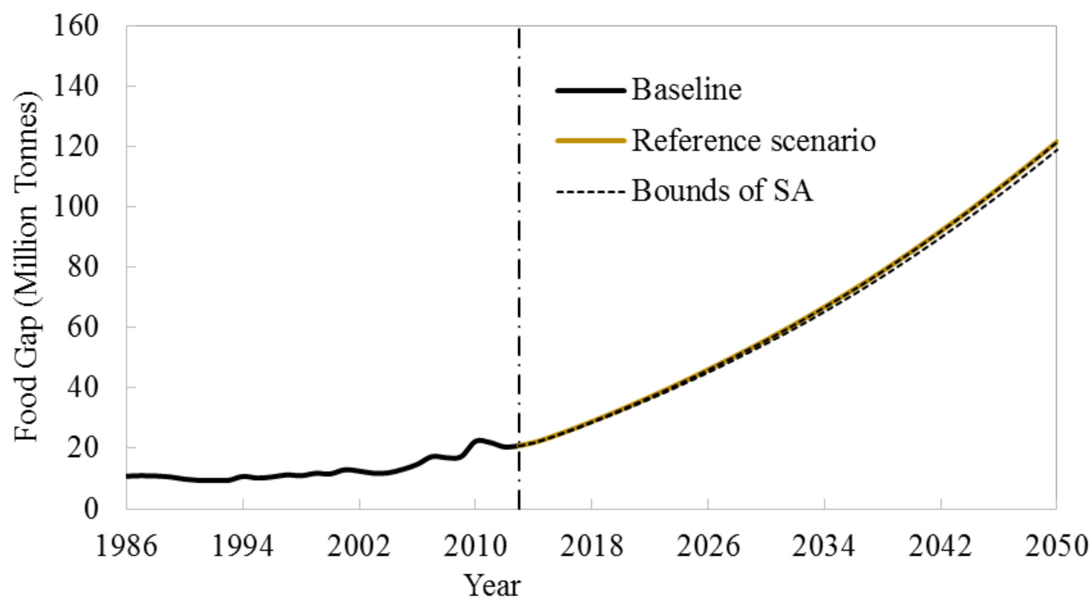

Figure B.32: Sensitivity Analysis for Deep GW, with other factors fixed as in the Reference scenario

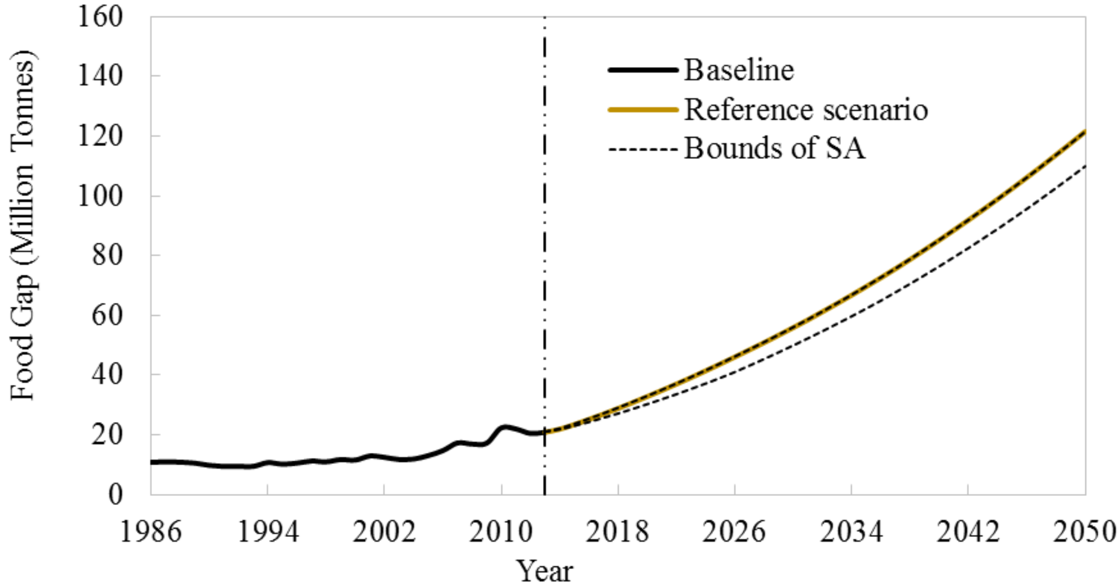

Figure B.33: Sensitivity Analysis for Irrigation Efficiency, with other factors fixed as in the Reference scenario

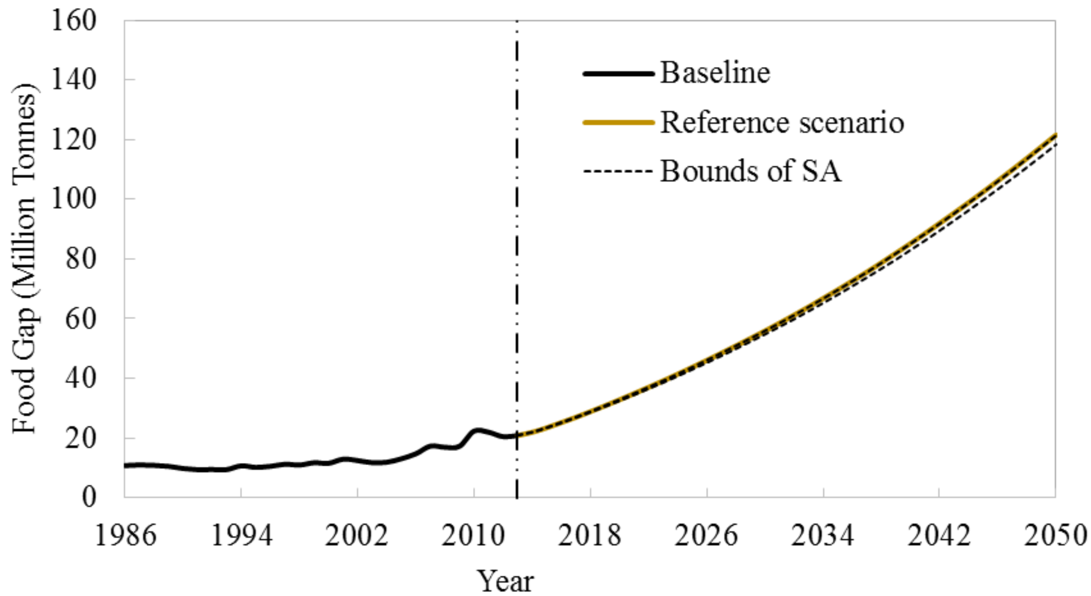

Figure B.34: Sensitivity Analysis for Efficiency of Municipal Network, with other factors fixed as in Reference scenario.

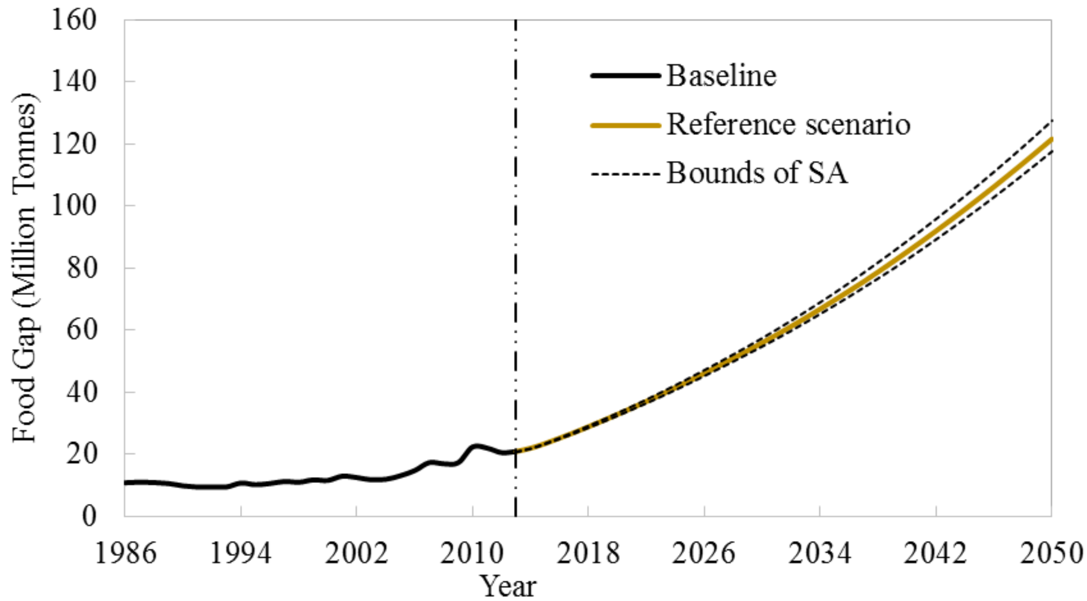

Figure B.35: Sensitivity Analysis for Municipal Demand Reduction Factor, with other factors fixed as in the Reference scenario.

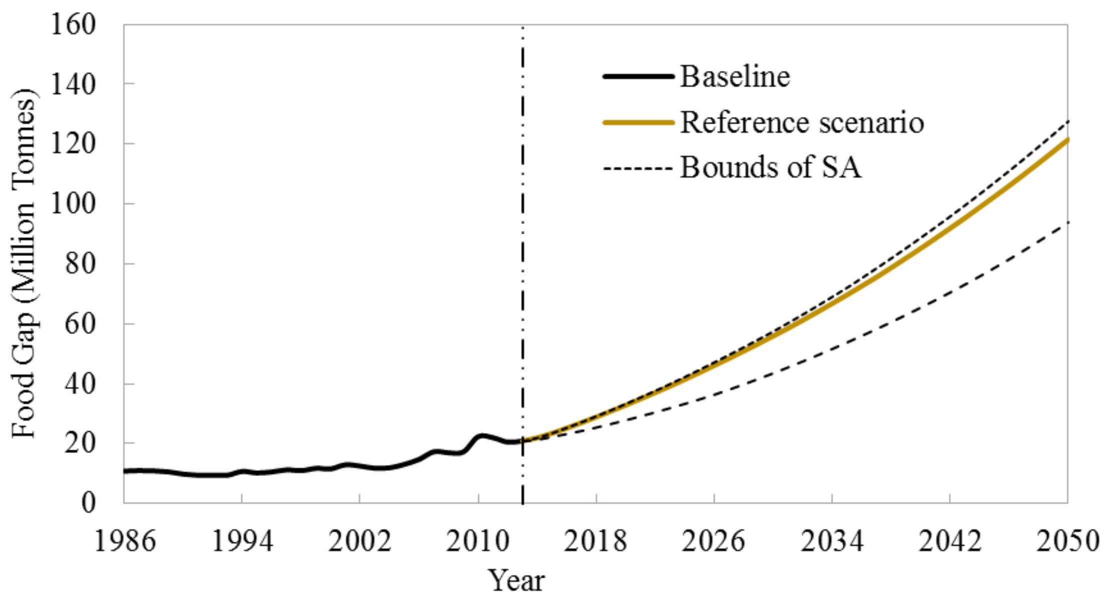

Figure B.36: Sensitivity Analysis for Internal Water Factors (i.e., Desalination, Deep GW, Irrigation Eff., Eff. of Municipal Network, and Municipal Demand Reduction Factor), with other factors fixed as in the Reference scenario.

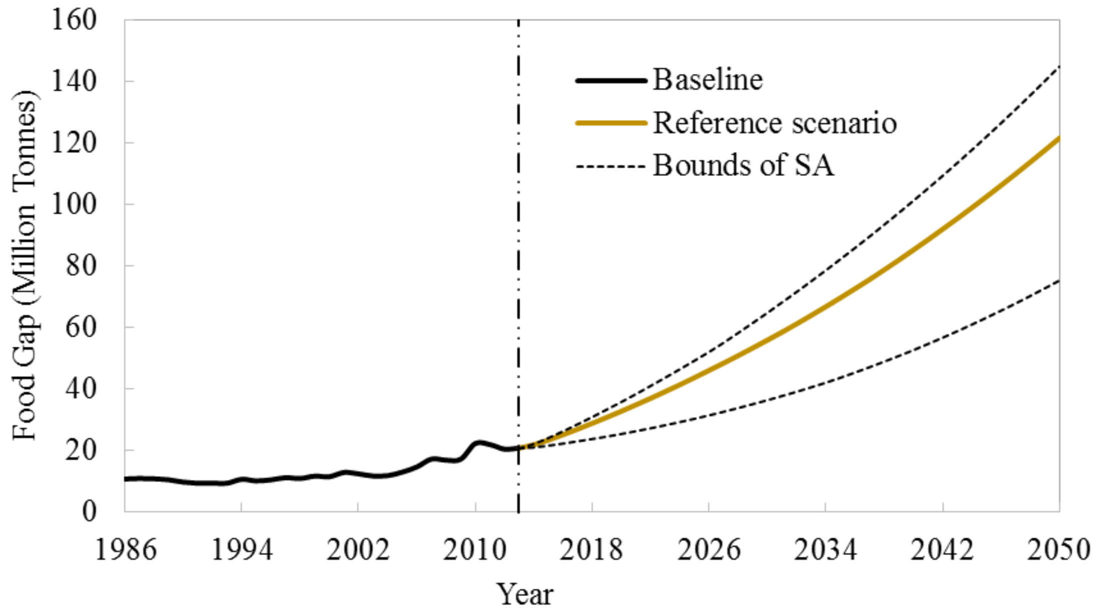

Figure B.37: Sensitivity Analysis for All Water Factors (internal and Nile water), with other factors fixed as in the Reference scenario.

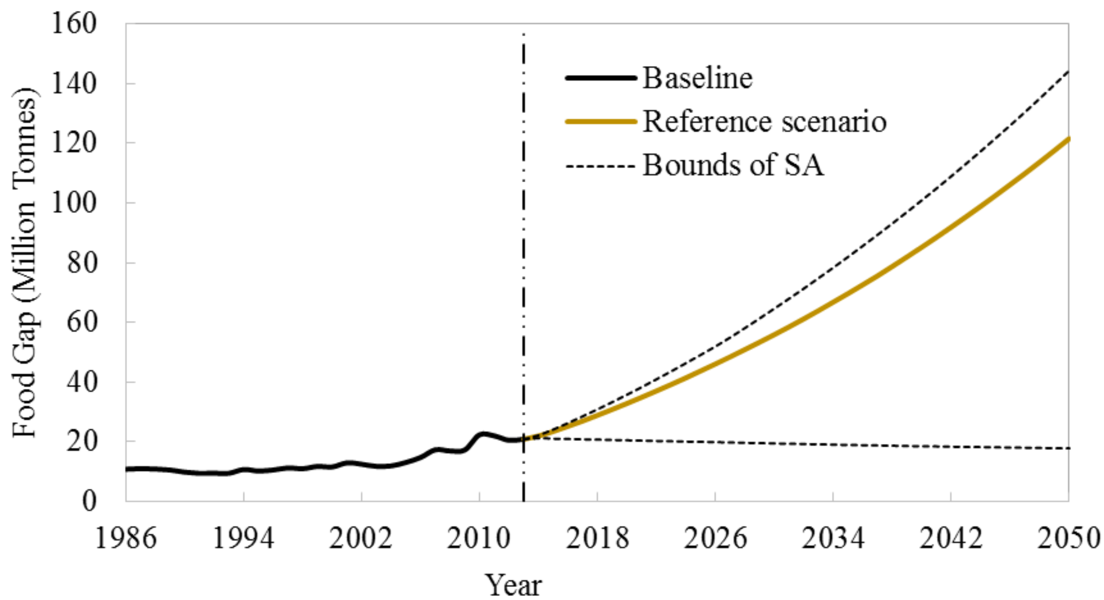

Figure B.38: Sensitivity Analysis for All Water Factors and Population Growth.

B.7 The national Critical scenario of Egypt with IIASA population

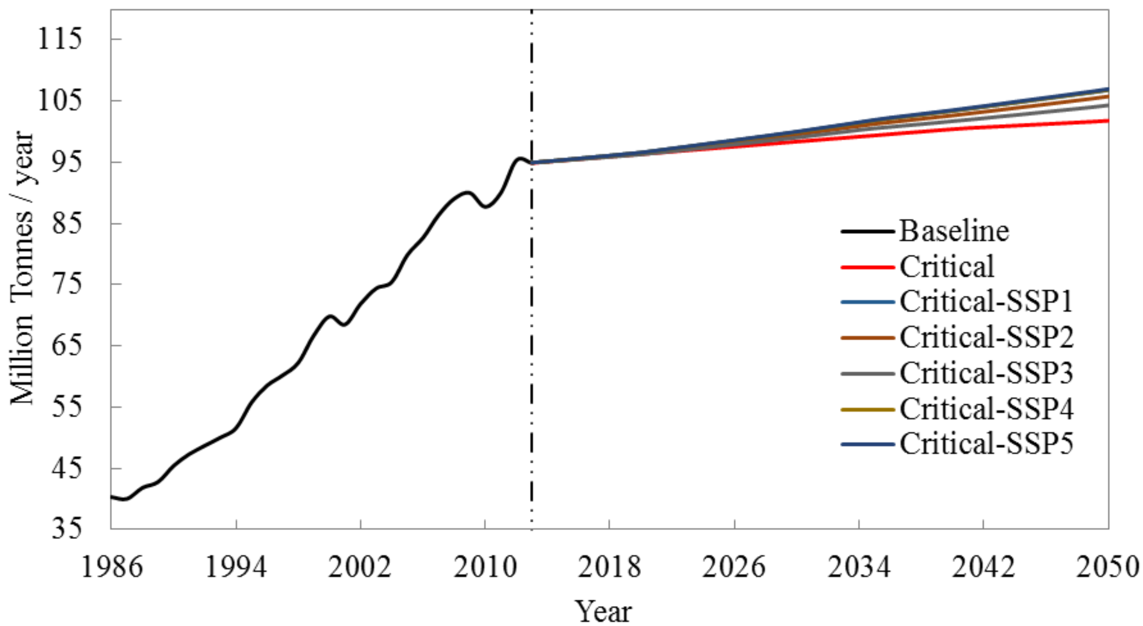

Figure B.39: The food and animal production of Egypt during the baseline period and under the projected *Critical* Scenario, assuming the population projections of the IIASA.

