Water-Food-Energy Nexus in Transboundary River Basins

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

Water, food and energy are fundamental for achieving our social, economic and environmental goals. The three domains are inextricably linked and the action in one sector could affect the two other sectors. Achieving the Water, Food and Energy (WFE) nexus balance and improving long-term sustainability through policy interventions is particularly challenging in transboundary river basins because of the dynamic nature and inter-sectoral complexity that may cross borders. Increased pressure from population growth, urbanization and economic growth in riparian countries induce each riparian country to maximise its resources to meet growing water, food and energy demands. Such infrastructure developments and policies in riparian countries could result in basin-wide cooperation or trigger conflicts among the countries. What is more, climate change is likely to exacerbate the risks associated with the hydrologic regime and affect the livelihoods in river basins.

The "nexus thinking" shifts the focus from one sector-centric towards multi-centric analytical frameworks to better understand the complexity and improve the management of disparate but interconnected sub-systems. This thesis builds upon the nexus approach and develops a novel systems-based approach to better understand the nexus interactions while considering other related important issues such as long-term uncertainty in river flow regime, socio-economic development, climate change and policy choices in river basins. The framework considers a biophysical water resource model of the river basin and integrated with an agricultural land and crop yield models to account for food production. The energy component includes hydropower generation from the system's hydropower plants, while energy demand is accounted for energy requirements in water and food sectors.

To account for the uncertainty in hydrologic river regime and large variability of the river flows, stochastic simulation is adopted with and without climate change. The population size and Gross Domestic Product (GDP) per capita represent socio-economic characteristics. The water resource model can accommodate future planned infrastructure projects and policies, e.g., improving irrigation efficiency, in the basin. The novel framework is applied for the Nile river basin as a case study.

The Nile River basin is a transboundary river basin in East Africa shared by eleven countries and home for about 250 million people. The riparian countries have devised ambitious master plans to utilise potential resources in the basin to meet the growing water, food and energy demands of their populations and sustain their expanding economies. The Nile is vulnerable to climate change that is likely to add further uncertainties to the hydrologic river regime. The – near completion – Grand Ethiopian Renaissance Dam (GERD) is the largest development in the basin and has the potential to deliver regional economic benefits and improve regional cooperation. However, it also has raised regional tensions – between Egypt, Ethiopia and Sudan – which have gained international attention and could hinder the livelihoods in downstream countries.

A System Dynamics model was built for the entire Nile basin to explore the WFE nexus in the basin. The integrated simulation model considers a complete WFE nexus for Egypt while partial consideration for the rest of the countries. The integrated simulation model consists of two main components: (a) partial WFE nexus outside Egypt and (b) complete WFE nexus in Egypt. The two model components are linked through High Aswan Dam (HAD). The first component consists of a water resource model for the entire Nile basin with 72 basin-wide river inflow tributaries. The Nile water resource model incorporates key components that affect the system's water management such as natural lakes, wetlands, water infrastructure (e.g., dams) and different water users. A simple crop yield model is linked to the Nile water resource model to account for food production from irrigated agriculture in the basin. Hydropower generation can be obtained from hydropower plants in the basin during model simulations.

The second component, i.e., complete WFE nexus in Egypt, includes population, gross domestic product, water balance and food balance, while the energy sector includes hydropower generation from HAD and energy demand in food and water sectors. To account for the uncertainty and hydrologic variability in river flow regime, a stochastic simulation is applied. Model simulations are driven by basin-wide stochastically generated data that is either based on historical stream flows (for the case of no climate change) or climate change projection of stream flows (for the case of climate change). The integrated simulation model runs at a monthly time-step. Model calibration and validation showed a satisfactory performance and the model is fit for the purpose for which it is developed.

The integrated simulation model was used to investigate the WFE nexus in the basin during the filling and subsequent operation of GERD using basin-wide stochastically generated river flows with no climate change. Results show that GERD filling during above-average years is likely to have a little impact on the downstream countries and it could accelerate the reservoir filling. Conversely, the reservoir filling during dry years is likely to cause significant impacts on the downstream countries. Once GERD comes online, it will generate an average of 15,000 GWh/year. Furthermore, model simulation results suggest further investigation and implementation of dynamic filling strategies that would maximize basin-wide benefits and reduce risks to downstream countries.

At the national level, the developed model was used to investigate the impacts of implementing policy measures (e.g., improving irrigation efficiency, developing new water resources, improving land productivity) on the WFE nexus in Egypt. For instance, improving irrigation efficiency and land productivity offer promising outcomes to improve the future of the WFE nexus in Egypt. For instance, achieving the potential crop yields alone would increase food production by 40% and reduce food imports by 32%. The simulation model is also used to explore the cooperation over the GERD and its impacts on the WFE nexus on the downstream countries during the operation phase. Simulation results show that during dry years, the risks to Egypt (e.g., water shortages and food production loss) can be substantially reduced if the riparian countries agree to cooperate and sacrifice for some loss (i.e., loss in hydropower generation) especially during severe droughts. However, a high level of coordination, commitment and trust among the riparian countries are urgently required to achieve cooperation benefits.

Basin-wide impacts of planned projects in the riparian countries are also analysed through different developments scenarios (e.g., hydropower development scenario, hydropower and irrigation expansions scenario) with and without climate change. Climate change is investigated here through two Representative Concentration Pathways (RCPs): RCP 8.5 and RCP 4.5 with two General Circulation Models (GCMs) per each climate scenario until 2050.

Projected streamflow of river tributaries under climate change are used to generate basin-wide synthetic streamflow series to drive model simulations. Simulation results demonstrate that the WFE nexus in the basin is less affected by planned developments than climate change. The analysis of climate change scenarios indicated that climate change exhibits large uncertainty and is likely to have significant impacts on the river flow regime, food production and hydropower generation in the basin. The average annual river runoff is likely to reduce by 7% in the RCP 4.5, while RCP 8.5 showed a wider range of change from -40% to +33%. Following river flow changes, hydropower generation and food production in the basin are impacted in a similar way under climate change but with varying degree of change in sub-basins.

At the general level, the novel framework developed in this work is a step forward for better understanding of the nexus interdependencies in river basins including but not limited to the challenging case of transboundary rivers. The novel framework addressed key nexus interlinkages and considered important issues such as uncertainty in river flow regimes, climate change and population growth. It can be beneficial in negotiations for transboundary systems, policy analysis, enhancing cooperation and trust among riparian countries, and promoting for cross-sectoral and cross-regional management. Systems-based approaches offer basis to improve our understanding of the interactions between the WFE nexus and other important issues in river basins. Furthermore, they allow for identifying trade-offs and synergies and improve coordination among sectors, countries and interested stakeholders.

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Finally, I dedicate this thesis to my grandmothers who passed away during my stay in the UK and to the people who got affected by the Coronavirus Pandemic “Covid-19”.

List of Publications

Key research outputs from this work include:

Journal papers

- Elsayed, H., Djordjević, S., Savić, D., Tsoukalas, I., and Makropoulos, C. (2020) The Nile Water-Food-Energy Nexus under Uncertainty: Impacts of the Grand Ethiopian Renaissance Dam. *Journal of Water Resources Planning and Management*, volume 146, no. 11, pages 04020085, DOI: 10.1061/(ASCE)WR.1943-5452.0001285.
- Elsayed, H., Djordjević, S., Savić, D., Tsoukalas, I., and Makropoulos, C. (Draft paper) Water-Food-Energy Nexus under Climate Change Uncertainty, Will shortly be submitted to *nature climate change*
- Elsayed, H., Djordjević, S., Savić, D., Tsoukalas, I., and Makropoulos, C. (Draft paper) Water-Food-Energy Nexus for Transboundary Cooperation

Conference papers and posters

- Elsayed, H., Djordjević, S. and Savić, D., (2020) Water-Food-Energy Nexus in the Nile River Basin, Poster presented online at DNC2020, *Dresden Nexus Conference 2020*, Saxony, Germany, 3-5 Jun. 2020.
- Elsayed, H., Djordjević, S. and Savić, D., (2019) The Nile Water, Food and Energy Nexus Model-A System Dynamics Model, CCWI 2019. *17th International Computing & Control for the Water Industry Conference*, Exeter, UK, 1-4 Sep. 2019.
- Elsayed, H., Djordjević, S. and Savić, D., (2018) The Nile Water, Food and Energy Nexus Model, *18th Conference of SDHI and SDH*, Niš, Serbia, 25-26 Oct. 2018.
- Elsayed, H., Djordjević, S. and Savić, D., (2018) The Nile System Dynamics Model for Water-Food-Energy Nexus Assessment, *13th International Conference on Hydroinformatics*, vol 3, pages 659-667, Palermo, Italy, 1-6 Jul. 2018