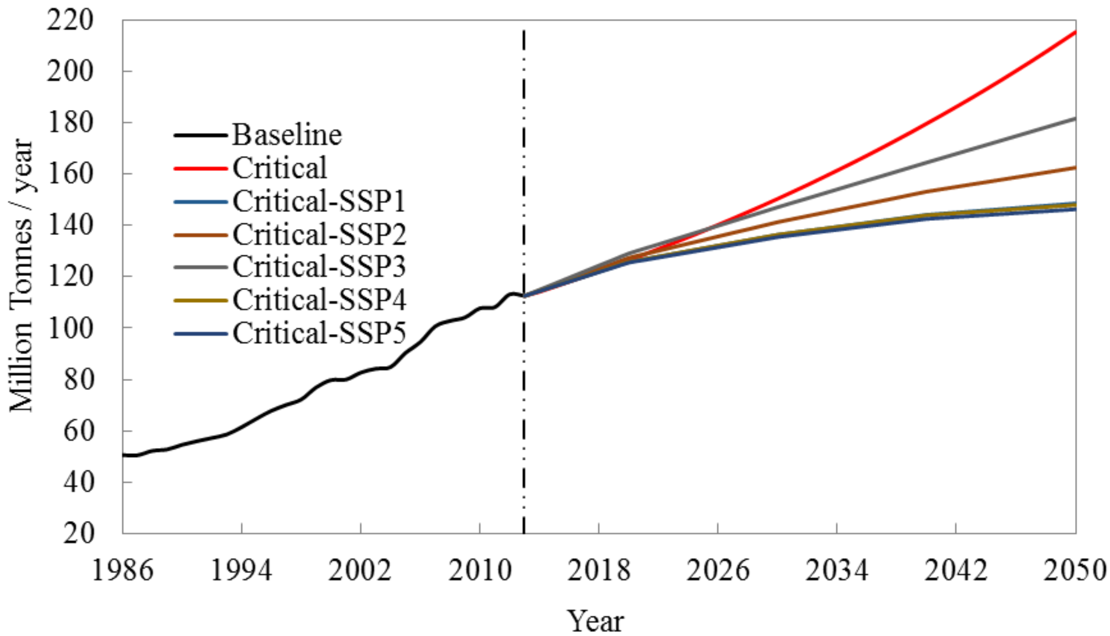

Figure B.40: The domestic supply quantity of Egypt during the baseline period and under the projected *Critical* Scenario, assuming the population projections of the IIASA.

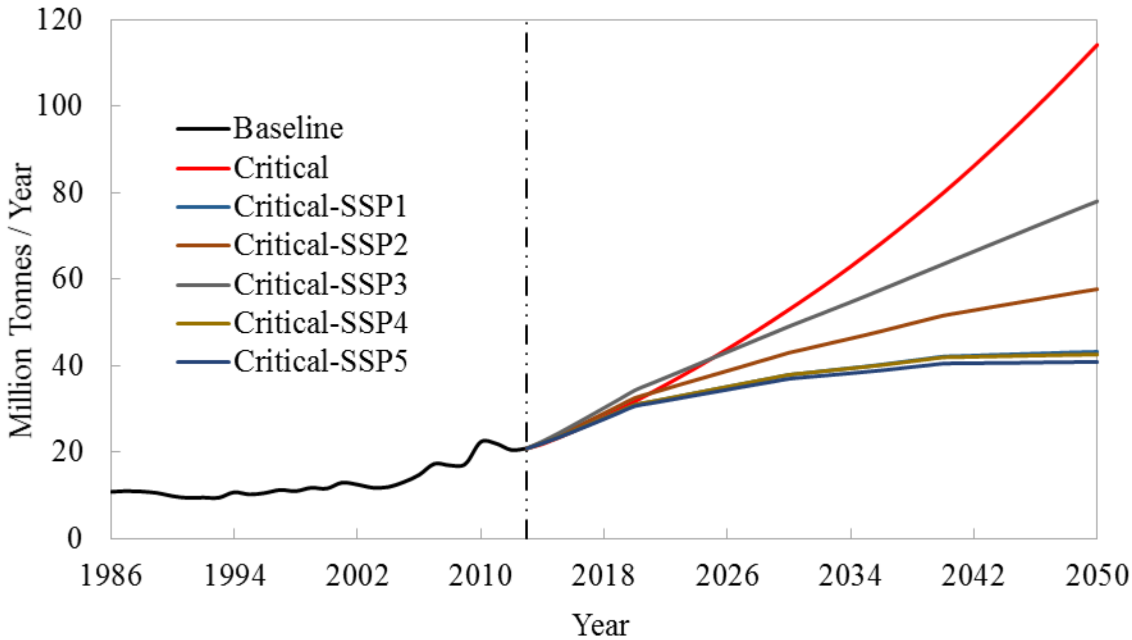

Figure B.41: The food gap (import) of Egypt during the baseline period and under the projected *Critical* Scenario, assuming the population projections of the IIASA.

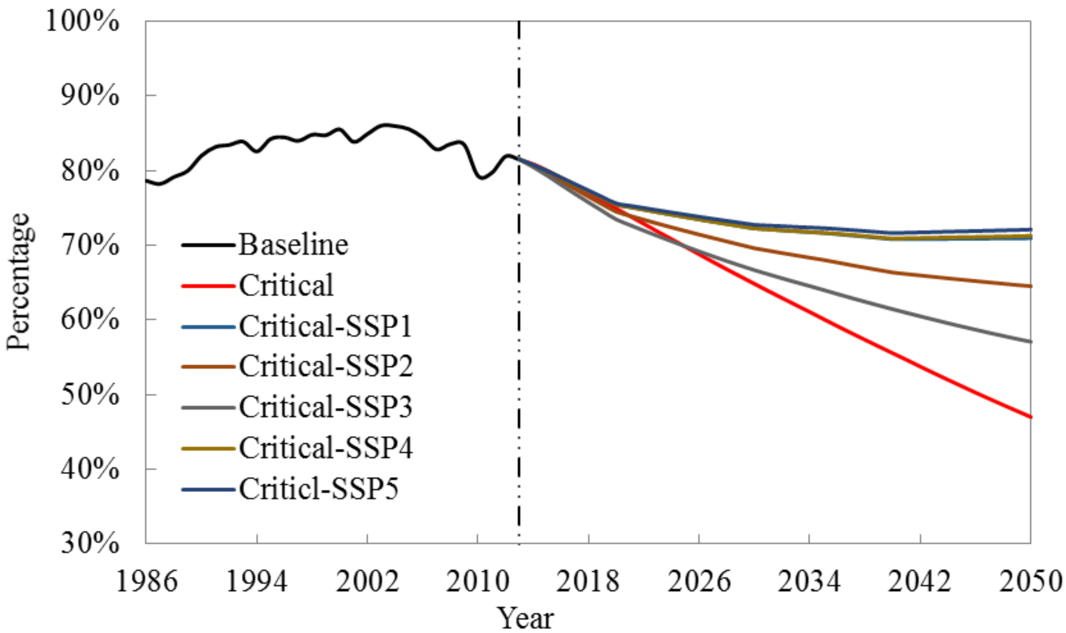

Figure B.42: The food self-sufficiency of Egypt during the baseline period and under the projected *Critical* Scenario, assuming the population projections of the IIASA.

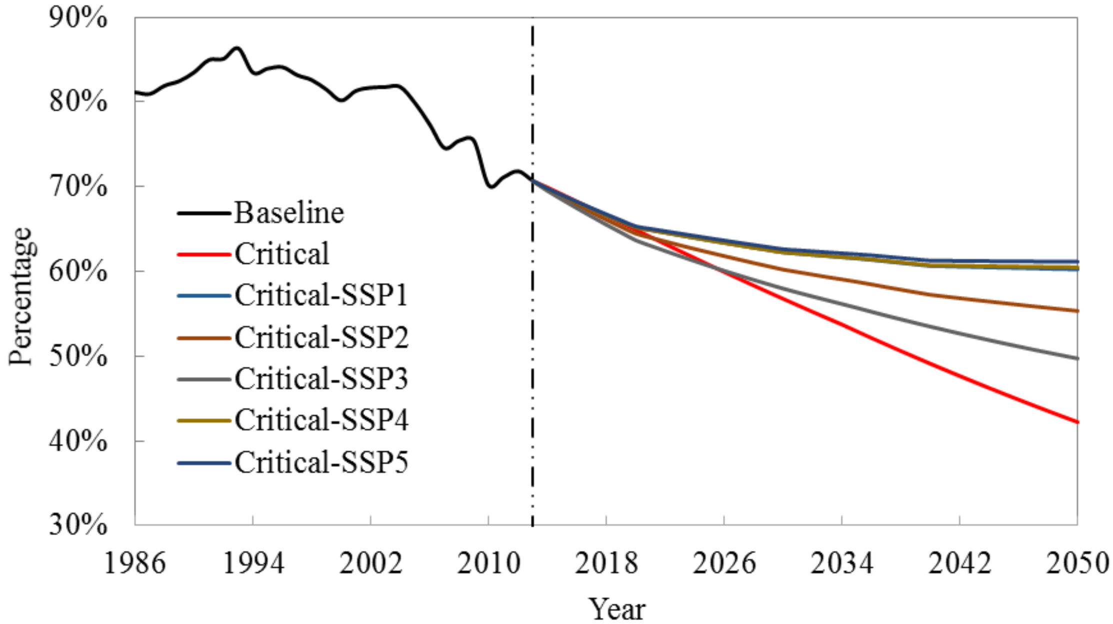

Figure B.43: The water resources self-sufficiency of Egypt during the baseline period and under the projected *Critical* Scenario, assuming the population projections of the IIASA.

B.8 References

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Appendix C: Supplementary materials for Chapter 3

C.1 Development level and aridity by region

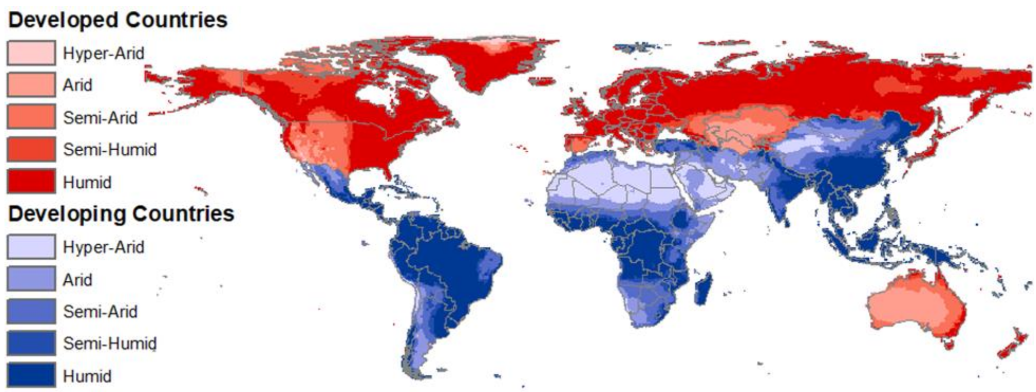


Figure C.1: Climatic areas in developed and developing countries; developed countries include countries in transition. Data for aridity are from FAO (2009), and the country development classification is from the UN (2017).

C.2 National development scenarios and global price scenarios

Table C.1: National and global scenarios included in this study and a short description of each.

National Scenario Name	Narrative
Critical	High population growth and low economic growth, accompanied with a low capacity for developments in the agriculture sector, per capita food consumption pattern is not different from the historical pattern.
Balanced	Moderate population growth and economic growth accompanied with a moderate capacity for developments in the agriculture sector, per capita food consumption pattern shifts toward more affluent animal-based pattern.
Optimistic	Low population growth and high economic growth accompanied by a high capacity for developments in the agriculture sector, per capita food consumption pattern shifts toward more affluent vegetarian-based pattern.
Global Scenario Name	**Narrative***
SSP1	(Green Road) reflects high investment in education and clean technology, low population growth, and rapid development of low-income countries to reduce inequality; observations on effects of climate change are a continuation of historical trends.
SSP2	(Middle of the Road) represents a continuation of current trends, slowly decreasing dependency on fossil fuels, uneven development of low-income countries, global markets are connected but partially functioning, and education investments are not high enough to rapidly slow population growth; observations on effects of climate change are a continuation of historical trends.
SSP3	(Rocky Road) is a scenario of regional rivalry and a fragmented world in which blocks of countries emerge with little coordination, focus on achieving energy and food security internally with barriers to trade, make low investments in education and technology, and achieve insignificant progress to reduce resource use intensity; observations on effects of climate change are a continuation of historical trends.
SSP2-HGEM	Same as SSP2 but considers climate change and its impact on food production; significant challenges to global climate change adaptation and mitigation according to the Representative Concentration Pathway (RCP) 8.5 and using the earth system model HADGEM.

* Narratives are based on Robinson et al. (2015).
This table should be read with Table C.2, Table C.3, and Table C.4 as they are all complementary.

Table C.2: Egypt's national future development scenarios for the period between 2014 and 2050.

Scenario*/ Variable	Critical	Balanced	Optimistic
Population annual growth	2.00%	1.80%	1.65%
Food consumption pattern	Unchanged	Increase in veg. & fruits (20%) and meat (26%), decrease in cereals (4%)	Increase in veg. & fruits (20%) and decrease in cereals (2.6%)
Water resources availability ($\times 10^9$ m^3)	Increase of 6.8	Increase of 4.2	Increase of 4.2
Domestic water demand (m^3/capita/year)	114 decreasing to 79 by 2050	114 decreasing to 82 by 2050	114 decreasing to 82 by 2050
Industrial water demand annual growth	0.65%	1%	1.35%
Agriculture area expansion at 2050 ($\times 10^6$ Feddan)* **	Increase to 10	Increase to 10.8	Increase to 11.8
Irrigation efficiency increase	From 63% to 65%	From 63% to 70%	From 63% to 75%
Crop yields 2050 multipliers**			
Wheat	1.0	1.4	1.7
Fodder	1.0	1.3	1.6
Pulses	0.8	1.3	1.8
Roots	1.0	1.5	1.9
Spices	0.9	1.2	1.5
Nuts	0.9	1.4	1.9
Other cereals	0.9	1.3	1.8
Maize	1.0	1.4	1.9
Rice	0.9	1.5	2.0
Fruits	0.9	1.6	2.1
Vegetables	0.9	1.2	2.3
Non-food	1.0	1.5	1.9
Oil crops	1.0	1.4	1.8
Sugar cane	1.0	1.2	1.4
Crop production losses 2050 multipliers**			
For all crops	1.2	0.7	0.2
Fertilizer Technology 2050 multipliers **			
For all crops	1.0	0.75	0.5

* National development scenarios are based on MWRI [2010]; the scenarios are built and named by MWRI to reflect different levels of population growth and economic growth. Abdelkader et al. [2018] added the per capita food consumption pattern changes for the Balanced and Optimistic, as to reflect the impact of economic growth on the food demand. In this study, we added the changes to the crop yield and crop production losses to match the degrees of economic growth reflected by each scenario and its impact on the food production system. ** 2050 multipliers are factors used to generate the crop yield and crop losses values of year 2050 by multiplying them with the value of 2013, then linearly interpolate the values in the period in between. Crop yield multipliers are from IFPRI [2017] and Jaggard et al. [2010]. ***Feddan = 4200 m^2.

Table C.3: Average annual global market and local market crop prices as in the year 2013 and their global scenarios value reported at the year 2050.

Global Prices	As for year 2013(USD/ tonnes) *	Future: as for the year 2050 (USD/ tonnes)**				
Crop Name		SSP1-Nocc	SSP2-Nocc	SSP3-Nocc	SSP2-HGEM	
Wheat	275	315	316	313	371	
Fodder	450	610	631	654	784	
Pulses	1061	1000	1050	1022	1213	
Roots	592	669	675	686	731	
Spices	5215	2929	2736	2515	3015	
Nuts	2800	3102	3177	3244	4252	
Other cereals	238	267	263	256	278	
Maize	384	437	430	420	534	
Rice	494	554	577	605	715	
Fruits	875	1266	1195	1086	1308	
Vegetables	729	955	928	898	966	
Non-food	1050	1145	1104	1101	1390	
Oil-crops	730	1052	1063	1069	1471	
Sugar cane	131	243	233	219	268	
Local Prices	**As for year 2013(USD/ tonnes) ***	**Future: as for the year 2050 (USD/ tonnes)*****				**Production costs to local price ratio ********
Crop Name		**SSP1-Nocc**	**SSP2-Nocc**	**SSP3-Nocc**	**SSP2-HGEM**	
Wheat	200	439	433	440	569	0.50
Fodder	235	315	330	322	380	0.35
Pulses	664	780	790	785	870	0.70
Roots	307	297	301	298	326	0.60
Spices	2393	3404	2965	3198	3487	0.50
Nuts	3016	3391	3560	3477	5591	0.60
Other cereals	329	378	364	373	395	0.70
Maize	298	377	358	369	502	0.45
Rice	278	379	460	413	693	0.60
Fruits	560	672	606	645	691	0.40
Vegetables	216	286	254	270	293	0.36
Non-food	1028	2605	2185	2446	3545	0.65
Oil-crops	808	909	926	919	1448	0.51
Sugar cane	52	100	135	120	105	0.32

* Average annual global market and local market crop prices as in the year 2013 are from FAO [2018b].

** Future average annual global market prices are produced in a global analysis using IMPACT model [IFPRI, 2017]. The analysis was performed using different scenarios of SSP1, SSP2, SSP3 which stands for the Shared Socioeconomic Pathways scenarios 1, 2 , and 3 [O'Neill, 2017]; Nocc stands for no climate change considered; and HGEM is a climate scenario based on RCP 8.5 using earth system framework HADGEM. The price values are reported just for the year 2050; however, in the NWFT model the annual time series for the period between 2014 and 2050 was used, prices are based on constant 2005 USD.

*** Future average annual local market prices are estimated by using regression models (RM) that link the global prices and local prices in the period between 1986 and 2016, as in Figure C.4, those RM are assumed to be valid in the future.

**** Production costs to local prices ratios are calculated for the year 2013 based on production cost and prices data from MALR [2016], those ratios are assumed valid for the future.

Table C.4: All the possible combinations between the national and the global scenarios of change and their numbers.

Scenario number	Combination
0	Baseline
1	Critical & SSP1-Nocc
2	Critical & SSP2-Nocc
3	Critical & SSP3-Nocc
4	Critical & SSP2-HGEM
5	Balanced & SSP1-Nocc
6	Balanced& SSP2-Nocc
7	Balanced & SSP3-Nocc
8	Balanced & SSP2-HGEM
9	Optimistic & SSP1-Nocc
10	Optimistic & SSP2-Nocc
11	Optimistic & SSP3-Nocc
12	Optimistic & SSP2-HGEM

C.3 Optimization method parameterization

In this study, the ACPAR framework solves the national cropping pattern planning as a multi-objective optimization problem, where four objective functions were determined to reflect the conflicting interests of decision makers. In such problems, the optimization process does not result in a single "optimum" or "best" solution as the case of single-objective optimization, but a set of solutions known as Pareto optimal solutions (PF, Pareto optimal frontier). This set represents the tradeoffs that exist among the conflicted objectives, as it is not possible to improve one objective without degrading one or more other objectives. Determining this PF is the target of a multi-objective optimization process, which can be achieved by finding the group of solutions that have minimum (or maximum) values in all objectives compared to any other possible solution, assuming minimization (or maximization) problem. Although this might seem easy for trivial problems, it is not the case for complex and real-world problems, as it would be computationally intensive and inefficient to find all possible solutions until the true (global) PF is found. Rather, the multi-objective optimization methods seek high quality approximation to the PF that can be found with the least possible computations. In this regard, multi-objective evolutionary optimization algorithms (MOEAs) are found to be of great value and advantage (Goldberg, 1989). Nonetheless, MOEAs require rigorous parameterization procedures to guarantee finding high quality approximation of the PF. In this section, a brief generic description of the optimization method used in ACPAR framework is introduced, followed by an explanation of the parametrization exercise performed to insure its efficiency in finding high quality approximation to the PF.

ACPAR framework incorporates an optimization method named Uniform Spacing Multi-objective Differential Evolution (USMDE; Chichakly and Eppstein, 2013). The method simply depends on sampling and search techniques to explore the space of all possible solutions until it finds the PF. In doing so, the method uses a population of solutions that are simultaneously evaluated at each single run of the search algorithm (Storn & Price, 1997). USMDE is similar to other MOEAs methods, in which they are all inspired by biological evolution processes like reproduction, mutation, recombination, and selection. Those evolution-like processes are performed in USMDE based on four general conceptual steps: (i)

Initialization: using Latin hypercube sampling (LHS) technique to assign initial solutions to the members of the population of size N; (ii) *Mutation*: expanding the search space by creating random changes in one or more members of the current population, yielding new solutions that might be better or worse than existing population members; (iii) *Crossover or Recombination:* inspired by the crossover of DNA strands that occurs in reproduction, the algorithm attempts to find better solutions by combining some of the current solutions; and (iv) *Selection:* inspired by natural evolution, the algorithm performs a selection process in which the 'fit' members of the population survive and contribute to the PF, and the 'least fit' members are partially eliminated, except few that are kept in the PF as they might lead to better solutions in following steps. This selection process is performed such that it keeps the size of the PF less than or equal to the population size N throughout the search procedures. To reach a final PF, the three steps of Mutation, Recombination, and Selection are repeated iteratively to improve the PF quality, until a stopping criterion is met, which is usually maximum number of iterations (i.e., generations).

The USMDE method has five major parameters that govern these four conceptual steps, namely: the seed number (S), which controls the initial values of the population in the initialization step; Population size (N), which determines the size of the PF and the count of search zones to be explored throughout the four steps; Scaling factor (F), which controls how far the search would expand and cover new zones in the mutation process; Recombination Probability (Cr), which controls the diversity of solutions selected for recombination process; and Maximum number of iterations (Gmax), which causes the algorithm to stop. The values of those parameters should be selected carefully, as they influence the search capabilities and deepness of exploration of USMDE of the possible solutions, and thus, eventually affect the overall quality of the reached PF.

In this study, to ensure that USMDE was used efficiently in the ACPAR framework, a diagnostic assessment framework, which is originally used to evaluate and compare different MOEAs, was adopted to find the best parameters set (Reed et al., 2013). In this parameterization exercise, there are six steps that were performed: (a*) Latin hypercube sampling*: to create 1,000 parameters value combinations for the USMDE's parameters of (N, F, Cr, and Gmax) considering their full range indicated in Table C.5; (b) *Running USMDE* for the case study of Egypt under each of those 1000 generated samples and finding the PF for each of them; (c) *Considering the influence of the randomness of initial population on the produced PFs* by generating random 50 seed numbers and rerunning each of the 1000 samples under those 50 seed values to produce their PFs (i.e. 50,000 PFs in total); (d) *Evaluating* each of the produced 50,000 PFs by comparing them with a reference PF (RPF) using three evaluation metrics (explained later); (e) *Summarizing* the evaluation results for the 50,000 PFs and building expressive figures named control maps (explained later); and finally (f) *Selecting* the best parameters set guided by those control maps.

In the parameterization of MOEAs, the identification of a reference PF (RPF) is an essential step, as this RPF acts as a benchmark for the highest possible quality a PF can achieve. Nonetheless, identifying this RPF is a real challenge for a complex problem like the one using the ACPAR framework, as the true (global) PF that acts as a RPF is unknown. Alternatively, the best known PF is usually considered as the RPF (Reed et al., 2013), which is followed in this study, as we considered the best PF of the generated 50,000 PFs to be the RPF(see Figure C.2). This best PF happened to be the one with the highest computational demand. In parameterization exercise, our goal is to select the parameters set that yields a PF of a quality that approaches the RPF's quality with the least computational demand possible. Although many metrics exist to evaluate the PF's quality, they eventually measure one or more of three main characteristics, namely: (a) convergence, which refers to the proximity of the solutions of the PF to those of the RPF; (b) consistency, which refers to the degree of coverage of the PF to all the zones existing in the RPF (i.e. express the existence of any gaps in the PF); and (c) diversity, which refers to the degree of extent of the PF to represent the full range of tradeoffs as represented by the RPF. In this study, we used three different evaluation metrics that are extensively used and recommended in the literature. The generational distance (IG) mainly measures convergence (the lower, the better); it is estimated by averaging the Euclidian distance between each PF solution and its nearest neighbor RPF solution over all the solutions of a PF (Van Veldhuizen and Lamont, 1998). The additive ε-indicator ($I\varepsilon$) is a good measure for the consistency (the lower, the better), it expresses the existence of gaps by estimating the largest distance required by any PF solution to dominate (i.e., be better than) its nearest neighbor in the RPF solution (Zitzler et al., 2002). The last metric is the hypervolume (Hv), which is an overall measure of convergence and diversity but less sensitive to consistency changes (the higher, the better). Hv is estimated as the volume of the objective space dominated by a PF relative to that dominated by RPF; the more dominance reflects more convergence and diversity (Zitzler et al., 2002). The

Hv is the most challenging metric to estimate, especially for multi-objective problems, as in our case study. However, there are some methods that approximate the Hv calculations and evaluate it with good accuracy for such high dimensional cases; the HypE is one of those methods that was used in this exercise for this purpose (Bader and Zitzler, 2011).

In the parametrization exercise performed in this study, each of the 1000 parameter set samples was evaluated using the three evaluation metrics mentioned above, and repeated for 50 random seeding for each sample. To summarize the huge results of this evaluation, there are figures known as control maps that are typically used (see Figure C.3; Reed et al., 2013). A control map provides information about the 1000 parameter sample values, their evaluation metric values averaged over the 50 random seeds. It also indicates the number of function evaluations (NFE), which reflects the computational demand corresponding to each parameter set, and estimated by the multiplication of the population size (N) by the maximum number of iterations (Gmax), it acts as an effectiveness measure because it implicitly reflects the time required to perform the optimization procedure. In those maps, the population size (N) is used as a proxy for the parameter set samples, as this is more convenient and consistent with the literature (Salazar et al., 2016), where generally, the quality of a PF is mainly driven by the population size (N). The purpose of a control map is to illustrate the "sweet spots" in the parameter space that yield PF of high quality (Goldberg, 2002).

Figure C.3 shows that this "sweet spot" for the three evaluation metrics exists for a wide range of parameter sets. Figure C.3a reflects the ability of a PF to converge, and generally, it can be noticed that the majority of parameter sets of $N > 100$ tend to converge with the RPF. The consistency in USMDE application for ACPAR seems to be a function of both N and NFE, as indicated in figure C.3b. Generally, with very few exceptions, NFE between 20,000 and 40,000 and N between 50 and 150 would give consistent PF. The hypervolume is the most expressive evaluation metric and most commonly used for PF evaluation, thus it would be decisive in selecting parameter sets, as figure C.3c shows the majority of parameter sets of $N > 200$ tend to have Hv value > 0.8, which reflects a high degree of convergence and diversity compared to the RPF. In conclusion, the best parameter set that fulfills the three evaluation metrics and produces high quality PF should have $N \geq 200$ and $20{,}000 \leq NFE \leq 40{,}000$, which was followed in this study. The N was taken as 200 and the Gmax was taken as 150 (i.e. NFE = 200*150 = 30,000). For the Cr and F parameters, it was found that their sweet spot range is (0.05, 0.2) and (0.3, 0.65), respectively. Thus, Cr was assigned a value of 0.2 and F a value of 0.6.

Table C.5. USMDE parameters' range used in the Latin Hypercube sampling.

Parameter	minimum	maximum	Sample Size
S*	0	100	50
N	10	1000	1000
F	0	1	
Cr	0	1	
Gmax	10	1000	

* Seed number (S) changed 50 times then combined with each of the 1000 samples generated for (N, F, Cr, and Gmax).

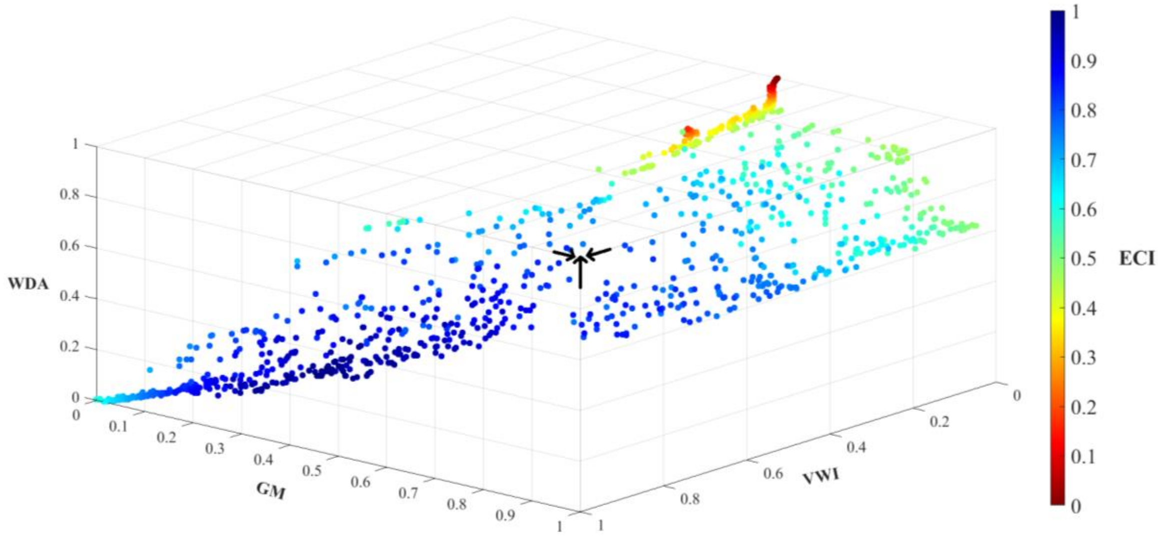
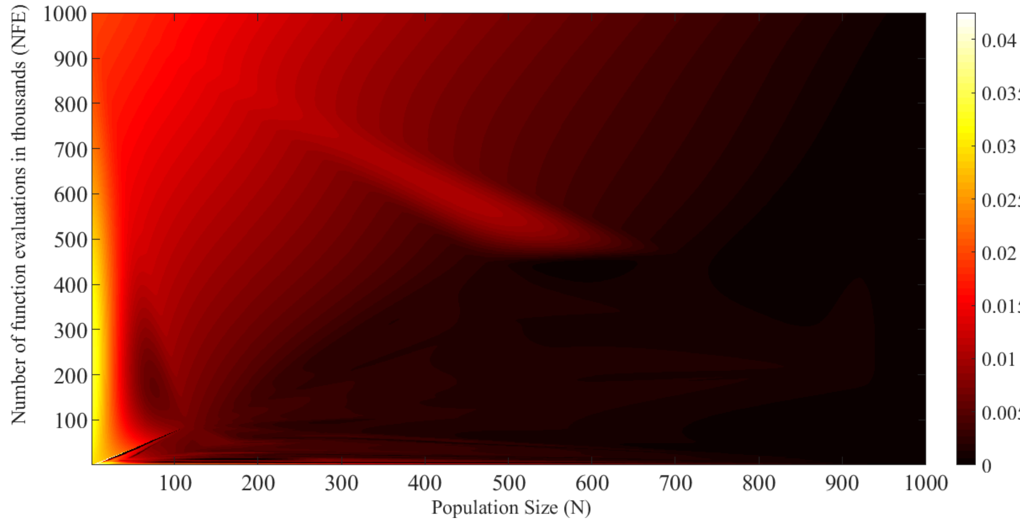
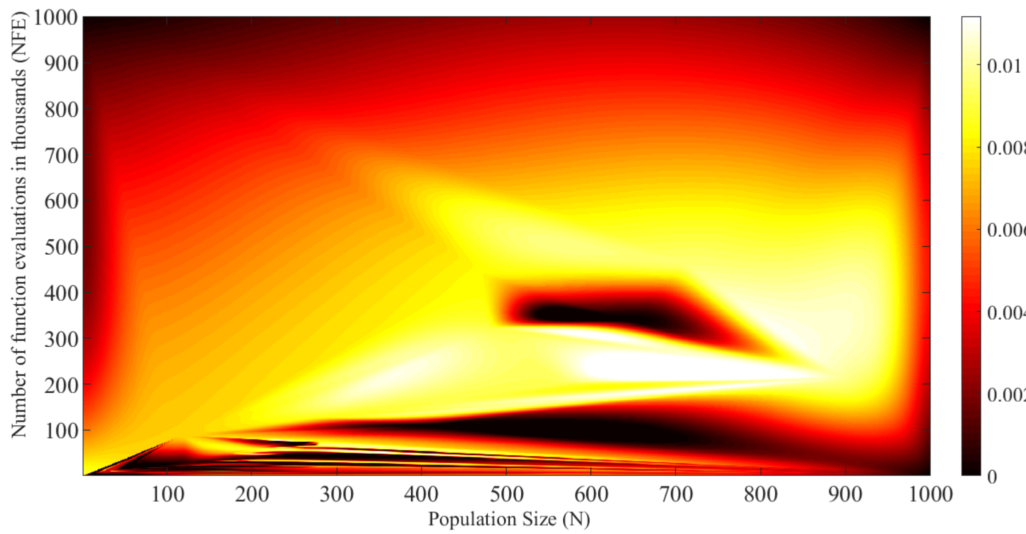


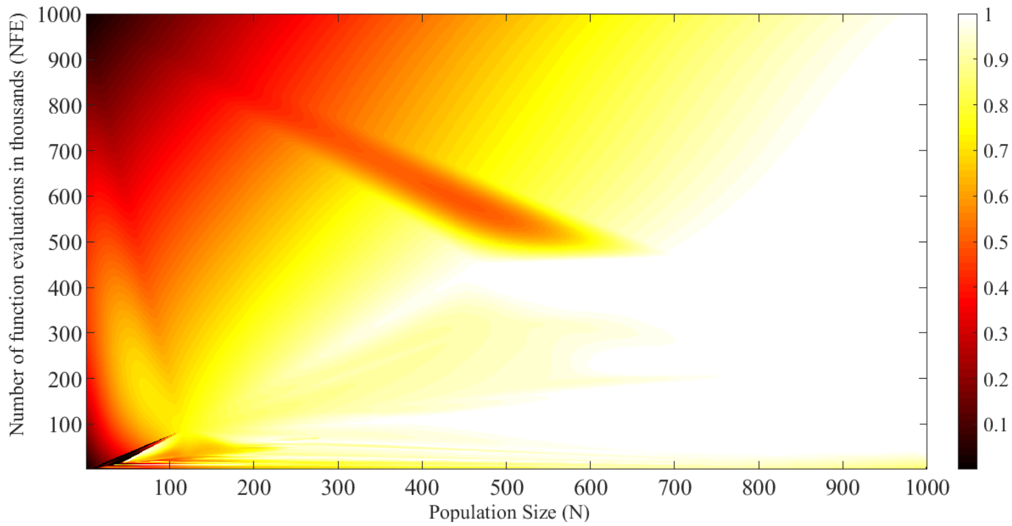
Figure C.2: A 3D scatter plot for the best known approximate Pareto optimal frontier produced by ACPAR, which is considered as the reference Pareto optimal frontier. Each of the plotted points represents a normalized Pareto optimal solution that is described by four values ranges between 0 and 1. The four objective functions are Agriculture gross margin (GM), Virtual water imports (VWI), Water demand for agriculture (WDA), and Economic costs of import (ECI), respectively.