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Notation

A_i	Area of crop i
AD_i	Desired annual demand for food commodity (i)
ADF_i	Desired annual demand for food commodity (i) from the population
$AEDM$	Annual energy demand for machinery
$AEDW_{activity}$	Annual energy demand in a water activity
Agr_{land}	Agricultural land
AHP	Annual hydropower generation
AWD	Monthly agricultural water demand
C_i	Agricultural land percentage of the crop (i)
CBR	Crude birth rate
CC_i	Kcal content per 1.0 kg of food commodity (i)
CD	Desired kcal demand
CD_i	Desired kcal demand from food commodity (i)
CDR	Crude death rate
CWR_i	Consumptive water requirement of crop i
D_{rural}	Daily per capita rural water demand
D_{urban}	Daily per capita urban water demand
DWD	Monthly domestic water demand
E_{rate}	Energy consumption rate per tractor
E_t	Evaporation from the reservoir at time (t)
EC	Energy content per unit volume of fuel
$EI_{activity}$	Energy intensity of water activity
ET_O	Reference evapotranspiration
ET_{ai}	Actual evapotranspiration of crop i
ET_{ci}	Maximum evapotranspiration of crop i
ET_{Ci}	Crop i evapotranspiration
F	Fertility rate (number of children per woman)
F_i	Crop food factor of crop (i)

F_{rate}	Fuel consumption rate per tractor
FD_i	Desired demand for food commodity (i)
FP	Food production
$f(LE)$	Function of the life expectancy (LE)
GDP_{pc}	Per capita GDP
GDP_{t+1}	GDP at time $t+1$
GDP_t	GDP at time t
H_i	Turbine water head in month i
I_t	Reservoir inflow at time (t)
$K_{c\ end}$	Crop factor of late-season
K_{Ci}	Crop factor of crop i
$K_{c\ ini}$	Crop factor of initial-season
$K_{c\ mid}$	Crop factor of mid-season
Mor_{rate}	Mortality rate of each age-specific group
N_b	Number of births
$N_{tractors}$	Number of tractors used in agricultural activities
N_{hrs}	Average working hours per tractor
N_l	Number of tractors per unit land
N_d	Number of deaths
$N_{d/month}$	Number of days per month
$N_{d/year}$	Number of days in a year
O_t	Reservoir outflow at time (t)
P	Rainfall
P_e	Effective rainfall
P_t	Precipitation over the reservoir at time (t)
P_{time}	Woman's reproductive lifetime
PD_i	Annual production demand from crop (i)
Pop	Population size
Pop_{group}	Population in the age group

$Pop_{(0-14)}$	Population in age group (0-14)
$Pop_{(15-44)}$	Population in age group (15-44)
$Pop_{(45-64)}$	Population in age group (45-64)
$Pop_{(65+)}$	Population in age group (65+)
Q_i	Turbine discharge in month i
Q_{water}	Water quantity
r_{GDP}	GDP growth rate
R_{pop}	Rural population
S_d	Reservoir's dead storage
S_i	Share of food commodity (i) in the food mix
S_{max}	Maximum reservoir storage
S_t	Storage in the reservoir at time (t)
S_{t+1}	Reservoir storage at time ($t + 1$)
SP_t	Spill from the reservoir at time (t)
U_{pop}	Urban population
W_r	Women ratio in the age group (15-44) population
Y_{ai}	Actual yield of crop i
Y_{mi}	Maximum possible yield of crop i
η	Turbine efficiency
η_{irr}	Irrigation method efficiency
η_{net}	Drinking water network efficiency
ΔS_t	Change in storage
γ	Specific weight of water

CHAPTER ONE: AIMS AND OBJECTIVES

1.1 Introduction

Global water, food and energy demands are projected to increase by over 50% between 2015 and 2050 (FAO 2014; Ferroukhi et al. 2015). The growing pressure on our limited resources increases the competition among the resources that may cause conflicts among resources, livelihood and environment. Water, food and energy are essential resources on which we rely to achieve our social, economic and environmental goals. The three domains are interlinked in different ways and the action in one sector would not only affect that sector but also impact other sectors (Lawford et al. 2013; FAO 2014). From a food production perspective, water and energy are inputs, while from an energy perspective water and biomass, e.g., biofuels, are resource requirements. Considerable energy is required for irrigation especially for groundwater pumping, as well as in the production of agricultural fertilisers. Thermal power stations and fossil fuel extraction require water and can cause serious environmental pollution. According to FAO (2014), the Water, Food and Energy (WFE) nexus is a useful concept that addresses the interdependency of natural resources, on which we depend to achieve socio-economic and environmental goals. The WFE nexus approach focuses on overall system efficiency rather than the productivity of the individual sectors, which strengthens the collaboration among the resources and improves the resources management (Endo et al. 2017).

Achieving the WFE nexus balance and improving long-term sustainability through policy interventions is particularly challenging in a transboundary river basin, because of the nexus dynamics and inter-sectoral complexity that may cross borders (UNECE 2018). Rapid population growth, economic growth and urbanization in riparian countries increase the pressure on common shared resources in a river basin. This, in turn, induce riparian countries to maximise their own water, food and energy resources in the basin to meet the growing demands and sustain their economies (Jalilov et al. 2016). Such development plans (e.g., dams) and policies can result in basin-wide cooperation or trigger conflicts among the riparian countries. For example, large dams may have synergetic impacts, e.g., production of cheap and clean energy and providing water storage facilities for different water uses. However, dam development may also have serious implications on the downstream countries, e.g., water supply reduction (FAO 2014) or detrimental environmental impacts.

The “nexus thinking” shifts the focus from one sector-centric towards multi-centric analytical frameworks to better understand the complexity and improve the management of interlinked water, food and energy systems (Bazilian et al. 2011; de Strasser et al. 2016). Furthermore, the nexus promotes dialogue between nexus domains and interested stakeholders within and beyond national borders as in transboundary river basins (Liu et al. 2017; UNECE 2018). These make the nexus a relevant approach for managing interlinked resources and related socio-economic dynamics in transboundary river basins (Jalilov et al. 2016; Basheer et al. 2018; UNECE 2018). Despite the progress in developing qualitative tools for addressing the WFE nexus, quantitative tools are still lacking (Liu et al. 2017; Albrecht et al. 2018; Liu et al. 2018). Holistic tools and frameworks are required to assess the WFE nexus interdependencies and their interactions with other actors and drivers of change, e.g., population growth and climate change (Liu et al. 2018; Bazilian et al. 2011; Lawford et al. 2013; Liu et al. 2017). System analysis approaches have been widely applied in coupled human-water systems (Mirchi et al. 2012; Brown et al. 2015; Cai et al. 2018). Accordingly, system-based analysis approaches can be extended to address the WFE nexus complexities while considering other critical dimensions (Cai et al. 2018).

The Nile River is considered one of the most complex river systems in the world because of its unique characteristics, e.g., vast size, transboundary nature, wide variety of climatic zones and topography, low runoff and high system losses in addition to its geopolitical environment. With a length of 6700 km, the Nile is the longest river in the world whose watershed covers an area of some 3.2 million km^2. The river rises from east African highlands and stretching over eleven countries on its journey northward the Mediterranean Sea. Although large in terms of length and its importance to riparian countries, the mean annual Nile runoff is relatively small compared to major rivers in the world (84 km^3), (Sutcliffe and Parks 1999). It is distinguished from other major rivers in the world that half of its course flows through countries with no effective rainfall (Shahin 1985; Awulachew 2012).

The Nile is a transboundary river shared between Burundi, DR Congo, Egypt, Eretria, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. Population and economic projections in the Nile basin indicate continued growth (NBI 2016b). New developments across the riparian countries (e.g., the recently commissioned Merowe dam in Sudan, the TK5 dam, the Koga dam and the Fincha-Amerti-Neshe dam in Ethiopia and the Bujagali hydropower station in Uganda) are developed to meet the growing demand for water, food and energy, while also contributing to poverty alleviation and improving the livelihood in the basin (Whittington et al. 2005). The Nile River is currently challenged by rapid population growth and the prospect of a significant economic growth, which in turn have sparked development plans in the basin.