(a) Generational Distance (IG)



(b) Additive ε-indicator ($I\varepsilon$)



(c) Hypervolume (Hv)

Figure C.3: Control maps showing the average evaluation metrics of: (a) Generational distance, (b) Additive ε-indicator, and (c) Hypervolume, averaged over 50 seeding for 1000 parameter samples. The horizontal axis represents the population size (N) as an indicator of the parameter sets and the vertical axis represents the number of function evaluations (NFE) to reflect the computational demand, and the colors reflect the corresponding averaged evaluation metric value. The hypervolume is calculated relative to the maximum value that belongs to the reference Pareto frontier (RPF) (i.e., hypervolume of RPF = 1).

C.4 NWFT model variables and constrains

Table C.6: Key variables in NWFT model and their sources (Abdelkader et al., 2018).

NWFT model sector/ module	Variable Name	Symbol	Units	Notes	Source
Agriculture Production system	Nominal crop yield	$Yn_i(t)$	tonnes/ha/yr	Maximum crop yield under ideal conditions	FAO (2018b)
	Crop yield	$Y_i(t)$	tonnes/ha/yr	crop yield under water deficit (Doorenbos and Kassam, 1979)	Calculated
	Land area/ crop	$A_{ij}(t)$	feddan/yr	feddan = 4200 m^2	
	National land area	A(t)	feddan/yr	Maximum annual national area available for agriculture	FAO (2018b)
	Cropping Pattern	Xi	-	Ratio of annual land area per crop	Decision variable
	Crop water requirements	CWR_{ij}	m^3/season		
	Water demand for agriculture	WDA (t)	m^3/yr		Calculated
	Irrigation Efficiency	Ieff (t)	Percentage	Annual averaged national irrigated agriculture efficiency	MWRI (2010)
	National food production	PROD i (t)	tonnes/yr		Calculated
	National crop production losses	LOSS i (t)	Percentage	Annual percentage of food production (PRODi (t))	FAO (2018b)
	National crop stock change	ΔS i (t)	Percentage		FAO (2018b)
Demographic system	Population growth rate	p (t)	-		FAO (2018b)
	Per capita food consumption pattern	Ci (t)	kg/cap/yr		FAO (2018b)
	National food consumption (demand)	CONS i (t)	tonnes/yr		Calculated
	Per capita municipal water demand	MD (t)	m^3/cap/yr		MWRI (2010)
	National municipal water demand	WDM (t)	m^3/yr		Calculated
Water resources system	Water resources available from desalination	WRA_d (t)	m^3/yr	Time series data collected from MWRI (2010), Abu Zeid (2007), and Allam and Allam (2007)	
	Water resources available from Nile river	WRAn (t)			
	Water resources available from deep ground water	WRA_{dg} (t)			
	Water resources available from shallow ground water	WRA_s (t)			
	Water resources available from rainfall harvesting	WRA_{rh} (t)			
	Rainfall	Rr(t)	mm /yr		FAO (2018a)
	Water supply for municipal	WSM(t)	m^3/yr		Calculated
	Water supply for industry	WSI(t)			
	Water supply for agriculture	WSA(t)			

NWFT model sector/ module	Variable Name	Symbol	Units	Notes	Source
Food trade system	National imported crop quantity	$IMP_i(t)$	tonnes/yr		Calculated
	National exported crop quantity	$EXP_i(t)$	tonnes/yr		
	Crop blue water footprint	WFPbi	m^3/tonnes	Volume of blue water consumed to produce unit weight of crop (i)	Mekonnen and Hoekstra (2011)
	Crop green water footprint	WFPgi	m^3/tonnes	Volume of green water consumed to produce unit weight of crop (i)	
	National crop virtual water import	$VWI_i(t)$	m^3/yr	Calculated for each crop	Calculated
	National crop virtual water export	$VWE_i(t)$	m^3/yr		
	Virtual water import	VWI(t)	m^3/yr	Water consumed to produce the imported food (summed over all food products)	
Economy	Local market crop price	$PL_i(t)$	USD/tonnes		FAO (2018b)
	Variable crop production costs	$VC_i(t)$	USD/tonnes		MALR (2016)
	Average global market crop price	$PG_i(t)$	USD/tonnes	Historical time series retrieved from FAO (2018b), and future scenarios from IMPACT model (IFPRI, 2017).	
	Agriculture Goss Margin	GM (t)	USD/yr		Calculated
	Economic costs of food Import	ECI (t)	USD/yr		
Industry	Industrial water demand growth rate	g	Percentage		MWRI (2010)
	Water demand for industry	WDI(t)	m^3/yr		Calculated
Environment	Crop fertilizer application rate	FAR_{ijk}	tonnes/ha		FAO (2005)
	National fertilizer application rate	NFAR	kg/ha		Calculated

Land, water, trade, and cropping pattern are variables that are constrained in the NWFT model. For every year of simulation, the total area of the cropping pattern is not allowed to exceed the land available for agriculture. The water allocated for all uses in a given year (t) (i.e. industrial, municipal, and agriculture) should not exceed the national water resources available from all sources in the same year. For municipal and industrial sectors, water supply should equal exactly the demand. Agriculture water supply cannot exceed the agriculture water demand but can be less. The trade constraints guarantee that the import and export of food are according to food shortages and surpluses, so national food balance remains valid for every year for each crop. The cropping pattern non-negativity constraint assures that none of the decision variables has negative value. The equations of these constraints are stated below:

Land: $\sum_{i=1}^{n} \text{xi} * A(t) = A(t)$ $\forall$ t (C.1)

Water: WSA(t)+WSM(t)+WSI(t) = WDA(t)+WDM(t)+WDI(t) $\forall$ t (C.2a)

WSA(t) ≤ WDA(t), WSM(t) = WDM(t), WSI(t) =WDI(t) $\forall$ t (C.2b,c,d)

Trade: PROD i (t) + IMP i(t) = EXP i(t)+ CONS i(t)+ LOSS i(t)+ ΔS i(t) $\forall$ t, i (C.3)

Non-Negativity: xi ≥ 0 $\forall$ i (C.4)

Where,

A(t): the national land available for agriculture in a given year t

WSA(t), WDA(t): national water supply, and demand for agriculture in a given year t

WSM(t), WDM (t): national water supply, and demand form municipal in a given year t

WSI(t), WDI (t): national water supply, and demand for industry in a given year t

PROD i (t): national food production for crop i in a given year t

CONS i (t): national food consumption for crop i in a given year t

LOSS i (t): national food losses for crop i in a given year t

$IMP_i(t)$: is the national imported quantity of crop *i* in year *t* (tonnes)

$EXP_i(t)$ is the national exported quantity of crop i in year t (tonnes)

ΔS i (t): national food stock variations for crop i in a given year t xi: Decision variables (i.e. each crop ratio of the national land available for agriculture

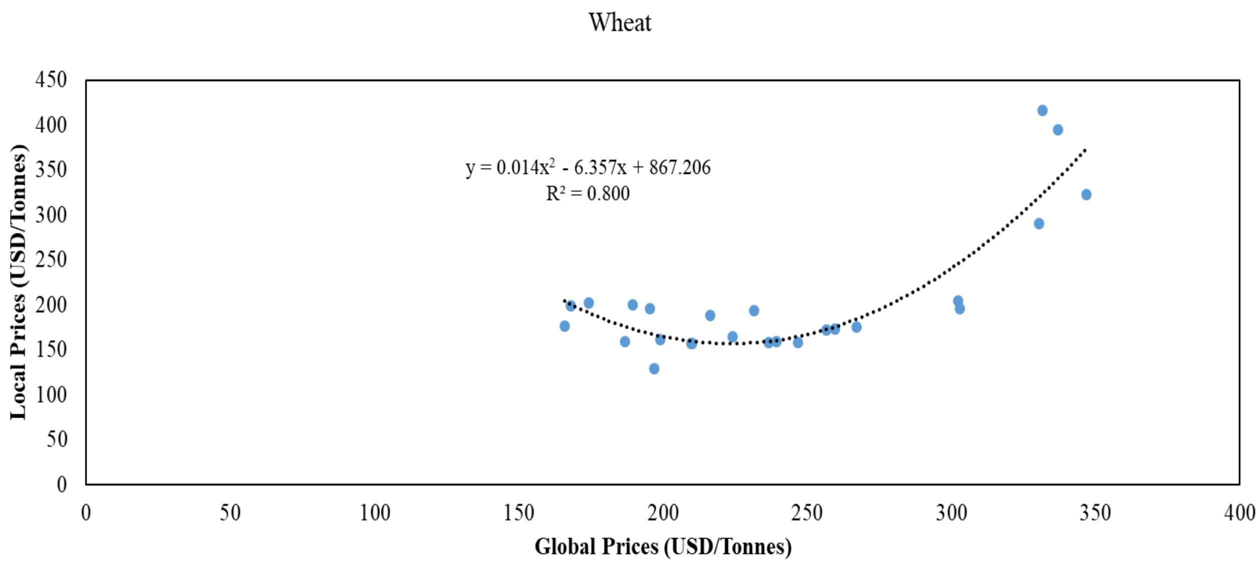
C.5 Egypt's historical cropping pattern

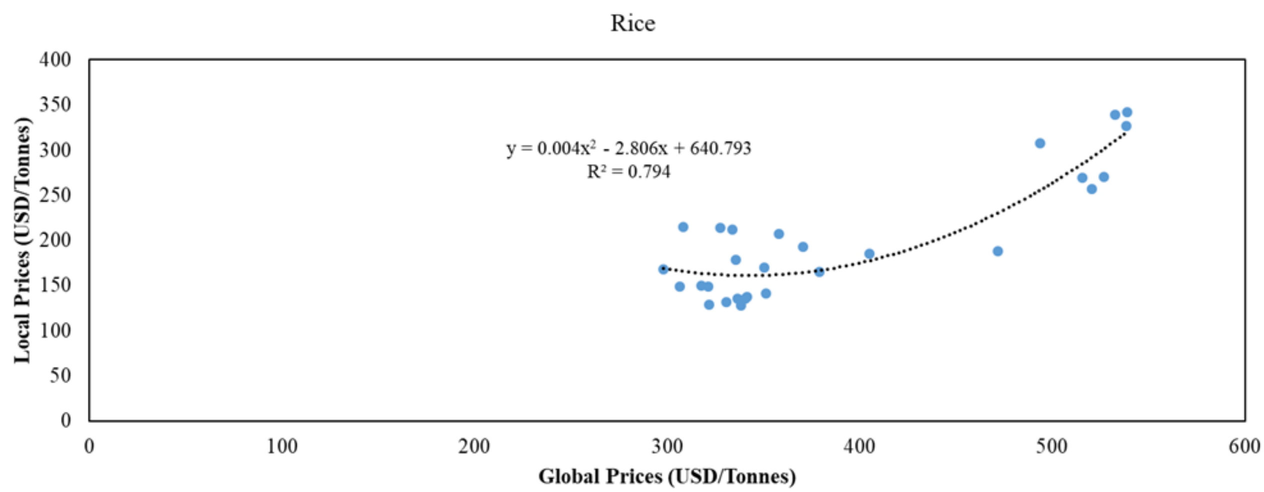
Table C.7: Major crops cultivated in Egypt and the decadal average cropping pattern and average cropping pattern during the period between 1986 and 2013.

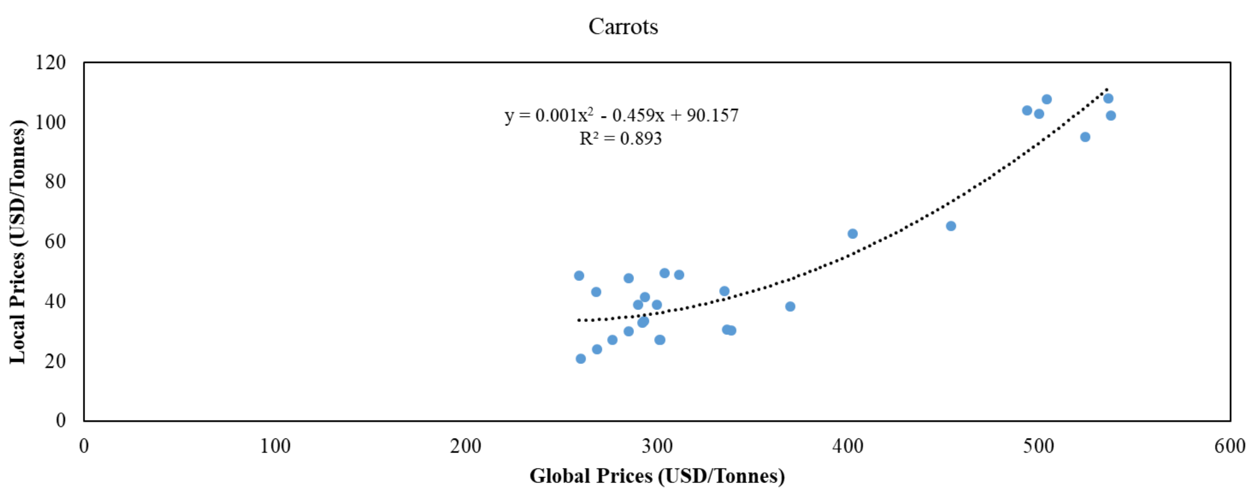
Crop Name	1986-1996	1996-2006	2006-2013	**1986-2013**	Notes
Wheat	17%	20%	20%	19%	
Fodder	15%	14%	17%	15%	Mainly Egyptian clover (i.e. Berseem)
Pulses	4%	4%	2%	4%	Mainly Beans
Roots	2%	3%	5%	3%	Mainly potatoes and sugar beets
Spices	1%	1%	1%	1%	
Nuts	1%	1%	1%	1%	
Other cereals	5%	4%	4%	4%	Sorghum, Barley, and Rye
Maize	17%	15%	14%	16%	
Rice	10%	11%	10%	10%	
Fruits	8%	9%	9%	9%	22 crops but mainly oranges, grapes, and watermelons
Vegetables	7%	8%	9%	8%	16 crops but mainly tomatoes
Non-food	9%	6%	3%	6%	Cotton, Flax fiber, and Jute
Oil-crops	1%	2%	2%	2%	Soybeans, Linseed, groundnuts, sunflower seed, sesame seed, and olives
Sugar cane	2%	2%	2%	2%	
Total Area* ($\times 10^6$ ha)	4.71	5.47	6.35		

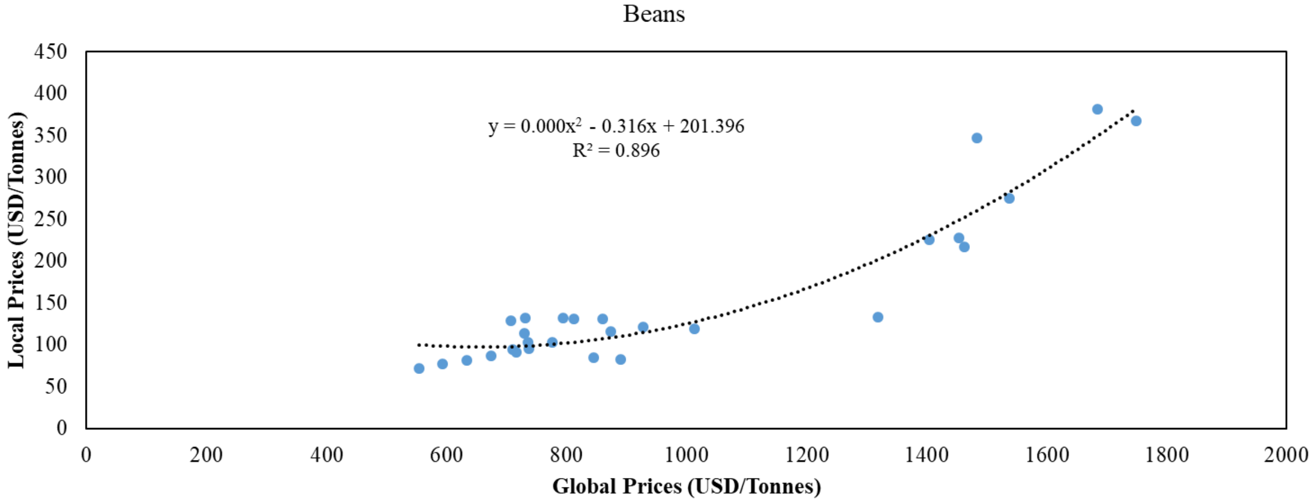
* Total agricultural area is larger than the physical land area, as the same land is cultivated more than one time each year.

C.6 Regression models linking global and local prices for selected crops









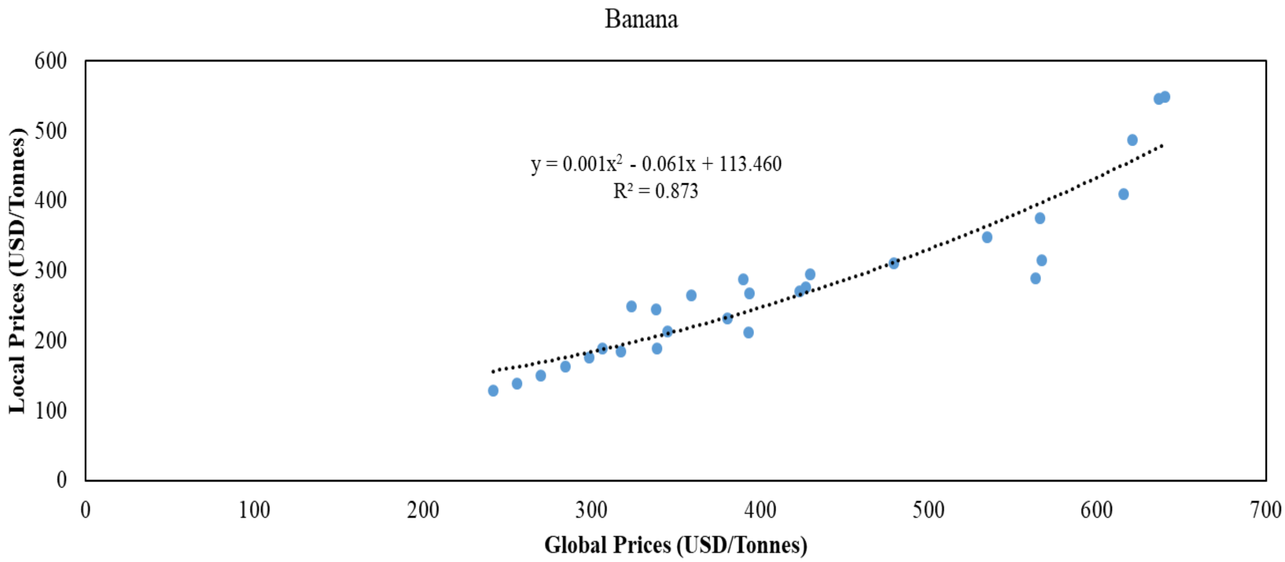


Figure C.4: Regression models linking global and local crop prices for selected crops, during the baseline period (1986-2013).

C.7 Filtered ACPs under the baseline conditions

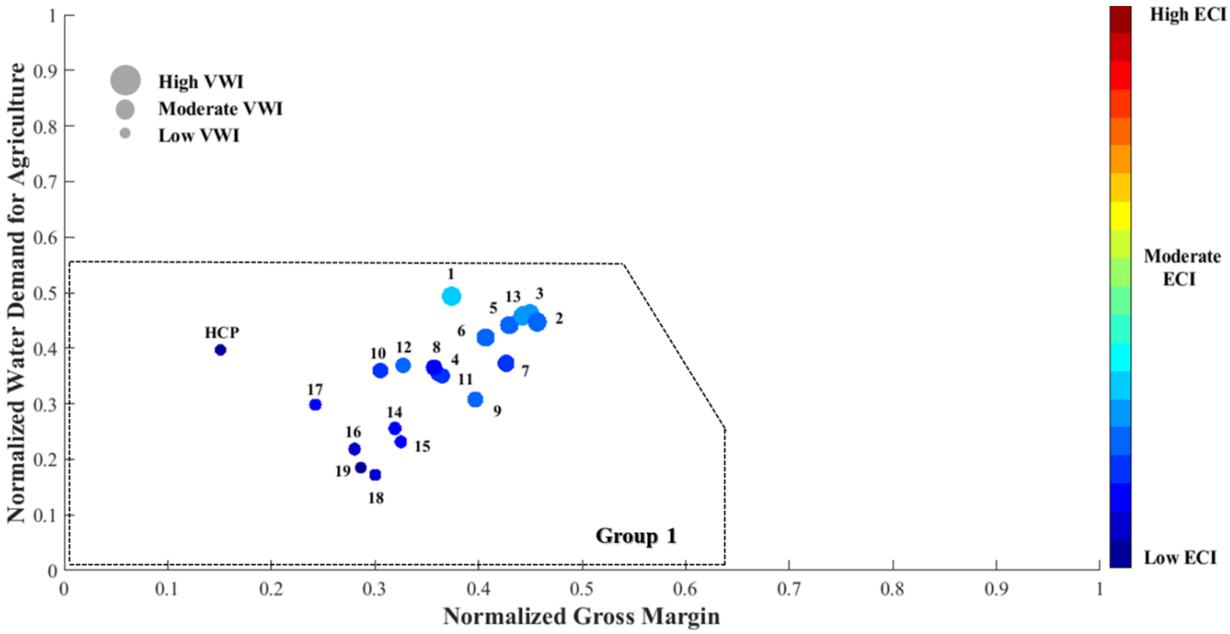


Figure C.5: Filtered 19 alternative cropping patterns (ACPs) under the baseline conditions and the historical cropping pattern (HCP), all of which are part of group1.

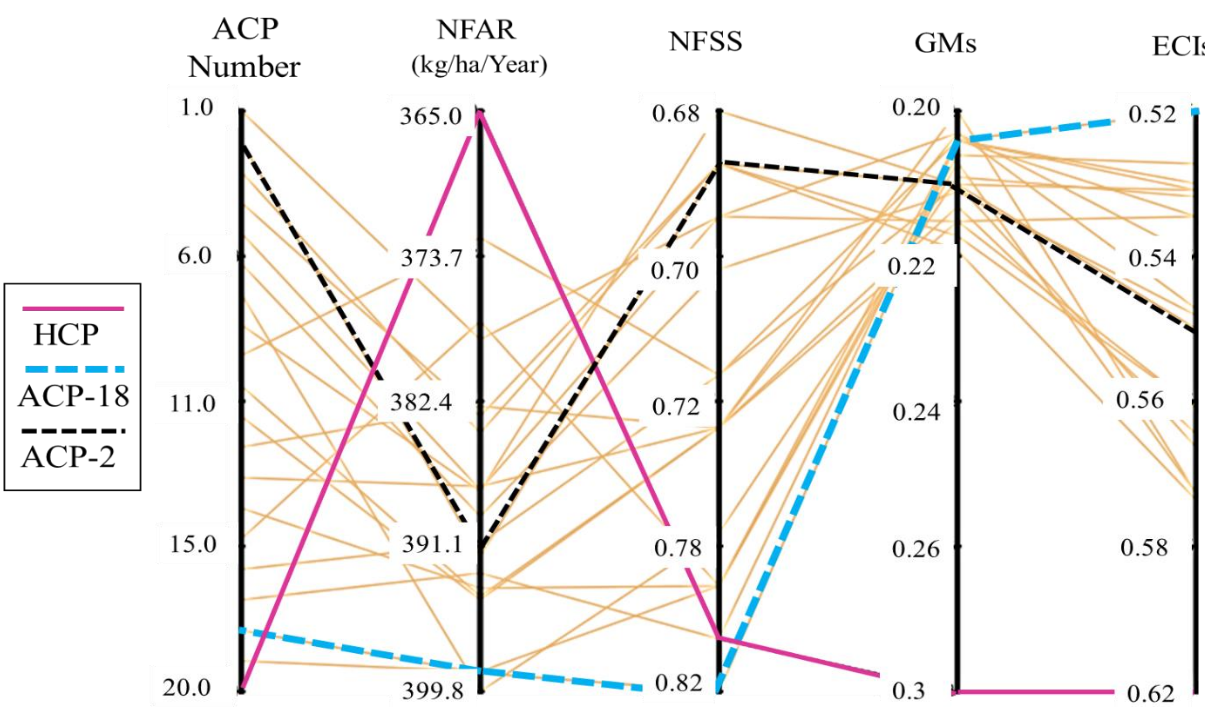


Figure C.6: Parallel coordinate plot shows the filtering criteria for the 19 filtered ACPs found in the baseline period (1986-2013), and the historical cropping pattern (HCP). All axes values increase from top to bottom.

Table C.8: The cropping patterns of the 19 alternative cropping patterns (ACPs) filtered in the baseline (1986-2013), along with the historical cropping pattern (HCP); expressed as a ratio of each crop area to the total cultivatable land available.

CP Name	Wheat	Fodder	Pulses	Roots	Spices	Nuts	Rice	Maize	Other Cereals	Fruits	Vegetables	Non-food	Oil crops	Sugar cane
HCP	0.19	0.15	0.04	0.03	0.01	0.01	0.10	0.16	0.04	0.09	0.08	0.06	0.02	0.02
ACP-1	0.19	0.28	0.00	0.02	0.00	0.00	0.07	0.11	0.17	0.02	0.06	0.03	0.03	0.02
ACP-2	0.18	0.30	0.00	0.02	0.01	0.00	0.07	0.13	0.13	0.02	0.10	0.00	0.02	0.02
ACP-3	0.19	0.31	0.00	0.00	0.00	0.00	0.08	0.13	0.14	0.02	0.09	0.00	0.02	0.02
ACP-4	0.19	0.31	0.00	0.00	0.01	0.00	0.08	0.13	0.14	0.02	0.08	0.00	0.02	0.02
ACP-5	0.18	0.30	0.00	0.02	0.00	0.00	0.08	0.13	0.14	0.02	0.09	0.00	0.02	0.02
ACP-6	0.21	0.28	0.01	0.00	0.00	0.01	0.06	0.14	0.15	0.02	0.09	0.00	0.02	0.02
ACP-7	0.26	0.22	0.00	0.01	0.01	0.01	0.07	0.13	0.07	0.07	0.08	0.02	0.03	0.02
ACP-8	0.26	0.24	0.00	0.01	0.00	0.00	0.06	0.07	0.12	0.07	0.09	0.00	0.06	0.02
ACP-9	0.18	0.32	0.00	0.01	0.00	0.00	0.08	0.19	0.03	0.06	0.06	0.00	0.06	0.02
ACP-10	0.24	0.24	0.00	0.02	0.00	0.00	0.08	0.14	0.15	0.04	0.07	0.00	0.01	0.02
ACP-11	0.24	0.26	0.01	0.00	0.00	0.00	0.08	0.14	0.12	0.04	0.09	0.00	0.01	0.02
ACP-12	0.24	0.25	0.00	0.00	0.01	0.00	0.07	0.13	0.14	0.04	0.07	0.00	0.03	0.02
ACP-13	0.24	0.26	0.00	0.00	0.00	0.00	0.08	0.13	0.11	0.04	0.09	0.00	0.03	0.02
ACP-14	0.25	0.25	0.00	0.00	0.00	0.00	0.07	0.16	0.08	0.06	0.08	0.00	0.03	0.02
ACP-15	0.24	0.26	0.00	0.01	0.00	0.00	0.08	0.18	0.03	0.04	0.09	0.00	0.07	0.02
ACP-16	0.17	0.31	0.00	0.02	0.00	0.00	0.09	0.19	0.08	0.04	0.08	0.00	0.00	0.02
ACP-17	0.29	0.21	0.00	0.00	0.00	0.00	0.08	0.14	0.14	0.04	0.07	0.00	0.01	0.02
ACP-18	0.24	0.24	0.01	0.02	0.00	0.01	0.10	0.18	0.03	0.06	0.09	0.00	0.01	0.02
ACP-19	0.26	0.22	0.01	0.01	0.01	0.00	0.08	0.14	0.04	0.08	0.09	0.02	0.04	0.02

C.8 Cropping patterns of the filtered ACPs when grouped based on their robustness

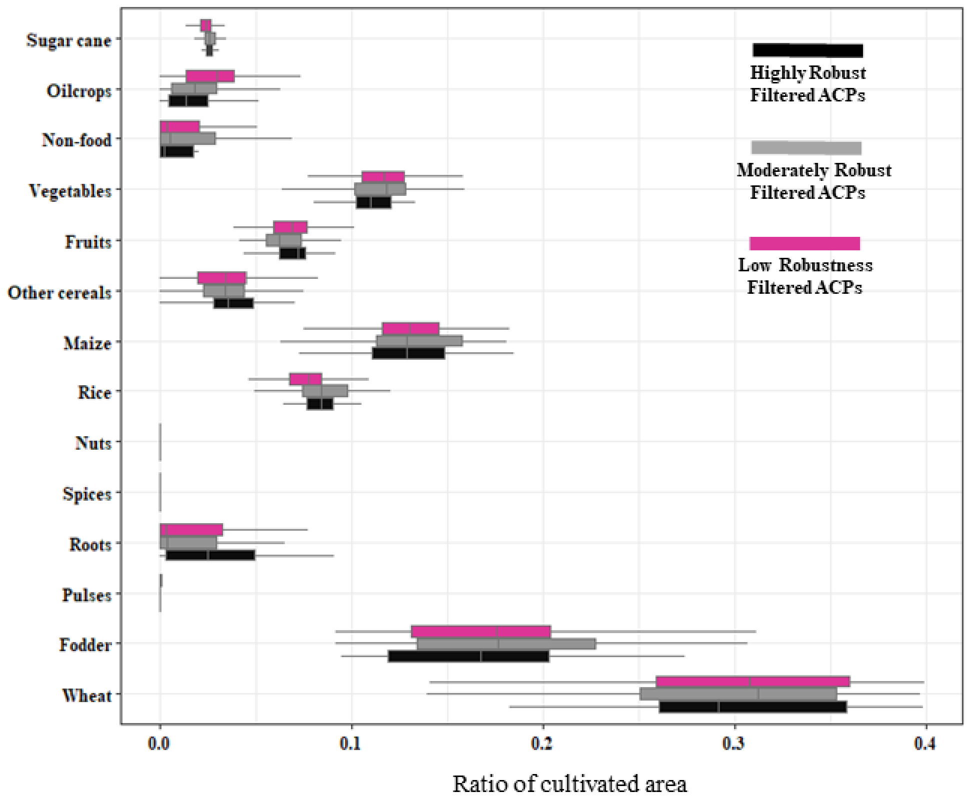


Figure C.7: The cropping patterns of the filtered 480 (based on both baseline period and future conditions) ACPs divided into three groups based on their robustness: highly robust, moderately robust, and low robustness.

C.9 References

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Appendix D: Supplementary materials for Chapter 4

D.1 Modeling components of the WEFNAF framework

D.1.1 The hydrological model

The soil water assessment tool (SWAT; Arnold, 1994) is the hydrological model used to simulate the daily streamflow of thirteen river sub-basins of the Eastern Nile Basin (ENB) countries (Sub-basin outlets are listed in Table D.5 and indicated in Figure 4.1). The model is spatially semi-distributed, in which a river basin is divided into smaller units, based on land slope, soil type, and land cover, to create homogenous hydrological response units (HRUs). For each HRU, the surface runoff is estimated using the SCS curve number method. Infiltration, percolation to different soil layers, evapotranspiration, and soil moisture content are also simulated. Water is allowed to flow on the surface and within the subsurface layers of the HRUs until it reaches the river network to form the streamflow that is routed to the watershed outlet using Muskingum-Cunge method (Cunge, 1969). In this study, the model was set to run for the period between 1981 and 2016 with the first two years as a spin-up period. Observed daily and monthly streamflow were used to calibrate and validate the model using the dynamically dimensioned search calibration algorithm (Tolson and Shoemaker, 2007). Calibration and validation results are shown in section D.8. The main purpose of this model is to generate streamflow to drive the second model (i.e., the WEF model).

D.1.2 The water, energy, food (WEF) model

The water-energy-food (WEF) model was built for this study using a system dynamics simulation environment (i.e., Stella Architect; https://www.iseesystems.com) to simulate the water and food (agricultural and animal products) demand and supply and the hydropower production for each of the ENB countries. The surface water resources system of the study area was incorporated in the WEF model, whereby the daily flow generated by SWAT was used as a boundary condition for the river and reservoir networks as in Figure D.1. The daily municipal water demand at a specific location of the river system was estimated by multiplying the per-capita water demand (MWRI, 2010; and NBI, 2017) and the portion of the country's population living at this particular location (WorldPOP, 2020). The daily irrigation demand at each irrigation scheme was estimated by summing the daily irrigation water requirements over all the cultivated crop areas divided by irrigation efficiency. The daily irrigation water requirement was evaluated based on the soil moisture shortage estimated from a daily soil moisture balance, as illustrated in (Allen et al., 1998). This soil moisture balance considers the antecedent soil moisture, precipitation data, and potential evapotranspiration that was calculated based on the Hargreaves method (Hargraves and Samani, 1982). The industrial water demand was defined in the model as input data at the relevant locations (MWRI, 2010; and NBI, 2017). Water supply occurs based on logical priority rules; municipal demand takes the highest priority, followed by industrial demand, then the irrigation water demand. Accordingly, in case of insufficient water to meet all demands, irrigation water supply would be less than the irrigation demand, resulting in an irrigation water shortage. Daily hydropower generation was calculated within the WEF model at each relevant dam location as the multiplication of the dam water release, the head of water stored in that dam, the specific weight of water, and power generation efficiency at each dam (Munoz-Hernandez and Jones, 2012).

In Ethiopia, Sudan, and South Sudan there is insufficient and uncertain information about groundwater use and potential, thus, we only considered river flows as the major source of blue water supply (Berhanu et al., 2014; Omer, 2008). However, for Egypt the increased scarcity of surface water flows through the Nile means that the hyper-arid country utilizes other water sources. These include deep and shallow groundwater, wastewater and agricultural drainage water reuse, and desalination, which are all included in the WEF model as water supply sources for Egypt as described in detail in Abdelkader et al. (2018).