The Nile basin countries have carried out ambitious master plans to tap the resources potential in the basin to meet their growing water, food and energy demands and sustain their economies (Whittington et al. 2005; Awulachew 2012). Prefeasibility and feasibility studies for a number of planned projects (e.g., irrigation expansions and hydropower projects) have been completed with few projects currently being under construction in the riparian countries (Cervigni et al. 2015). The largest of those developments is the Grand Ethiopian Renaissance Dam (GERD), which has the potential to improve long-term sustainability through collaboration between all riparian countries, but also has caused tensions and could lead to hydro-political conflicts. However, conflicts among the riparian countries are likely to emerge without cooperation, coordination and with unilateral developments (Digna et al. 2018). Furthermore, the Nile river basin is vulnerable to climate change that is likely to add further uncertainties to the hydrologic river regime (Di Baldassarre et al. 2011; Barnes 2017). Therefore, a comprehensive approach is required to better understand the interactions between the WFE nexus interdependencies and other related dimensions, e.g., climate change, population growth and planned developments in complex river systems such as the Nile River basin. System Dynamics (SD) is a systems analysis paradigm that is suitable for addressing the nexus interdependencies since it allows for multi-sectoral analysis while considering the interlinkages among the system domains. To do so an integrated simulation model based on SD approach is developed in this work.

1.2 Aim and Objectives

The aim of this study is to improve our understanding of the nature of the nexus in river basins using a systems approach that will equip decision-makers with negotiation and policy tools for achieving cooperation among riparian countries. To achieve this broad aim, the following objectives were identified:

1. Develop an integrated framework that considers the WFE nexus interdependencies in river basins together with other related themes including climate change, planned developments, policy options, population growth and the inherent uncertainty of the hydrological river regime;
2. Develop and apply an integrated model for the entire Nile basin – as a case study – to explore the WFE nexus during GERD filling and subsequent operation;
3. Identify and investigate the impacts of policy measures on the WFE nexus at the national level in Egypt as a case study;
4. Explore the cooperation opportunities among riparian countries over planned developments in the Nile basin using the GERD as a case study;
5. Investigate the future of the WFE nexus considering climate change and planned developments in the Nile basin.

1.3 Scope

The current work can be divided into five major categories: (1) literature review, (2) developing an integrated modelling framework and the WFE nexus model for the Nile basin, (3) investigating the WFE nexus at the basin level including: (a) initial GERD filling and subsequent operation phase, (b) cooperation among riparian countries over GERD development and (c) climate change and planned developments in the basin, (4) investigating impacts of policy options on the WFE nexus at the country level and (5) conclusions. The flowchart of these categories and their interactions are shown in Figure 1.1.

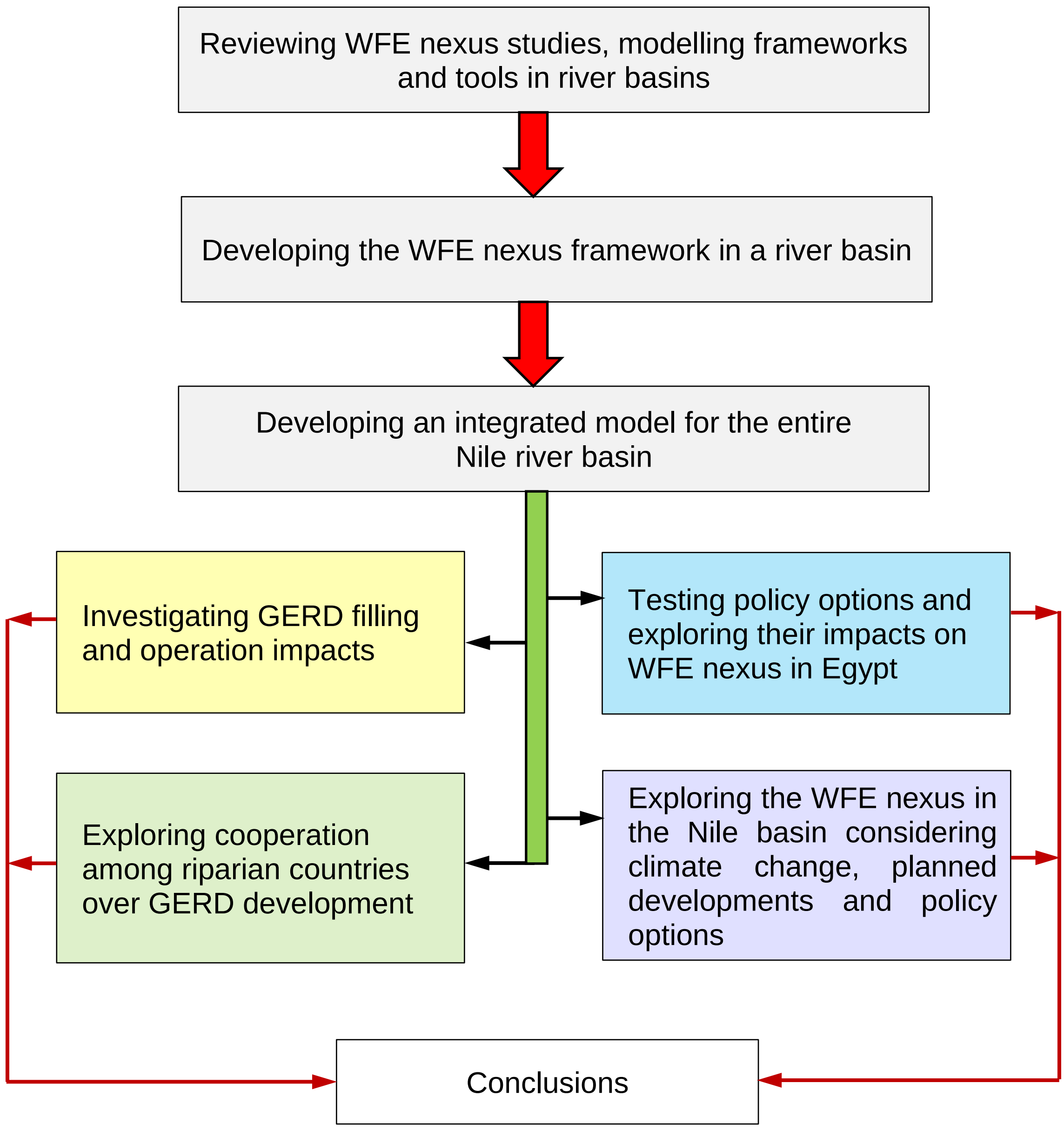


Figure 1.1 Thesis components

1.4 Thesis Outline

This thesis is presented in seven chapters and is organised as follow:

Chapter one presents the overall aim and objectives of the current study and thesis scope and outline.

Chapter two provides a comprehensive review of the literature and identifies the gaps in previous studies. The chapter contains a detailed description of the study area, i.e., the Nile River basin, and review modelling tools and approaches developed to explore the water, food and energy in the basin.

Chapter three presents the modelling framework of the WFE nexus in river basins. The chapter provides a detailed description of the integrated water resources model developed for the entire Nile basin together with a complete WFE nexus model for Egypt. The underlying structure and data requirements, model calibration and validation for each sub-model are also provided.

Chapter four presents the application of the integrated model – developed in chapter three – to explore the future of the WFE nexus in the basin during the GERD filling and operation phases using stochastic simulation and assuming that the current WFE nexus management policies in the basin stay unchanged. The impacts of GERD development on riparian countries (i.e., Egypt, Ethiopia and Sudan) are presented and discussed through the chapter. Potential applications of the developed model are discussed, e.g., investigating means of cooperation among riparian countries over GERD and addressing the WFE nexus in river basins considering climate change and planned developments. The potential of the modelling framework to be integrated with real-time streamflow forecasting tools to inform dynamic filling strategies is also highlighted.

Chapter five discusses the impacts of policy options on the WFE nexus at the national level. An example from Egypt is presented to show the impacts of implementing individual and combined policies on the WFE nexus. Different policy options were considered such as improving irrigation efficiency, achieving land productivity and utilizing water resources potentials. The potential of each policy measure is also highlighted.