The agricultural production of 21 crops and crop groups cultivated in the study area was simulated within the WEF model. Crop yield was assumed to vary spatially, where due to the technology gap, the maximum yield achievable for each crop (Ym) varies between the four countries. Further, to estimate the actual crop yields (Ya), Ym is adjusted for spatial soil moisture availability, which varies based on the specific location inside each country (Doorenbos and

Kassam, 1979). For this purpose, each country in the study area was divided into smaller units named agriculture calculation units (ACU; Figure D.2), where a daily soil water balance was calculated for each crop based on antecedent soil moisture, precipitation, and potential evapotranspiration estimates for each ACU (Allen et al., 1998). To account for the effect of irrigation water application on soil moisture, the soil water balance was performed for the rainfed sub-sector and the irrigation sub-sector separately. Accordingly, the crop production of each crop, for the crops indicated in Figure D.4, was calculated for each ACU and each sub-sector by multiplying the adjusted crop yield (tonnes/ ha) and its cultivated area (ha). The national crop production was calculated by summing the crop production over the sub-sectors and ACUs of each country. To estimate food production, the crops used by humans as food were accounted for separately. Additionally, animal production was estimated for each country in the study area, where the per head animal productivity (kg/head; FAO, 2021) of each animal product was multiplied by the number of producing animals (heads, FAO, 2021). This was done for four major animal products of red meat, milk, poultry, and eggs, following the approach used in Abdelkader et al. (2018) for Egypt.

Food demand was also calculated in the WEF model, whereby the per capita nutritional energy demand (NED; Kcal/cap) from all food products was partitioned over each food product by multiplying the NED by the ratios of each food product in the daily NED. Then using conversion factors (kg/Kcal), the per capita food demand was calculated in weight units (kg/cap) for each product. The national demand for the different food products can be calculated by multiplying the per capita food demand (kg/cap) by the national population. Net food exports were calculated for the different food products as the surplus in production over the demand, after accounting for food production losses. Animal feed demand and supply were estimated within the WEF model, where the per head annual feed demand was compiled from Mekonnen and Hoekstra (2012) and multiplied by the annual population of livestock available in each country to calculate the national feed demand. For Egypt, the feed supply was assumed to occur from irrigated fodders (i.e., Egyptian clover), and in case of shortage, feed imports occur. As for Ethiopia, Sudan, and South Sudan, the source of feed was assumed to be rainfed pasture as those countries rely heavily on grazing (NBI, 2017).

Existing Dam Code	Dam Name	Purpose
ED 0	High Aswan Dam	HP/irrig
ED 1	Merowe	HP
ED 2	Khashm Elgerba	Irrig
ED 3	Rumaylah Complex	HP/irrig
ED 4	Tekeze'	HP
ED 5	Sennar	Irrig
ED 6	Rosieres	HP/irrig
ED 7	GERD	HP
ED 8	Jebel Aulia	HP/irrig
ED 9	Abobo	Irrig
ED 10	Gibe I	HP
ED 11	Gibe II	HP
ED 12	Gibe III	HP
ED 13	Melka Wakena	HP

Future Dam Code	Dam Name	Purpose
FD 0	Humera	HP/irrig
FD 1	Mendaia	HP/irrig
FD 2	Beko-Abo	HP
FD 3	Karadobi	HP
FD 4	Gambella	Irrig
FD 5	Tams	HP
FD 6	Birbir	HP
FD 7	Baro II	HP
FD 8	Baro I	HP
FD 9	Gilo III	HP/ irrig
FD 10	Gilo II	Irrig
FD 11	Gilo I	HP/ irrig
FD 12	Gibe IV	HP/ irrig
FD 13	Gibe V	HP/ irrig
FD 14	Genale-Dawa	HP/ irrig

Natural Lake Code	Lake Name
L0	Lake Tana

Wetland Code	Wetland Name
WL00	Mashar Marches

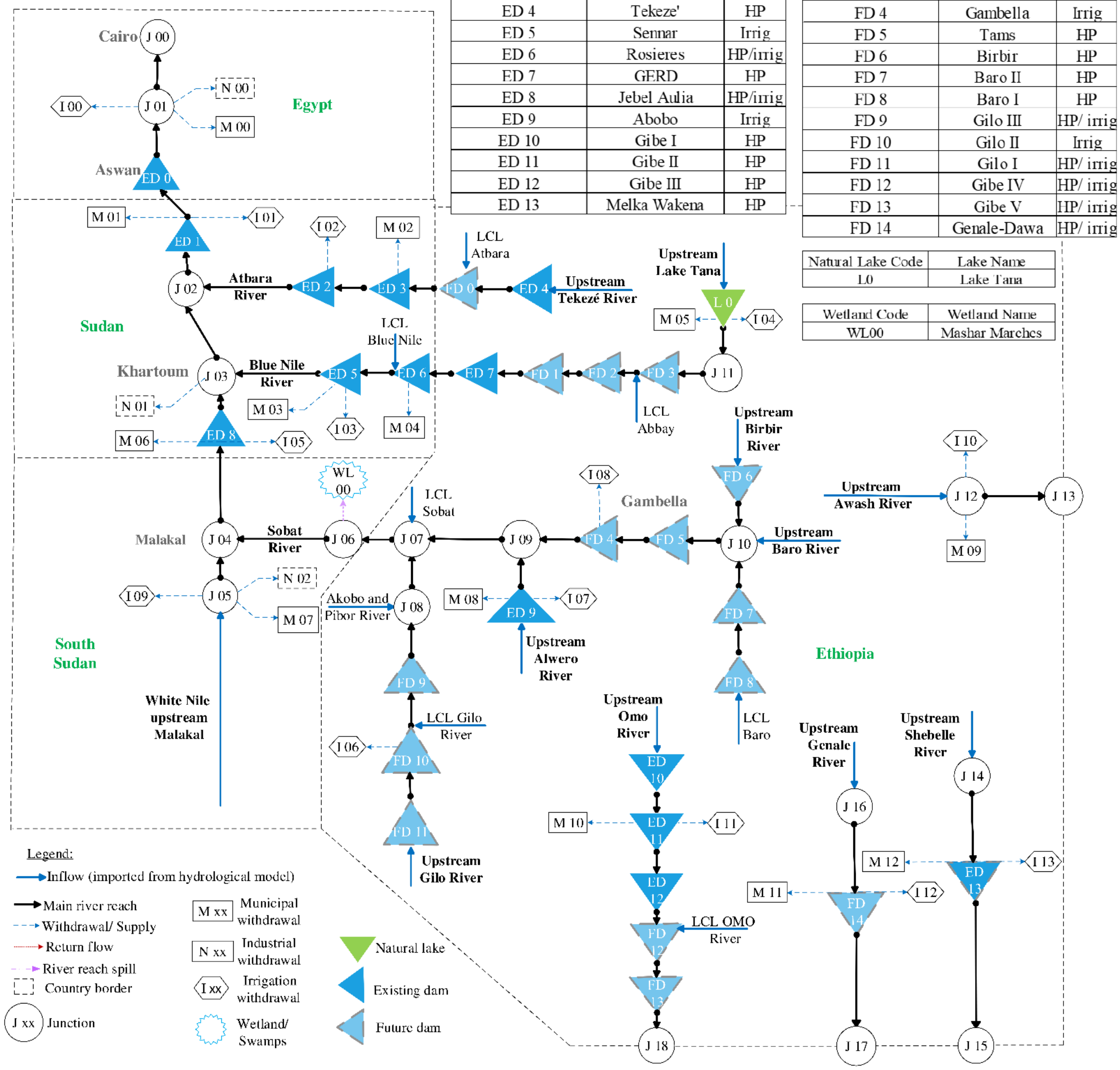


Figure D.1: A schematic diagram for the surface water resources system as represented in the WEF model.

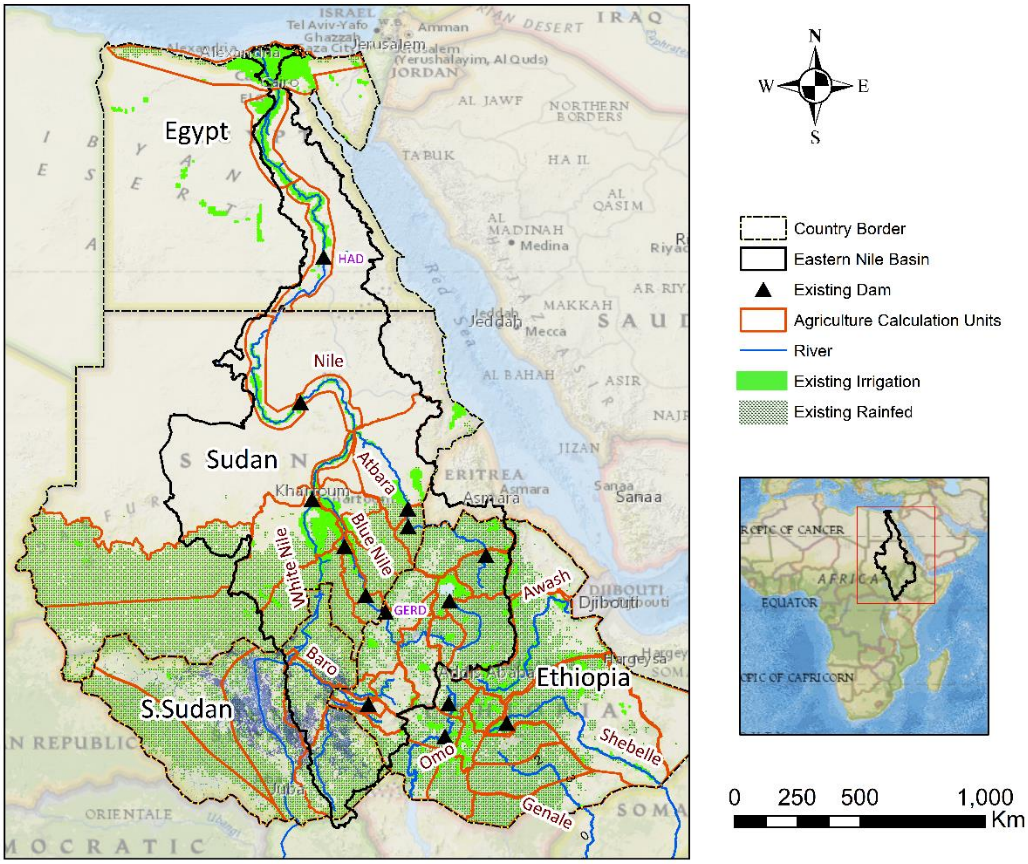


Figure D.2: The agriculture calculation units (ACU) of the ENB countries as represented in the WEF model.

D.2 Selected level of reliability for the RHP, GM equation, and weather generator

There is a tradeoff between a required level of reliability and the hydropower that can be generated at this level. Decision-makers must decide the level of reliability they want, which will differ from one decision-maker to another and could vary over time for the same decision-maker. In this study, a reasonable selection for the level of reliability is made using a value of 80%; it is understood that there is no right or wrong about this value, it is a matter of preference. It logically will not be 100%, and likely not less than 50%. Different decision-makers will pick different values according to their objectives and needs. Importantly, the selected value of 80% was fixed for all countries under all driver change scenarios and development plans, which sets a valid basis for comparing RHP.

The combined gross margin of agriculture and hydropower was calculated by adding the agriculture gross margin (AGM) and hydropower gross margin (HGM) that are calculated as in the following equations:

$$AGM_c(\text{t}) = \sum_{i=1}^{L}(PL_{ci}(t) - VC_{ci}(t)) * PROD_{ci}(t) + \left(PG_{ci}(t) - PL_{ci}(t)\right) * EXP_{ci}(t)$$

$$HGM_c(\text{t}) = \left(PE_c(t) - VE_c(t)\right) * NHP_c(t)$$

where $PL_{ci}(t)$ is the local market price of crop i in a country c and year t, $VC_{ci}(t)$ is the variable costs of producing the same crop. $PROD_{ci}(t)$ is the national production of crop i after accounting for any production losses. $PG_{ci}(t)$ is the global market price of crop i in a year t. $EXP_{ci}(t)$ is the exported quantity of crop i. L is the total number of crops produced. $PE_c(t)$ is the price of electricity in country c for year t. $VE_c(t)$ is the variable costs of hydropower production, a country average value was used for all power stations inside the same country. $NHP_c(t)$ is the national hydropower production from all hydropower dams of a country c and year t. All monetary values are in USD.

In this study, we used a daily weather generator based on the inverse approach (Culley et al., 2019), which was introduced as a technique to generate hydrometeorological timeseries that meets "target" changes in specific climate attributes, such as a specific mean annual precipitation. The approach begins by setting target values for the attributes that need to be changed. The target changes may be represented as absolute values (e.g., 3 °C increase in annual mean temperature) or percentage changes in attributes relative to historical climate (e.g., a 10% decrease in mean annual precipitation). Once the attribute targets are identified, the next step is to apply a formal optimization method that involves modifying the parameters of the daily weather generator, such that to optimize a measure between the relevant attributes of the simulated weather time series and the target attributes. In this study, we used Gamma distribution and Normal distribution to randomly sample the daily precipitation and temperature, respectively. The parameters of those distributions were optimized such that to generate daily timeseries that meet the target changes listed in Table D.4 More details about the used approach are provided in Culley et al. (2019).

D.3 Decision variables considered in WEF development plans

Table D.1: Decision variables names, limits, and allowed values of change in each country.

Country	WEF sector	Decision variable name	Current value/ State as in year 2016	Limits of increase/ change	Data / info. source	Set of allowed values for each decision variable as a percentage of the limits of increase/ change
Egypt	Food	Rainfed agriculture land area	0.04 million ha	-	(MWRI, 2010)	-
		Irrigated agriculture land area	3.8 million ha	Add 0.9 million ha		0% - 25% - 50% -100%
		Crop yield technology	Highest crop yield in the ENB (see Figure D.3)	Variant by crop but up to 30% increase for wheat and maize yield	(Ayyad and Khalifa, 2021)	0% - 25% - 50% -100%
		Cropping patterns	see Figure D.4	Shift between cereals, and cash crops within 10% of the historical cultivated area (see Figure D.4)	(FAO, 2021)	No-change - Cereal shift - Cash crop shift
	Energy	Hydropower generation	8000 GWh/ year	-	(MWRI, 2010; McCarl, et al., 2015)	-
	Water	Irrigation efficiency	63%	Increase to 90%		65% - 75% - 90%
		Water withdrawal from Non-River sources	25.0×10^9 m^3/year	Add 5.0×10^9 m^3/year		0% - 25% - 50% -100%
		Irrigation dam(s)	Only High Aswan Dam (HAD) Exists	-	-	-
		Hydropower dam(s)	Only High Aswan Dam (HAD) Exists	-	-	-
Sudan	Food	Rainfed agriculture land area	15.5 million ha	Add 38 million ha	(Berry, 2015)	0% - 25% - 50% -100%
		Irrigated agriculture land area	1.8 million ha	Add 0.5 million ha	(Berry, 2015)	0% - 25% - 50% -100%
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure D.3)	Increase to match Egypt's crop yields (see Figure D.3)	(FAO, 2021)	0% - 25% - 50% -100%
		Cropping patterns	see Figure D.4	Shift between cereals, and cash crops within 10% of the historical cultivated area (see Figure D.4)	(FAO, 2021)	No-change - Cereal shift - Cash crop shift
	Energy	Hydropower generation	10,000 GWh/ year	-	-	-
	Water	Irrigation efficiency	50%	Increase to 90%	(Al Zayed et al., 2015)	65% - 75% - 90%
		Water from Non-river Sources	-	-	-	0% - 25% - 50% -100%
		Irrigation dam(s)	6 Dams exist on the Nile River and its tributaries (as in Figure D.1)	-	-	-
		Hydropower dam(s)	4 Dams exist on the Nile River and its tributaries (as in Figure D.1)	-	-	-
South-Sudan	Food	Rainfed agriculture land area	1.62 million ha	Add 54 million ha	(Diao et al., 2012)	0% - 25% - 50% -100%
		Irrigated agriculture land area	0.12 million ha	-	(FAO, 2021)	-
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure D.3)	Increase to match Egypt's crop yields (see Figure D.3)	(FAO, 2021)	0% - 25% - 50% -100%
		Cropping patterns	see Figure D.4	Shift between cereals, and cash crops within 10% of the historical cultivated area (see Figure D.4)	(FAO, 2021)	No-change - Cereal shift - Cash crop shift

	Energy	Hydropower generation	-	-	-	-
	Water	Irrigation efficiency	50%	Increase to 90%	(NBI, 2012)	65% - 75% - 90%
		Water from Non-river Sources	-	-	-	-
		Irrigation dam(s)	-	-	-	-
		Hydropower dam(s)	-	-	-	-
Ethiopia	Food	Rainfed agriculture land area	15.0 million ha	Add more 35 million ha	(Alemayehu et al.,2020)	0% - 25% - 50% -100%
		Irrigated agriculture land area	0.89 million ha	Add more 1.0 million ha	(Seleshi et al., 2014)	0% - 25% - 50% -100%
		Crop yield technology	Crop Yield values are half of that of Egypt on average (see Figure D.3)	Increase to match Egypt's crop yields (see Figure D.3)	(FAO, 2021)	0% - 25% - 50% -100%
		Cropping patterns	see Figure D.4	Shift between cereals, and cash crops within 10% of the historical cultivated area (see Figure D.4)	(FAO, 2021)	No-change - Cereal shift - Cash crop shift
	Energy	Hydropower generation	10,000 GWh/ year	Add 42,000 GWh/year	(Seleshi et al., 2014)	0% - 25% - 50% -100%
	Water	Irrigation efficiency	50%	Increase to 90%	(Asres, 2016)	65% - 75% - 90%
		Water from Non-river Sources	-	-	-	-
		Irrigation dam(s)	5 dams exist on different rivers (see Figure D.1)	Add up to 9 dams on different rivers (See Figure D.1 and Table D.2)	(Seleshi et al., 2014)	Dams are selected based on the irrigated land expansion value and its spatial location
		Hydropower dam(s)	7 dams exist on different rivers (See Figure D.1)	Add up to 14 dams on different rivers (See Figure D.1 and Table D.2)	(Seleshi et al., 2014)	Dams are selected based on the irrigated land expansion value and its spatial location

D.4 Crop yield of major crops in the ENB countries

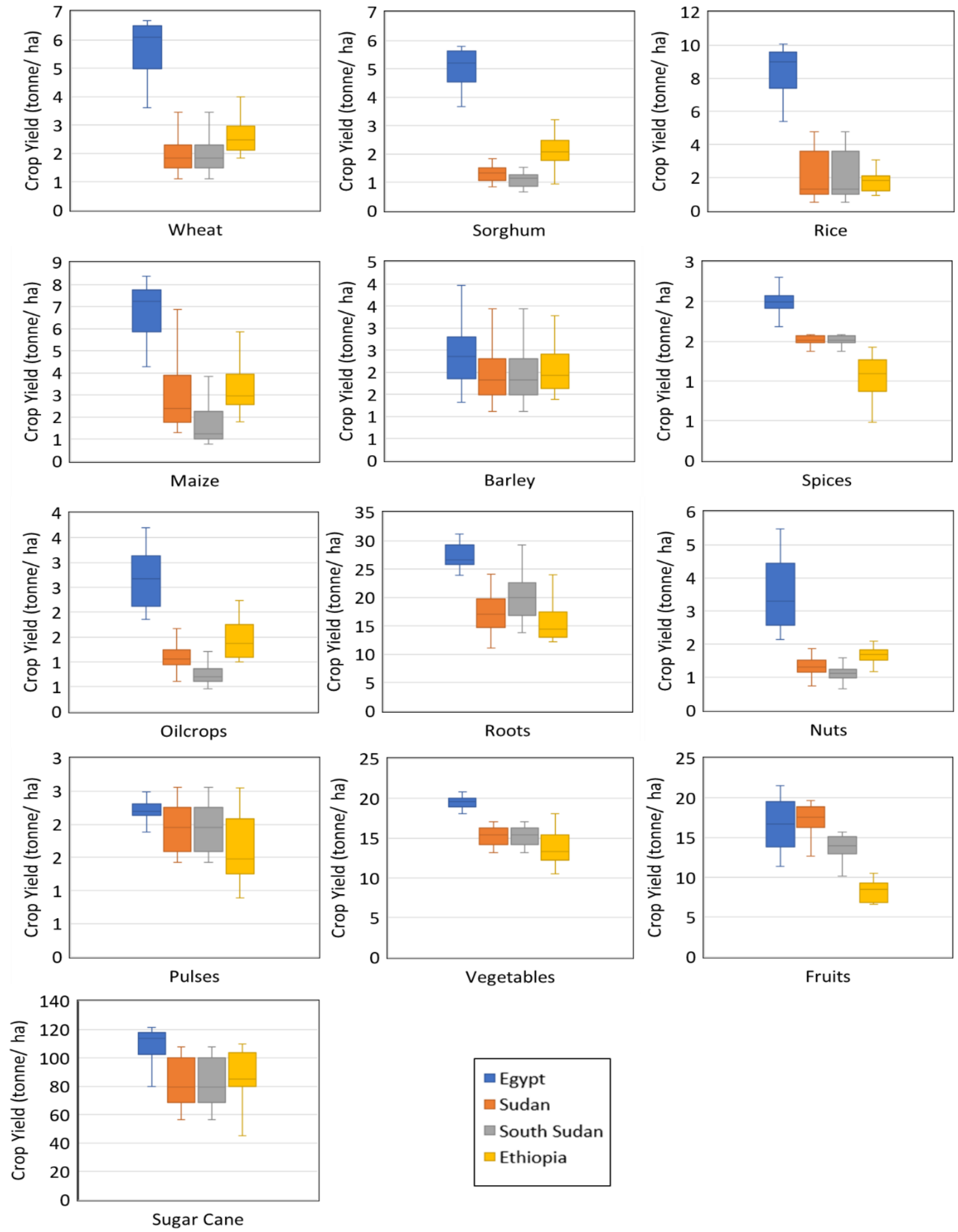


Figure D.3: The maximum yield achievable (Y_m) for major crops cultivated in each country in the ENB countries, boxplot shows the range of historical values between the years 1983 and 2016.

The figure shows the yield technology gap between Egypt and the three countries of Sudan, South Sudan, and Ethiopia. This figure was developed based on an analysis of FAO data (FAO, 2021).

D.5 Cropping patterns of the ENB countries

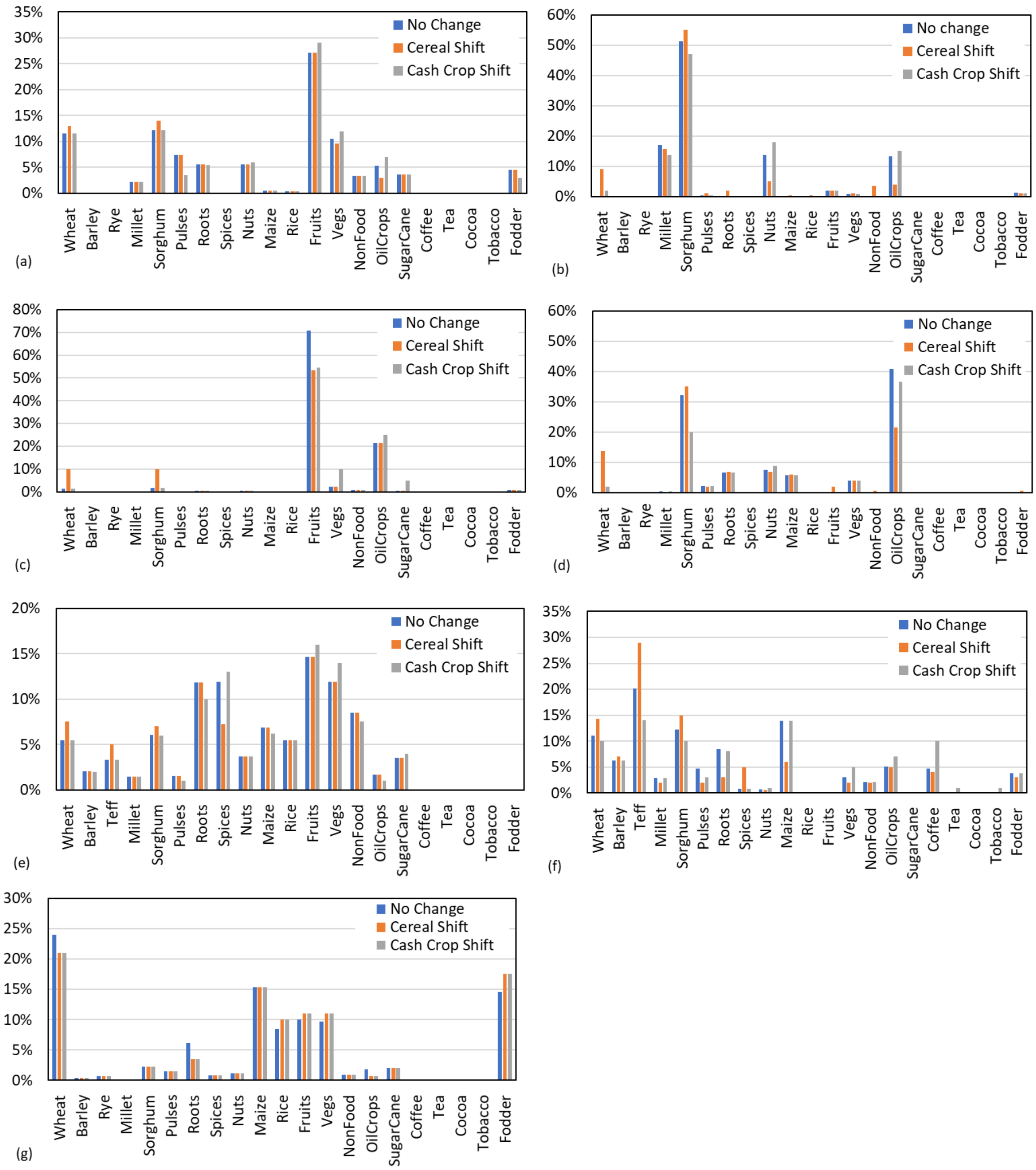


Figure D.4: Cropping Pattern of the ENB countries for (a) Sudan – Irrigation sub-sector, (b)

Sudan – Rainfed sub-sector, (c) South Sudan – Irrigation sub-sector, (d) South Sudan – Rainfed sub-sector, (e) Ethiopia – Irrigation sub-sector, (f) Ethiopia – Rainfed sub-sector, (g) Egypt – Irrigation sub-sector. The vertical axis indicates the percentage of the area of each crop from the total national cultivated area of each agriculture sub-sector. Figures are based on analysis of FAO data (FAO, 2021).

D.6 Planned dams in the ENB countries and sample development plans

Table D.2: the key characteristics of the planned and under-construction dams in the ENB countries.

Dam Name	Purpose	River Sub-Basin	Status	Storage ($\times 10^9$ m^3)	Hydropower Generation (GWh/ Year)	Irrigation Potential (ha)
Humera Dam	HP/irrig	Atbara/ Nile	planned	6.5	650.0	83,000
GERD	HP	Blue Nile	under construction	74.0	15000.0	-
Mendaia	HP/ irrig		planned	48.0	6350.0	300,000
Beko-Abo	HP			31.0	6000.0	
Karadobi	HP			37.5	3000.0	-
Gambella	Irrig	Baro/ Nile		2.5	-	91,000
Tams	HP			10.0	3000.0	-
Baro II	HP			0.1	1100.0	-
Baro I	HP			1.5	420.0	-
Birbir	HP			2.8	1000.0	-
Gilo III	HP/ irrig			1.5	50.0	33,000
Gilo II	Irrig			2.8	-	159,000
Gilo I	HP/ irrig			3.6	420.0	150,000
Gibe IV	HP/ irrig	Omo River		9.0	1500.0	75,000
GibeV	HP/ irrig			5.0	3500.0	75,000
Genale-Dawa	HP/ irrig	Genale		3.0	10.0	34,000
			Total	**239**	**42,000**	**1,000,000**

Table D.3 shows a sample of four out of the 6,912 development plans developed for this study. As the Table shows, each plan is composed of 9 decision variables, and each decision variable is changed simultaneously in the same way in each of the four ENB countries. The first development plan (DP 1) features very limited change from the reference scenario. The rainfed agriculture land area, irrigated land area, crop yield technology, cropping pattern, hydropower generation, water withdrawals from non-river sources, number of irrigation dams, and number of hydropower dams, are the same as the reference scenario for all four ENB countries. Only the Irrigation efficiency is assumed to increase from 63% in Egypt, and 50% in Sudan, South-Sudan, and Ethiopia, to 65% in each of the four countries, as indicated in Table D.3. Development plan DP 2 features limited changes from the reference scenario. The rainfed agriculture area is assumed to increase by 25% of the limit for expansion for each country. For Ethiopia, Sudan, South-Sudan, and Egypt this means additional rainfed land areas of 8.75, 13.5, 9.5, and 0 million ha, from the limits for expansion of 35, 54, 38, 0 million ha (Table 4.1), in the four countries, respectively. Likewise, the irrigated agriculture land area is assumed to increase by 25%, and the crop yields to increase by 25% of their limits of increase. Irrigation efficiency is assumed to increase to 65% in each of the four countries. Cropping pattern is the same as the reference scenario, while water withdrawals from non-river sources are assumed to increase by 25% from the limits of increase. The hydropower generation is also assumed to increase by 25% of the limits of increase, stated in Table 4.1. To meet these changes in the irrigated land areas, and hydropower generation, two Ethiopian dams of Mendaia (i.e., irrigation and hydropower dam) and Baro I (i.e., hydropower dam) were added to the ENB river system, as indicated by the values given to Irrigation dams and hydropower dams in Table D.3.

Development plan DP 3 features moderate changes from the reference scenario. The rainfed agriculture land area, irrigated land area, crop yield technology, hydropower generation, water withdrawals from non-river sources, all increase by 50% of the limits of increase. Irrigation efficiency is assumed to increase to 75% in each of the four ENB countries. Cropping pattern is assumed to change to a cropping pattern with increased cereal crops (cereal shift). To meet these changes in the irrigated land areas, and hydropower generation, five Ethiopian dams are added to the river system of the ENB: Mendaia, Gilo I (i.e., irrigation and hydropower dams); Beko-Abo, Baro II (i.e., Hydropower dams); and Gambella (i.e., Irrigation dam), as indicated by the values given to Irrigation dams and hydropower dams in Table D.3. Development plan DP 4 features the highest changes from the reference scenario. The rainfed agriculture land area, irrigated land area, crop yield technology, hydropower generation, water withdrawals from non-river sources, all increased by 100% from the limits of increase. Irrigation efficiency is assumed to increase to 90% in each of the four ENB countries. Cropping pattern is assumed to change to a cropping pattern with increased cash crops (cash shift). To meet these changes in the irrigated land areas, and hydropower generation, all the proposed Ethiopian dams listed in Table D.2 are added to the river system of the ENB.

Table D.3: Four sample development plans from the 6,912 development plans generated in this study.

Development Plan Number	Rainfed agriculture land area (million ha)				Irrigated agriculture land area (million ha)				Crop yield technology			
	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia
DP 1	0.04	15.5	1.62	15	3.8	1.8	0.12	0.89	Ref.	Ref.	Ref.	Ref.
DP 2	0.04	25	15.12	23.75	4.03	1.93	0.12	1.14	Ref. + 25%	Ref. + 25%	Ref. + 25%	Ref. + 25%
DP 3	0.04	34.5	28.62	32.5	4.25	2.05	0.12	1.39	Ref. + 50%	Ref. + 50%	Ref. + 50%	Ref. + 50%
DP 4	0.04	53.5	55.62	50	4.70	2.30	0.12	1.89	Ref. + 100%	Ref. + 100%	Ref. + 100%	Ref. + 100%

Development Plan Number	Irrigation efficiency (%)				Cropping patterns				Hydropower generation (GWh/ year)			
	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia
DP 1	65%	65%	65%	65%	No change				8,000	10,000	0	25,000
DP 2	65%	65%	65%	65%	No change				8,000	10,000	0	31,750
DP 3	75%	75%	75%	75%	Cereal Shift				8,000	10,000	0	38,500
DP 4	90%	90%	90%	90%	Cash crop shift				8,000	10,000	0	52,000

Development Plan Number	Water withdrawal from non-River sources ($\times 10^9$ m^3/year)				Irrigation dams (number of dams)				Hydropower dams (number of dams)			
	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia	Egypt	Sudan	South Sudan	Ethiopia
DP 1	25	0	0	0	1	6	0	5	1	4	0	8
DP 2	26.25	0	0	0	1	6	0	6	1	4	0	10
DP 3	27.50	0	0	0	1	6	0	8	1	4	0	11
DP 4	30.00	0	0	0	1	6	0	14	1	4	0	21

(Each table block is headed "Decision Variable Name / Country".)

D.7 WEF system drivers

Table D.4: WEF System Drivers, their Historical Values and Possible Future Values.

Driver Type	Country	Driver Name	Value as in 2016	Considered Socio-economic Scenarios: High	Moderate	Low
Social Drivers	Egypt	Population Growth Rate	2.00%	3.00%	2.00%	1.00%
	Sudan		2.50%			
	South Sudan		2.30%			
	Ethiopia		2.80%			
	Egypt	Per capita Food Demand (Kcal/ day)	3500	3800	3500	3000
	Sudan		2300	3500	3000	2300
	South Sudan		2300			
	Ethiopia		2300			
	Egypt	Per capita Municipal Water Demand (m^3/ year)	115	130	115	70
	Sudan		25	115	90	
	South Sudan		19			
	Ethiopia		11			

Driver Type	Country	Driver Name	Value as in 2016	Possible Future Changes (Increase by this value at the year 2050)				
Climate Drivers	-	Annual mean Temperature (°C)	Spatially Varied	+0.5	+1.5	+3	+3.5	+4

Driver Type	Country	Driver Name	Value as in 2016	Possible Future Changes (percent change in the long-term mean of the period between 2017 and 2050 Compared with the long-term mean of the period between 1983 and 2016)								
Climate Drivers	-	Mean Annual Precipitation	Spatially Varied	-10%	-5%	0%	5%	10%	15%	20%	25%	30%

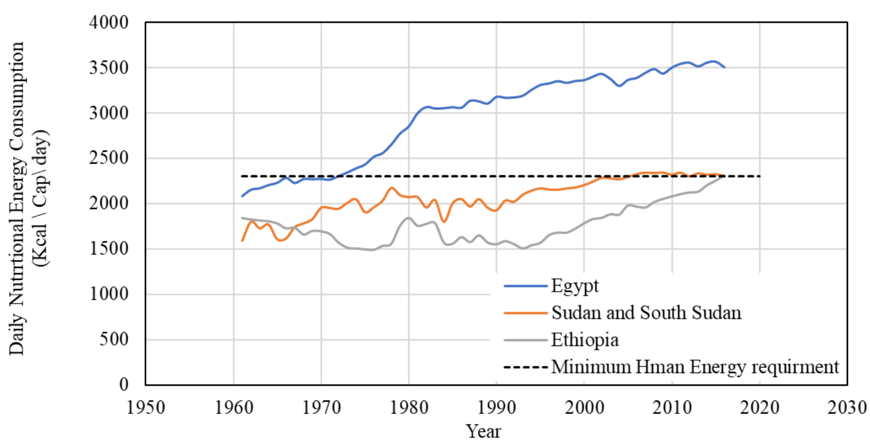


Figure D.5: The temporal variation of the Per Capita Daily Nutritional Energy Consumption for the Eastern Nile Basin Courtiers, 1960 to 2016.