Chapter five tests cooperation among riparian countries over new development. The cooperation concept was applied to the case of GERD development following the completion of the first impounding and explores the regional trade-off and synergies associated with the cooperation among Egypt, Ethiopia and Sudan. Furthermore, different scenarios were considered under different settings in the riparian countries, e.g., water demands in Egypt, operation of Sudanese reservoirs together with GERD operation modes.

Chapter seven presents the application of the integrated model to explore the future of the WFE nexus in the Nile basin considering planned developments, climate change and policy options in the basin. The WFE nexus – at the basin and the national level – is assessed under different developments scenarios with and without climate change using basin-wide stochastically generated river flows.

Chapter eight presents the key findings of this study, contribution to the knowledge and gives recommendations for future work.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Water, food and energy are essential resources on which we rely to achieve our social, economic and environmental goals. Despite substantial development in water, food and energy security over the past fifty years yet, there is an inequitable distribution of the resources at global and local levels. Over the next decades, the demands for water, food and energy are expected to increase under a number of pressures such as population growth, economic development, changes in living standards, urbanisation, and climate change (Hoff 2011). The global water, food and energy demands are projected to increase by over 50% by 2050 (FAO 2014; Ferroukhi et al. 2015). The growing pressure on our limited resources increases the competition among the resources and may cause potential conflicts among these resources, livelihood and environment.

The water, food and energy are inextricably interlinked, and their interlinkages are well documented (Bazilian et al. 2011; Hoff 2011; Lawford et al. 2013; FAO 2014). From this perspective, the WFE nexus concept has emerged as an integrated approach that recognises the interdependencies and interlinkages among the three domains (Hoff 2011). The WFE nexus considers the different dimensions of water, food and energy components equally (FAO 2014) and provides a transparent framework for investigating trade-offs and synergies among the resources, without compromising sustainability. Also, the nexus could assist in unveiling the unforeseen consequences (Liu et al. 2018). The WFE nexus approach focuses on overall system efficiency rather than the productivity of the individual sectors, which strengthens the collaboration among the resources and improves the resources management (Endo et al. 2017).

The WFE nexus interlinkages are shown in Figure 2.1. The water resources sector includes surface water, groundwater, water desalination, rainfall, agricultural drainage water reuse and treated wastewater. Also, the water demands may be included, e.g., municipal, agricultural and environmental water demands. The food sector may involve land-based agricultural, livestock, fisheries and aquaculture production and demands as well. The energy sector

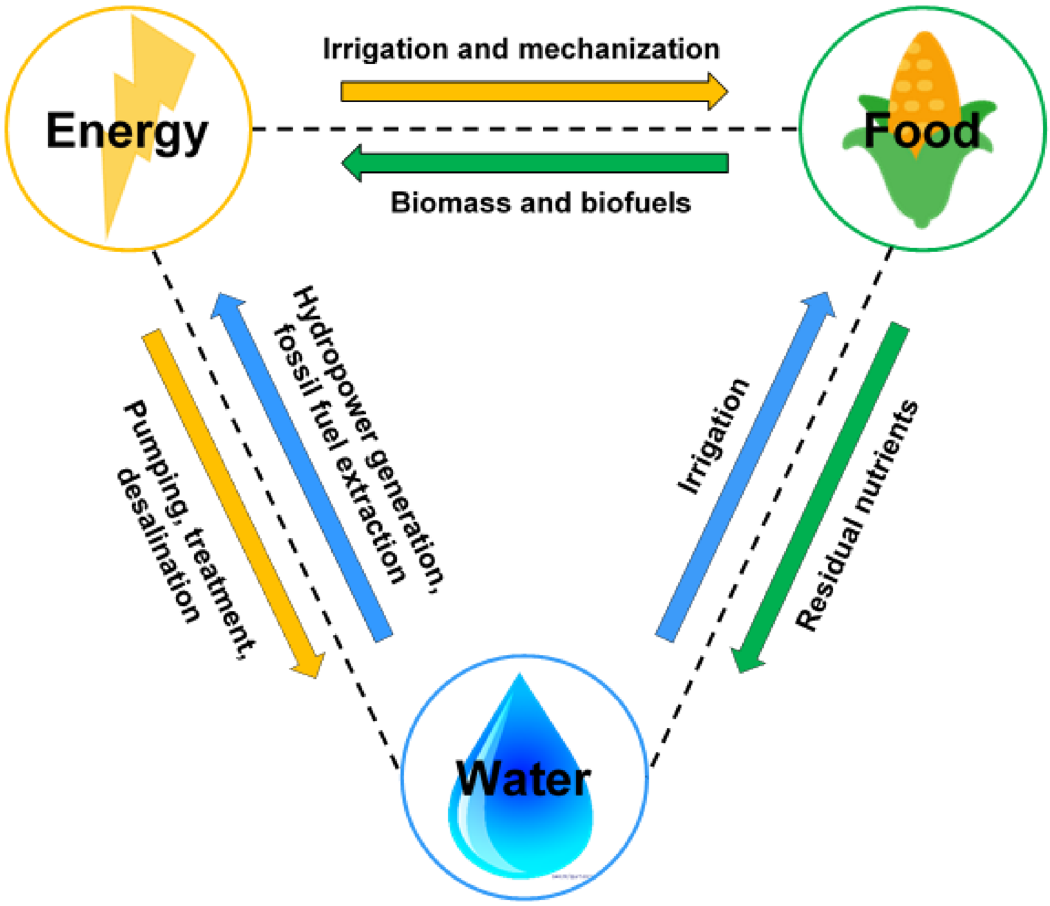


Figure 2.1 The Water, Food and Energy nexus interactions

may include a different range of energy supplies, e.g., fossil fuels, natural gas, hydropower, wind and solar panels. From a food production perspective, water and energy are inputs, while from an energy perspective water and biomass, e.g., biofuels, are resource inputs. Considerable energy is required for irrigation especially in groundwater pumping (water-energy nexus), as well as in the production of agricultural fertilizers (food-energy nexus). Domestic water supply and wastewater treatment require significant amounts of energy (water-energy nexus). Thermal power stations and fossil fuel extraction require water and can cause serious environmental pollution (water-energy nexus). Despite the advancement in the bioenergy sector, it could increase water scarcity and cause a food crisis through the competition with food crops (food-energy nexus) (Liu et al. 2018; Zhang et al. 2018). Water quality can be significantly impacted by food and energy systems activities. For instance, pollutants from on-farm practices such as fertilizer applications and pesticide use, and post-farm activities, e.g., food processing, can cause serious impacts on water quality in downstream environments. Energy production, e.g., fossil fuel and biofuel production, not only affect water withdrawals but have caused serious environmental problems, e.g., wastewater disposal. Therefore, the dynamic interactions among the nexus components call for integrated approaches that consider the interdependencies and address synergies and trade-offs among nexus components. Considering the three domains equally internalizes the driving forces that might be overlooked in dual-sector approaches (Albrecht et al. 2018).

Several frameworks have been developed and applied to understand the complex interlinkages among the nexus components and they are varied in their scope, scale, tools used, and drivers of change (FAO 2014; Keskinen et al. 2016; Liu et al. 2018; Zhang et al. 2018). Keskinen et al. (2016) argue that the nexus can serve as an analytical approach, a governance framework and an emerging discourse. As an analytical approach, quantitative and/or qualitative methods were used to understand the nexus, however, the nexus has remained in the conceptual domain (Albrecht et al. 2018). As a governance framework, the nexus promotes cross-sectoral integration, policy coherence and resource use efficiency. While as a discourse, the nexus aims to maximise the synergies and minimise trade-offs among the resources. However, there is less development in analytical approaches compared to conceptual approaches for understanding the nexus complexity (Foran 2015). There is a need for integrated analytical approaches that analyse and understand the three-pronged nexus interdependencies (Albrecht et al. 2018).

A large number of nexus studies has focused on the dual interactions between the nexus domains, e.g., water-energy nexus (Hussey and Pittock 2012; Zhuang 2014; De Stercke et al. 2018), water-food nexus (Kumar et al. 2012), and food-energy nexus (Karimi et al. 2012). The WFE nexus studies are increasingly growing (Daher and Mohtar 2015; Keskinen et al. 2016; Pittock et al. 2016; UNECE 2018; Yang et al. 2018; Allam and Eltahir 2019; Bakhshianlamouki et al. 2019 to name but a few). Moreover, nexus studies may include extra dimension(s), e.g., climate, land, ecosystems and human health (Beck and Villarroel Walker 2013; Liu et al. 2018). On the other hand, the geographic scale of the nexus application varied from city, national, transboundary to global scale (Liu et al. 2018; Zhang et al. 2018). The scale of the problem, research aims, and the local context (e.g., climate and resource demand) influence the level of the details (i.e., data aggregation vs detailed sector), tools to be utilised in the nexus application (Albrecht et al. 2018; Zhang et al. 2018). The nexus perspectives to address challenges, reduce unintended consequences, and promote policy coherence among the resources, makes the nexus approach relevant to address and analyse complex interactions of the water, food and energy in river basins (Lawford et al. 2013; Jalilov et al. 2016; UNECE 2018).

This chapter is organised under six major headings: (1) Introduction, (2) Water, food, and energy nexus in river basins, (3) Study area description, (4) Review of previous studies in the Nile basin, (5) Modelling approaches and (6) Discussions.

2.2 Water, Food and Energy Nexus in River Basins

In the context of a transboundary river, achieving the WFE nexus balance through policy interventions is challenging because of the nexus dynamics and inter-sectoral complexity and interlinkages that occur on large scales and may cross borders (de Strasser et al. 2016; Jalilov et al. 2016; Keskinen et al. 2016; UNECE 2018). Rapid population growth, economic growth, and urbanization in riparian countries increase the pressure on common shared resources in a river basin. Under these pressures, each country aims at maximizing its own resources to meet the growing water, food and energy demands. Such developments and policies in riparian countries, often uncoordinated, could result in basin-wide cooperation or trigger conflicts among the riparian countries (Lawford et al. 2013; Endo et al. 2015; Kibaroglu and Gürsoy 2015; de Strasser et al. 2016; Jalilov et al. 2016). For example, large dams may have synergetic impacts, e.g., production of clean and cheap hydropower energy and providing water storage facilities for different water uses. However, dam development may also have serious implications on the downstream countries, e.g., water supply reduction (FAO 2014) or detrimental environmental impacts.

In order to effectively manage and share the benefits of transboundary river basin resources, the cross-sectoral and transboundary interconnectedness needs to be addressed and understood in a broader perspective (Liu et al. 2018). Moreover, policy coherence is required not only within the national borders but across borders as well (de Strasser et al. 2016). The nexus approach provides a common ground to address and better understand the dynamic interdependencies and complexities among the water, food and energy in a transboundary river basin. Furthermore, the approach can address the trade-offs between the competing riparian stakeholders for the water, food and energy resources and enhance the understanding of shared benefits and cross-sectoral developments in the basin (Lawford et al. 2013; Endo et al. 2015; de Strasser et al. 2016; UNECE 2018).

Going beyond the well-known and internationally recognised Integrated Water Resources Management (IWRM) approach, the nexus view calls for multi-sectoral and holistic integration and coordination among the different sectors rather than being water-centric (Benson et al. 2015; Keskinen and Varis 2016). The nexus approach promotes resources security rather than demand management for achieving sustainable development, unlike the IWRM approach (Benson et al. 2015). That makes the nexus a relevant approach for addressing the broader interdependency and dynamic feedbacks among the nexus domains, coordinating and managing interlinked resources and development plans in river basins (e.g., hydropower, irrigation expansion) (Kibaroglu and Gürsoy 2015; de Strasser et al. 2016; Jalilov et al. 2016; Yang et al. 2016c; Basheer et al. 2018; UNECE 2018).

The tight connections among the water, food and energy have been investigated in a number of river systems across the world. Examples include the Amu Darya River system (Jalilov et al. 2016), the Brahmaputra River system (Yang et al. 2016b), the Indus River system (Yang et al. 2016a), the Mekong River basin (Keskinen et al. 2015; Pittock et al. 2016; Khan et al. 2017), the Niger River system (Khan et al. 2017; Yang et al. 2018), and the Nile River system (Basheer et al. 2018; Allam and Eltahir 2019). Guillaume et al. (2015) investigated the historical WFE nexus in Central Asia using a global water model during the 20th century and provided transferable principles to facilitate the nexus implementation. They showed that the inclusion/exclusion of subsystems (e.g., non-food crops) is case-specific and should be carefully recognised when implementing the nexus studies. Also, the acceptable limits of crossing the system boundaries, e.g., trade-off within the nexus should be fully understood and defined as the system dependencies could be modified when the boundaries are crossed. However, their approach was a water-centric (i.e., food and energy were considered as water users), utilised global modelled data, and the inter-annual storage variations were not considered.

Khan et al. (2017) developed a generalised agent-based modelling (ABM) framework by coupling Soil & Water Assessment Tool (SWAT) model with a water resources system model and called (ABM-SWAT). ABM-SWAT used to analyse the impacts of water agent’s management decisions on the food-water-energy-environment nexus at the basin level. The developed model was applied to two transboundary rivers basin: (a) the Niger River basin (shared between Benin, Guinea, Mali, Niger and Nigeria) and the Mekong river basin (shared between Cambodia, China, Laos, Myanmar, Thailand and Vietnam). The model showed its ability to capture the interactions between the water agents and the nexus. However, the future uncertainty in river hydrology was not considered, as the observed climate data were used in their analysis. The framework cannot capture the dynamics of water agents at fine time-step (e.g., monthly or daily) as the coupled models exchange information at annual time-step. Furthermore, the tool is computationally demanding and the difficulty in characterizing human decisions and replicating the behaviour of real-world management limits its application (Hyun et al. 2019).

Yang et al. (2018) assessed the impacts of climate change and socioeconomic developments on the water availability for water-food-energy-ecosystem nexus in the entire Niger basin using the ABM-SWAT modelling framework developed by Khan et al. (2017). A set of generic metrics (e.g., reliability, resilience, and vulnerability) were used to analyse the basin-wide sustainability and trade-off among the nexus sectors. It was concluded that the crop production was sensitive to the temperature changes, while hydropower generation and the river ecosystem health were sensitive to precipitation and dam development in the basin. However, the adopted sustainability metrics are limited to the use of the current population, production levels, the annual time step and the long-term average historical hydrological data. Moreover, the study fails to address the dynamic feedbacks and interlinkages among the nexus domains.

Jalilov et al. (2016) developed a hydro-economic optimization model to investigate the WFE nexus in the Amu Darya basin (Shared by Afghanistan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) under the planned Rogun Dam in Tajikistan. The model maximises the net present value across the water users in the Amu Darya basin. Two potential operation scenarios of the dam were examined: energy mode (to satisfy upstream hydropower demands) and irrigation mode (to satisfy downstream irrigation demands). The study provided insights into the benefits and risks to the WFE nexus in the riparian countries under the different operation modes of the dam. For example, the energy mode would double the energy capacity in Tajikistan (an upstream country) but could reduce the agricultural benefits in the downstream countries by 37% on average. Interestingly, none of the two operation modes would simultaneously benefit all the riparian countries from WFE nexus perspective. The latter reflects the challenges of managing the nexus, stresses the potential of trade-offs and promotes the synergies of such new developments in river basins. However, the study used simplified assumptions and simplifications regarding crop areas, crop yields, crop water demands, river flows and model constraints. Such assumptions might impact outcomes and underrepresent the nexus complexities. Moreover, the dynamic feedbacks among the WFE and socio-economic dynamics and the uncertainty in future river flows were not considered.

Yang et al. (2016b) developed a hydro-economic model to investigate the WFE nexus and inform policy-making under climate change and future developments in the Brahmaputra river basin, South Asia. The model optimises the net economic benefits from optimum water allocation in the basin. Results suggest that the combined uncertainty of climate change and upstream diversions would significantly affect the water, food and energy in the basin. For instance, reduction in precipitation and large upstream diversions could substantially impact water supplies, food production and hydropower generation in more than one downstream country. The modelling framework is generic and can be broadly applied in different river basins. However, the framework is bounded by limitations regarding approach and data, e.g., the use of simplified assumptions and thresholds, inherent uncertainty and requirement of large data.

Furthermore, the impacts of population growth on the water, food, and energy were not considered in the modelling framework.

Pittock et al. (2016) developed a conceptual model to analyse the hydropower-food nexus in the Mekong River basin using causal loop diagrams. The developed model can capture the interdependencies among the system components. Also, the model showed the impact of change in one sector or variable on other sectors in the basin (e.g., the impact of the hydropower development on fish production). The study offers a nexus dialogue and identifies different alternatives to minimise trade-offs and maximise benefits (e.g., non-hydropower renewables have the potential to conserve fish population and forest cover). However, the study lacks quantitative analysis of the nexus interactions and the effects of interventions in different sectors on the nexus.