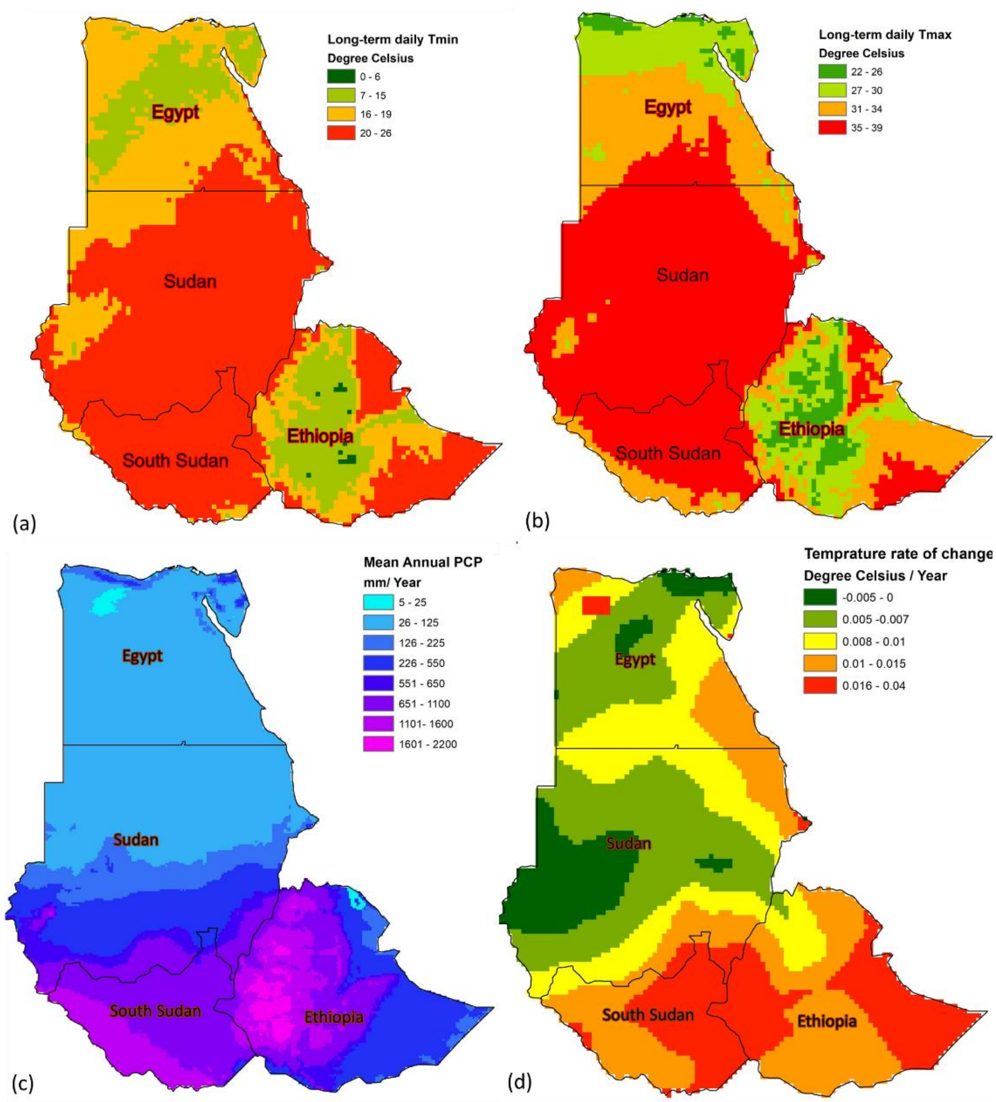


Figure D.6: The Spatial distribution of selected characteristics of climate variables in the ENB countries, (a) long-term mean of the daily minimum temperature, (b) long-term mean of the daily maximum temperature, (c) Mean annual precipitation, for the period between 1981 and 2016, and (d) annual rate of change of the mean annual temperature averaged for the period between 1981 and 2016. Data used to plot this figure are compiled from the climate hazards group infrared precipitation with station data (CHIRPS; Funk et al., 2015), and the observational reanalysis hybrid temperature dataset (ORH; Sheffield et al., 2006).

D.8 Results of the hydrological model calibration and validation

Table D.4: SWAT fitted calibration parameter values for selected major sub-basins. Table cells for Nile River sub-basins are in blue color, and green color indicates rivers in Ethiopia that are not connected to the Nile.

				Fitted Value/ Sub-Basin						
Model Parameter Name	Description	Change Method *	Calibration Range	Atbara	Blue Nile	Baro	Awash	Shebelle	Genale	OMO
RCHRG_DP	Deep aquifer percolation fraction	Replace	0 - 1	0.04	0.00	0.24	0.18	0.10	0.23	0.20
GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur (mm)		0 - 5000	3190.83	205.00	1407.56	1433.12	5000.00	1090.32	951.96
GW_REVAP	Parameter to control movement from shallow aquifer to root zone		0.02 - 0.2	0.08	0.16	0.12	0.03	0.02	0.18	0.09
GW_DELAY	Groundwater delay time (days)		15 - 450	15.00	39.80	15.00	50.48	15.00	51.10	15.00
REVAPMN	Threshold depth of water in the shallow aquifer to move to root zone (mm)		0 - 500	495.05	204.50	109.73	292.22	500.00	92.80	427.19
ALPHA_BF	Index of base flow response to recharge (1/day)		0 - 1	0.87	0.67	0.87	0.10	0.87	0.48	0.62
CH_N2	Manning's (n) for the main channel		0 - 0.3	0.16	0.17	0.21	0.03	0.01	0.26	0.28
CH_K2	Hydraulic conductivity of main channel (mm/hr)		0 - 150	49.12	82.35	0.00	18.46	28.95	45.10	44.83
SURLAG	surface runoff lag coefficient		0 - 24	6.99	1.27	24.00	19.48	23.68	0.40	0.00
CANMX	Maximum canopy storage as a water depth (mm)		0 - 10	6.31	5.07	4.96	1.81	6.38	10.00	5.74
SLSUBBSN	Average slope length (m)	Relative	-0.5 - +0.5	-0.14	0.21	-0.25	0.32	-0.01	0.11	0.20
SOL_Z()	Soil layer depth (mm)			0.11	0.02	-0.25	-0.50	0.32	-0.28	0.40
SOL_AWC	Available soil water capacity (mm)			-0.38	-0.02	0.44	-0.50	-0.47	-0.41	-0.24
SOL_K()	Saturated hydraulic conductivity (mm/hr)			-0.50	0.22	0.50	0.50	0.43	0.40	-0.33
CN2	SCS Curve Number			0.25	0.24	0.11	-0.17	-0.14	-0.21	0.18

* Changing method is the method used to perturb model parameters during the calibration process, *replace* method is used for parameters that do not change spatially within the sub-basin, where the fitted value replaces the parameter value in the model for all the HRUs., while *relative* change method is used with parameters that are spatially variant, where the parameter value in each HRU is multiplied by (1+ fitted value).

Table D.5: Results of calibration and validation of SWAT simulated river flow of the study area. SWAT model does not incorporate the capability of including detailed reservoir operation rules, thus, the simulated flows from SWAT were calibrated-validated first, then transferred to the WEF model, which has more accurate reservoir operation rules, thus, flows are refined and become more accurate in the WEF model. The values in the table reflect the results of both the calibration-validation within SWAT model, and the flow refinement in the WEF model. The model was calibrated at nine flow gauges on the Nile River and its tributaries (blue color), and four other gauges for rivers in Ethiopia that are not connected to the Nile (green color). See Figure 4.1 for the flow gauge locations, and Figure D.7 for flow timeseries plots. Calibration and validation periods differ between gauge station, as indicated in Figure D.7.

Flow gauge station	**Sub-Basin/ River**	**Calibration**		**Validation**	
		NSE	**PBIAS**	**NSE**	**PBIAS**
Atbara K3	Atbara/ Nile	85%	-13%	78%	6%
Eldeim	Blue Nile	91%	-1%	90%	-7%
US Roseries Dam		88%	-3%	86%	-4%
DS Sennar Dam		85%	-13%	82%	-10%
Khartoum		88%	1%	85%	8%
Gambella	Baro/ Nile	90%	-16%	82%	-15%
Hillet Dolieb		85%	8%	80%	8%
US Jebel Aulia Dam (White Nile at Malakal, Upstream of Baro confluence)	White Nile	68%	-2%	67%	3%
Dongola	Main Nile	89%	4%	70%	1%
Awash DS	Awash River	78%	-11%	80%	-15%
Shebelle DS	Shebelle River	60%	-5%	60%	4%
Doolow	Genale River	61%	-3%	60%	-1%
OMO DS	OMO River	82%	9%	88%	3%

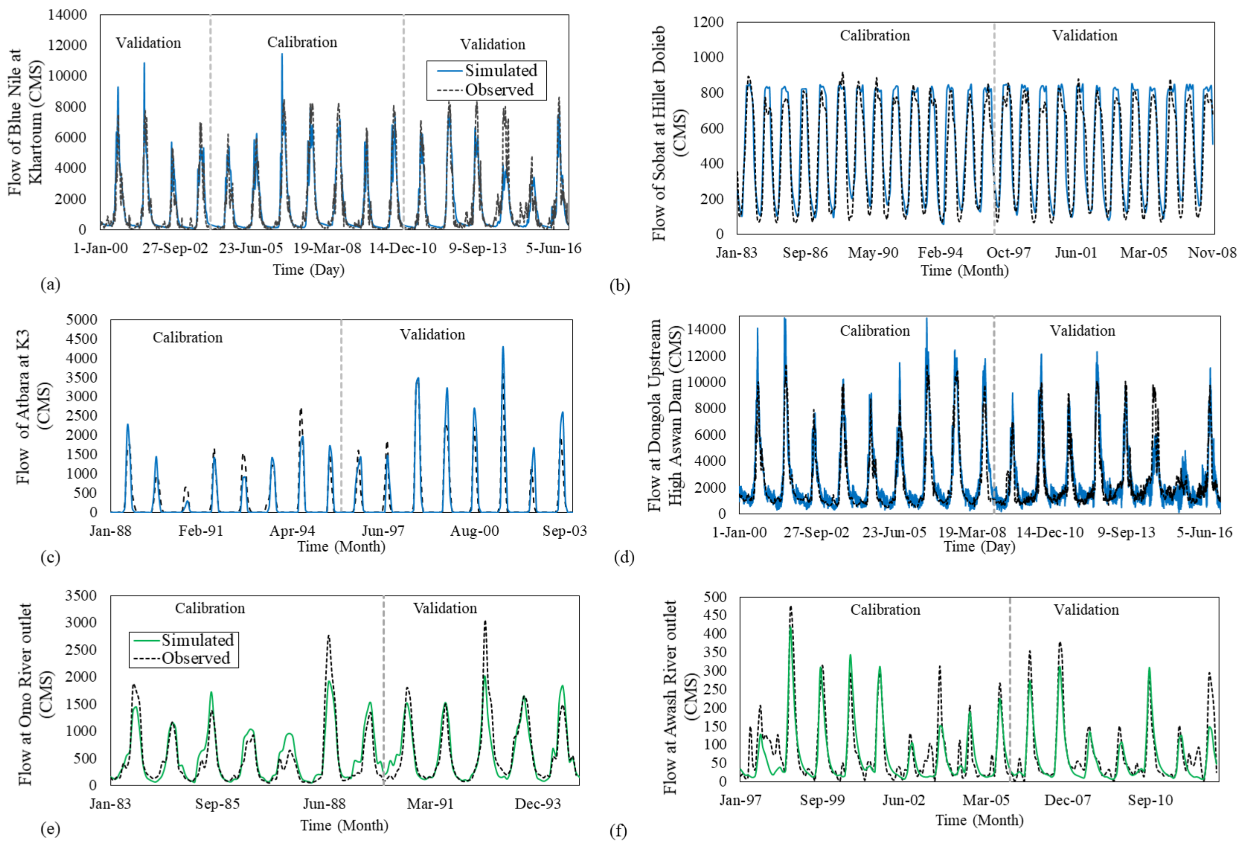
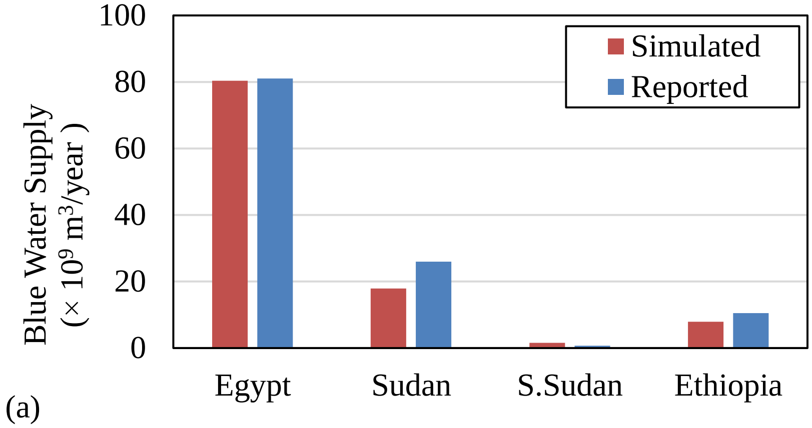


Figure D.7: Simulated and observed flow timeseries for the calibration-validation period at selected gauge stations of (a) Khartoum, (b) Hillet Dolieb, (c) Atbara at k3, (d) Dongola, (e) OMO DS, and (f) Awash DS. The first four sub-plots are for gauge stations on the Nile, while the last two stations are for rivers in Ethiopia that does not contribute to the Nile. Notably, to prevent initialization issues, during model calibration run at Khartoum station, the regular spin-up period of 2 years was increased to 22 years, then was set back to 2 years during model validation run.

D.9 Modeled and reported water supply of the ENB countries



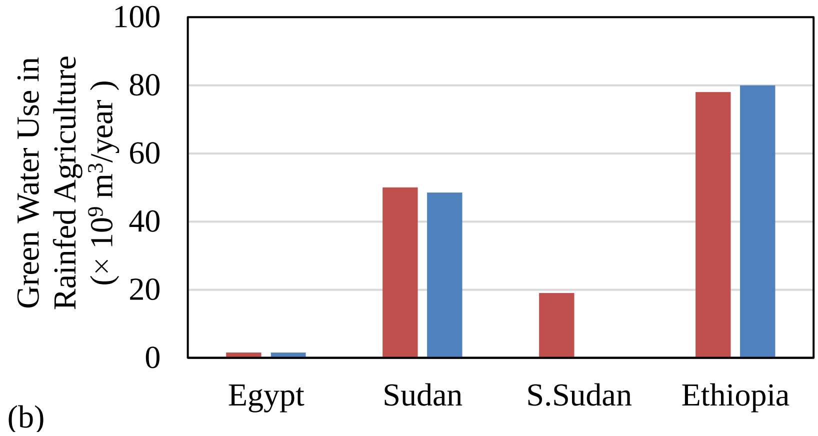


Figure D.8: Simulated and reported (a) blue water use, and (b) green water use. For the four countries of the ENB. Reported blue water supply of South Sudan, Sudan, and Ethiopia are from FAO (2015a; 2015b; 2016), while reported green water use in these three countries is retrieved from (Mekonnen and Hoekstra, 2011). Egypt's reported blue water supply and green water use is from MWRI (2010).

D.10 Selected WEF development plan under drivers change

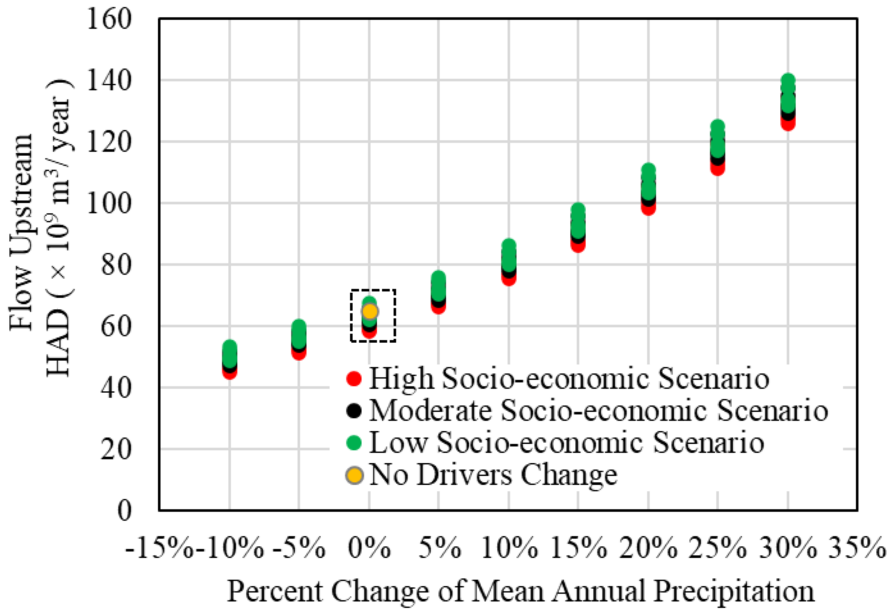


Figure D.9: Nile River flow reported upstream of the High Aswan Dam. Evaluated for the selected development plan (SDP) under different combinations of driver changes. The horizontal axis indicates the percent change of the mean annual precipitation, the vertical axis indicates the annual flow averaged for the period between 2016 and 2050. The orange point on the figures refers to evaluations under no social nor climate drivers change, whereas point colors of green, black, and red, refer to one of the three socio-economic scenarios, as listed in Table D.4. At a given value for the percent change of mean annual precipitation, the vertical variations of the points with the same color are due to the different annual mean temperature changes. Points surrounded by a dotted box represent the flow values under social drivers change, but no mean annual precipitation change.

D.11 References

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