Another class of studies that use mixed approaches and gives a holistic view are developed to implement and analyse the WFE nexus in transboundary river basins through stakeholder engagement (Albrecht et al. 2018). For example, the Transboundary River Basin Nexus Approach (TRBNA) is an integrated approach developed by the United Nations Economic Commission for Europe (UNECE). TRBNA was developed to promote cooperation and assess riparian countries to identify trade-offs and synergies across sectors through nexus assessment in a series of selected river basins. TRBNA employs both qualitative and quantitative methods (e.g., questionnaires, indicators, resource flows, and demographic data analysis). TRBNA has six consecutive steps as follow; (1) characterise the socio-economic and geographical context of the basin, (2) identify key sectors and actors, (3) analyse key sectors, (4) analyse inter-sectoral issues, (5) nexus dialogue, (6) solutions and benefits.

de Strasser et al. (2016) applied TRBNA methodology in three transboundary river basins; Alazani/Ganykh, the Sava and the Syr Darya river basins. They showed that TRBNA has the potential to serve as a flexible and pragmatic tool to implement the nexus approach in transboundary river basins. Moreover, they stressed that the nexus approach can address the broader interdependencies and increase the cooperation opportunities among the nexus domains compared to traditional approaches, such as IWRM. However, the methodology has limitations, e.g., the use of ambiguous definitions and inconsistent indicators. Also, the approach is water-centric and underestimates the other nexus linkages (e.g., food-energy).

The number of nexus studies conducted in river basins is growing and various modelling frameworks were developed to understand and analyse the cross-sectoral interdependencies of the nexus in river basins, particularly transboundary river basins. The developed frameworks ranged from integrated, coupled, to quantitative and/or qualitative methods (see Table 2.1). However, there is no unified framework to understand and evaluate the inherent complexity and interdependency among the nexus domains. The above-reviewed studies gave valuable insights into the water, food and energy interlinkages in watersheds under different settings, e.g., historical or in the future with and without climate change, and socio-economic developments (e.g., new dams and water diversions). However, these studies failed to address the dynamic feedbacks among the nexus domains and the socio-economic impacts on the nexus due to limitations in the methods used or computational capacity.

Table 2.1 Modelling tools and approaches used to assess the WFE nexus in transboundary river basins

Method type	Model	Source
Quantitative and qualitative	WaterGAP model data Historical data analysis	Guillaume et al. (2015)
Quantitative	Agent-based modelling (ABM-SWAT model)	Khan et al. (2017), Yang et al. (2018)
Quantitative	Hydro-economic model	Jalilov et al. (2016) Yang et al. (2016b)
Qualitative	Conceptual model, Causal loop diagrams	Pittock et al. (2016)
Quantitative and qualitative	Transboundary River Basin Nexus Approach (TRBNA)	de Strasser et al. (2016), UNECE (2018)

For instance, most of the previous studies apply loose coupling frameworks, a multi-model integration approach that is commonly used in performing nexus analysis (Liu et al. 2017). Such an approach fails to adequately capture the feedbacks among the nexus sectors (Liu et al. 2017). Another important dimension related to the nexus is the inclusion of population growth projections when quantifying the nexus, which have not been considered in most of the previous studies as in Yang et al. (2016a) and Yang et al. (2018) for example. Also, previous studies were bounded by the inherent uncertainties of the employed models (Zhang et al. 2018) and the use of simplified assumptions. For example, Räsänen et al. (2015) used simplified operation rules for reservoirs and Jalilov et al. (2016) considered simple assumptions for the crop water use and river flows and excluded groundwater consumption in irrigation. The long-term uncertainty associated with future river flows has been rarely addressed and the average historical river flows were used instead. In this regard, the Nile is a transboundary river in north-eastern Africa, shared among 11 countries that lacks comprehensive water, food and energy nexus studies.

The above-mentioned gaps in the literature will be addressed through the application of a WFE nexus framework that captures the socio-economic dynamics and the WFE nexus interlinkages in the Nile river basin, addresses the future of the WFE nexus in the Nile basin with and without climate change and new developments (e.g., dams and irrigation expansions) in the riparian countries. The next section gives an overview of the Nile river basin and comprehensive review of the previous studies conducted across the basin.

2.3 Study Area Description

The River Nile is considered the longest river in the world with a length of about 6,700 km. The River Nile extends from its remote source at the head of the river Luvironza (near Lake Tanganyika, Burundi) to its mouth on the Mediterranean Sea. The Nile basin in its present situation covers a drainage area of about $3.2x10^6$ km^2. The basin extends from 4°S to 31°N latitude and from 21° 30'E to 40° 30'E longitude. The highest point in the basin located at the top of the Ruwenzori Mountain range (DR Congo), with an elevation of 5,120 m (a.m.s.l), while the lowest point in the basin located in the trough of the Quattarah depression (Egypt), with an elevation of 159 m below mean sea level (b.m.s.l.).

The Nile is a transboundary river shared between 11 riparian countries, Burundi, DR Congo, Egypt, Eretria, Ethiopia, Kenya, Rwanda, South Sudan,

Sudan, Tanzania, and Uganda. The river considered one of the most complex rivers because of its transboundary nature, its size, a variety of climates and topographies and the high system losses in addition to its geopolitical environment (Howell and Allan 1994; Sutcliffe and Parks 1999; Awulachew 2012). Although large in terms of length and its importance to riparian countries, the mean annual Nile runoff is relatively small compared to major rivers in the world (84 km^3). It is distinguished from other major rivers in the world that half of its course runs through countries with no effective rainfall. The Nile water almost generated from areas covering about 20% of the basin, while the rest of the basin is arid or semi-arid regions at which the water supply is small and the water losses (i.e., evaporation and seepage) are high (Shahin 1985; Howell and Allan 1994; Karyabwite 2000). The Nile originates from two main tributaries, the White Nile, and the Blue Nile, Figure 2.2. The White Nile originates from the equatorial lakes plateau, while the Blue Nile originates from the Ethiopian highlands. The Main Nile is formed by the confluence of the White Nile and the Blue Nile at Khartoum, Sudan and continue its journey to the Mediterranean Sea near Cairo, Figure 2.2.

2.3.1 The White Nile

The White Nile starts at the equatorial lakes' region. River Kagera is the farthest tributary of the White Nile and drains mountains regions in Rwanda, Burundi, Tanzania and Uganda into Lake Victoria with an average annual rainfall of about 1800 mm. Other tributaries of Lake Victoria contribute to about double the amount of Kagera inflows. The two rainy seasons over Lake Victoria are linked to the migration of InterTropical Convergence Zone (ITCZ). The main rainy season lasts from March to May and the second rainy season falls between October and December. The direct rainfall over the lake surface is a major component of the lake water balance and contributes about 85% of the total lake inflows (Sutcliffe and Parks 1999). The upper Victoria Nile is considered the only outlet of Lake Victoria and was controlled naturally by Ripon falls in the past. Since 1953, it is controlled by Owen Falls Dam (now Nalubaale power plant). The dam is operated according to an international agreement that is fundamentally based on an Agreed Curve between the interested parties (Tate et al. 2001). The mean annual lake discharge is about 23.50 km^3 (Sutcliffe and Parks 1999). It is worth mentioning here that there was a sudden increase in the rainfall over the lake basin during the period (1961-1964). This led to a sudden rise in the lake levels of about 2.50 m and the lake outflows as well.

The outflows from Lake Victoria are modified by the passage through Lake Kyoga and Lake Albert. Lake Kyoga is a net contributor during wet periods and a net loss in dry periods. Lake Kyoga outflow runs through rapids and falls culminating in the Murchison falls and swamps before entering Lake Albert. Lake

Figure 2.2 The Nile River basin adapted from NBI (2012)

Albert receives flows from Semiliki River that drains Lake Edward and Lake George basins. The rainfall regime over Lake Kyoga and Lake Albert basins is in between the bimodal rainfall of Lake Victoria and the unimodal rainfall of South Sudan. Lake Albert outflows run northeast toward Nimule in a flat reach and surrounded by swamps (Sutcliffe and Parks 1999).

Downstream Lake Albert the river called Bahr ElJebel. Downstream Nimule the River turns to the north-west until reaches Mongalla through a steeper reach and rocky rapids. The River flows at Mongalla are composed of outflows from Equatorial Lakes and torrential flows that occur during the rainy season in the reach between Lake Albert outlet and Mongalla. Downstream from Mongalla, Bahr ElJebel enters the Sudd region, huge swamps and seasonally flooded area. Within the Sudd, the river channels have capacities less than the high flows and excess flows spill over the river banks and inundate the adjacent swamps and floodplains. The net evaporation from the flooded area is very high, while evaporation and transpiration losses from the swamps are high. As a result, the outflows from the Sudd swamps have little seasonal variations with an annual outflow approximately half the Sudd inflows. Bahr El-Jebel is divided into two main channels downstream Bor as follows: Bahr El-Jebel and Bahr El-Zaraf that joins the White Nile at 80 km from Lake No. About 30 % of annual Sudd inflows enters Bahr el-Zaraf and the rest remains in Bahr El-Jebel (Howell and Allan 1994; Sutcliffe and Parks 1999).

Bahr El-Ghazal has a large basin area and receives the highest rainfall in Sudan. However, its contribution to the river flows is negligible. A huge volume of its water is lost through the evaporation from its permanent and seasonal swamps. Bahr El-Ghazal drains into Lake No from the west. Downstream Lake No, the river turns to the east and called the White Nile. At Malakal, located short distance downstream Lake No, the Sobat River joins the White Nile from the east.

The Sobat River provides about half of the White Nile flow (i.e., the Sobat runoff is almost equal to the Sudd outflows). Also, the river is responsible for the White Nile seasonality due to the lack of storage in the basin. The Sobat River has two main tributaries: the Baro and the Pibor River. The Baro River drains the south-eastern part of the Ethiopian highlands above Gambella and receives flows from tributaries upstream the Baro-Pibor junction. The Pibor River drains the southern part of Baro (i.e., through Akobo and Gila tributaries) and a large area of the plains east of Bahr El-Jebel but with runoff is likely to be small in most of the years due to low rainfall. A significant proportion of Baro high flows is lost through channel spills or overbank spilling. Spills from Baro to the south wetlands (called swampy Khors) return to the river through channels that flow into Pibor above the Baro-Pibor confluence.

The Machar marshes are the major wetland in the Sobat basin and located to the north of Baro. The marshes receive inflows from several tributaries north Baro, in addition to overbank spill from the Baro River. The Baro spills into the Machar marshes return to the White Nile and Sobat River but in small amounts. Downstream the Baro-Pibor confluence, small seasonal tributaries join the Sobat River. The Baro River has a tendency of two rainy seasons with 1300 mm at Gambella between April and October. While the Pibor basin has lower rainfall with an average of 950 mm over the same months, but the rainfall over the plain is just 800mm (Sutcliffe and Parks 1999; Karyabwite 2000).

The White Nile downstream Malakal to its confluence with the Blue Nile is relatively simple with a well-defined channel and a mild slope. The White Nile receives only significant amounts of water during the exceptional conditions in Machar marshes. In this reach, the river is subjected to evaporation losses and delays resulted from flood plain storages. Upstream the White Nile and the Blue Nile confluence, Jebel Aulia Dam regulates the White Nile flows. The average annual discharge of the White Nile at Malakal is estimated to be about 28.50 km^3 (Shahin 1985; Howell and Allan 1994; Tate et al. 2001).

2.3.2 The Blue Nile

The Blue Nile or the Abay River as it is called in the Ethiopian lands originates from the Ethiopian highlands in the region of west Gojam. The river contributes about 60% of the Main Nile flows. The river drains a major part of the western Ethiopian highlands and a small part of these highlands is subjected to storage through Lake Tana. Lake Tana has many tributaries such as Gilgel Abay and located at elevation 1800 m (a.m.s.l) with a surface area 3000 km^2. The Blue Nile leaves the southern corner of Lake Tana through a series of cataracts. Then the river runs south-west, before looping back on itself, flowing west and then turning north-west near the Sudanese borders.

The Blue Nile in the Ethiopian region receives major tributaries such as Beshilo, Muger, Guder, Fincha, Anger, Didessa, Dabus, Beles. Didessa and Dabus contribute about a third of the total river flow (Sutcliffe and Parks 1999; Tate et al. 2001; McCartney et al. 2012). The river enters Sudan at an elevation of 490 m (a.m.s.l). and the average slope of the river from the Ethiopian borders to Khartoum is about 15cm/km. Inside Sudan, the Blue Nile receives two major tributaries: the Rahad and the Dinder. The two tributaries originate from Ethiopia and have shorter runoff season. At Khartoum, the Blue Nile joins the White Nile at an elevation of 400 m (a.m.s.l) and forms the main stem of the Main Nile.

The rainfall across the Blue Nile basin is characterised by a significant variability with the altitude. The rainfall is governed by the movement of air masses associated with ITCZ from south to north and back, therefore the rainfall duration decreases from south to north. The Blue Nile basin is confined to a single rainy season (July-October), unlike the White Nile basin. The rainfall decreases while the evaporation increases as the river flows from the highlands to the northern parts of the basin. The average rainfall in the upper parts of Ethiopia ranges from 1400 to 1800 mm/yr and exceeds 2000 mm/yr in some regions in the south. Near the Ethiopian-Sudanese borders, the rainfall decreases and reaches of 1000 mm/yr on average. Inside Sudan, the rainfall reaches an average of 500 mm/yr and at Khartoum, is estimated to be 140 mm/yr (McCartney et al. 2012). Likewise, the potential evapotranspiration varies significantly with the altitude. In the Sudanese territory, the annual potential evapotranspiration is estimated to be about 2200 mm, but during the wet season, the rainfall hardly exceeds half of the potential evapotranspiration. In Ethiopia, the annual potential evapotranspiration ranges from 1300 to 1700 mm and is less than rainfall in the wet season (McCartney et al. 2012). The Blue Nile flows are characterised by great seasonality and inter-annual variability. About 80% of the river flows occur during the wet season (July-October). The long-term average annual discharge of the Blue Nile at the Diem gauge station, near the Ethiopian-Sudanese borders, is estimated at 48.66 km^3 (Sutcliffe and Parks 1999).

2.3.3 The Main Nile and Atbara

The Blue Nile joins the White Nile at Khartoum, Sudan and forms the main Nile stem. The reach from Khartoum to Aswan is about 1885 km and receives the last major tributary in the basin, the Atbara, at 320 km below Khartoum. The main tributary of Atbara River is the Setit or Tekeze, as it is known in Ethiopia and drains areas of northern Ethiopia and Eritrea. The Atbara River is the most seasonal tributary in the Nile basin and runs dry for about 5-6 months per year. The average rainfall over Atbara basin is about 950 mm, with a rainy season shorter than the rainy season of the Rahad and the Dinder rivers (August and September). The Main Nile from Khartoum to Aswan stretches through reaches with extremely variables gradients ($1x10^{-3}$-$3.2x10^{-5}$) and separated by six cataracts (Sutcliffe and Parks 1999; Shahin 1985). Within the reach, the river runs in arid and hyper-arid regions with inconsiderable rainfall but subjected to high channel losses (e.g., evaporation and seepage losses). The first key gauge station below the Atbara confluence is Dongola where the river enters Lake Nasser or Nubia as it called in Sudan at Wadi halfa. In Egypt, the water is released from the High Aswan Dam (HAD) to meet the downstream water demands before reaching the Mediterranean sea (Sutcliffe and Parks 1999; Tate et al. 2001).

The average annual river flows, tributaries inflows, rainfall, and evaporation at key sites across the basin are shown in Figure 2.3a. Also, the average monthly flows for the Blue Nile, White Nile and Main Nile are shown in Figure 2.3b. The longitudinal bed profile of the main Nile tributaries and their elevations are shown in Figure 2.4. The longitudinal profile shows the significant variations in the riverbed gradients, which reflects the sedimentation problems especially in the Blue Nile as well as its hydropower potential.

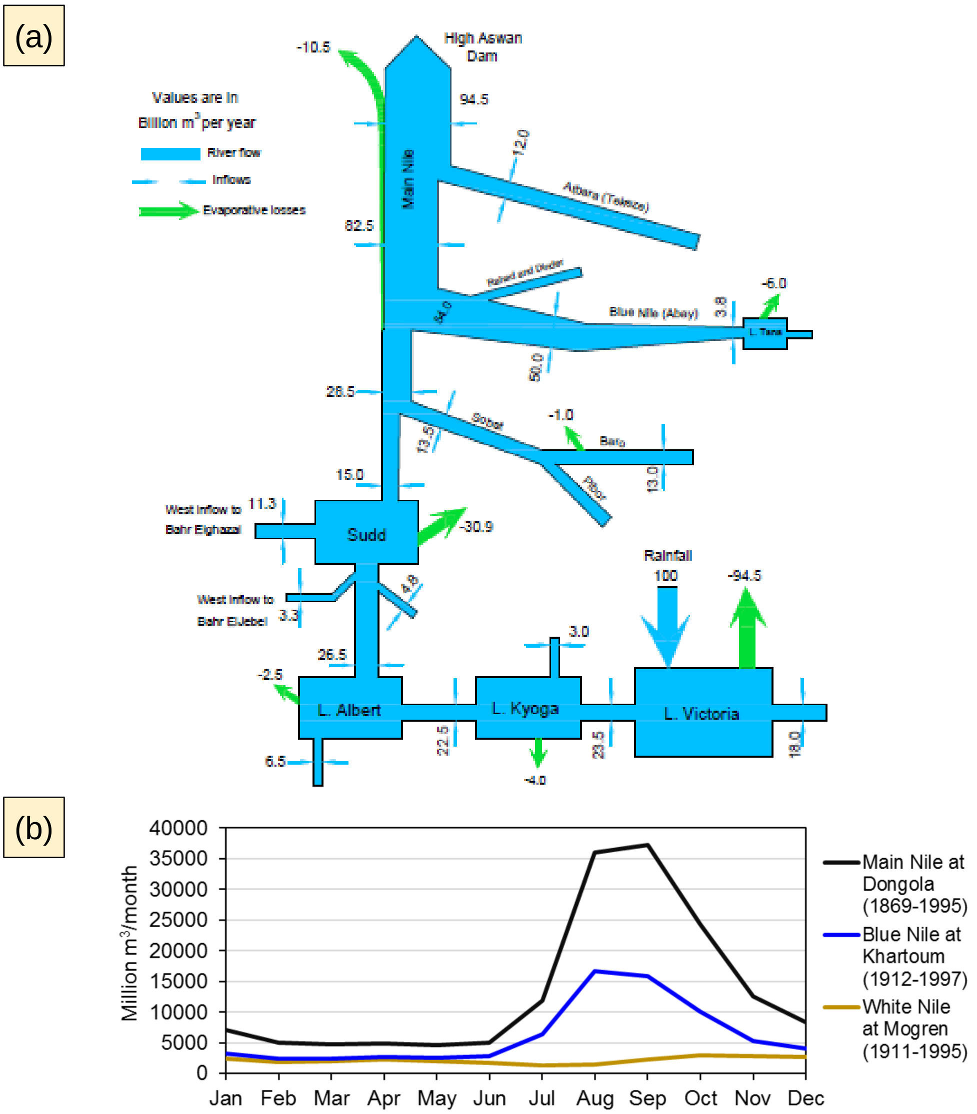


Figure 2.3 The Nile River flows: (a) annual water balance (adapted from Blackmore and Whittington 2008) and (b) average monthly flows (adapted from Sutcliffe and Parks 1999)

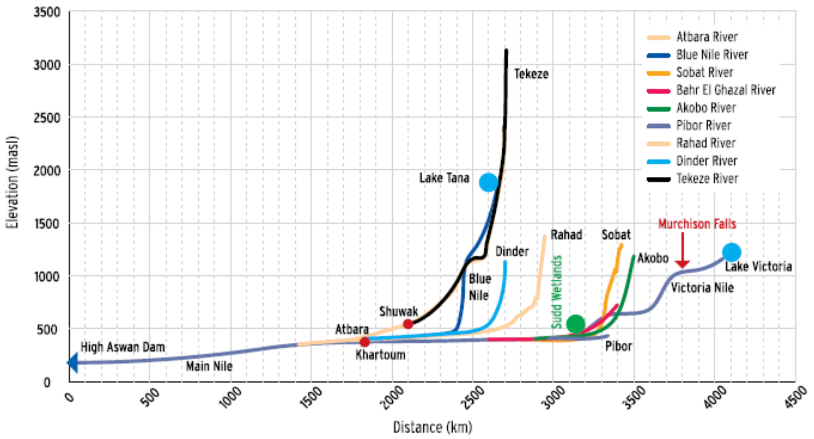


Figure 2.4 The longitudinal profile on the main river tributaries, adapted from NBI (2016b)

2.3.4 Socio-Economic Profiles of the Nile Basin Countries

The population has grown rapidly over the last five decades in the Nile basin countries as shown in Figure 2.5.a. The population increased by more than five folds between 1950 and now. In 2015, the population is estimated to be about 488 million in the riparian countries, with about 250 million people reside within the basin (NBI 2016b). The population projections in the Nile countries indicate continued population growth in the basin as shown in Figure 2.5.a. By 2050 the population is projected to grow and would reach 1,000 million in the riparian countries. Urban population is also projected to increase in the Nile countries (NBI 2016b) that is most likely to increase the pressure on the basin resources, increase demands for water, food and energy and increase the risks to environmental problems, e.g., water pollution.

The per capita Gross Domestic Production (GDP) for most of the Nile countries falls below the poverty line (695$ per year), (The World Bank 2019). However, the economic growth is currently increasing and the annual GDP growth rate ranged from 1.1 to 9.5% during the period 2013-2018, (The World Bank 2019). Ethiopia showed a relatively high growth rate of about 9.5%, while Burundi showed an average growth rate of 1.1% over the same period. Current

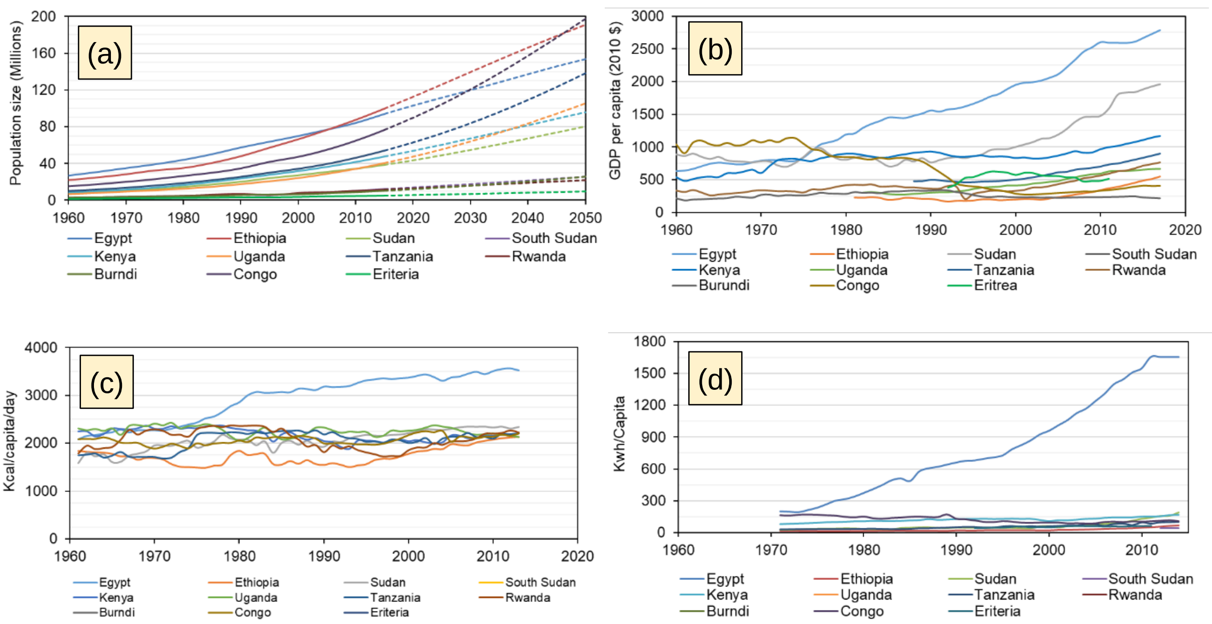


Figure 2.5 Socio-economic conditions of the Nile countries; (a) Population, (b) GDP per capita, (c) Kcal per capita per day and (d) annual electricity consumption per capita

trends in GDP growth in the Nile countries indicates the fast-growing economies of the Nile countries, as a consequence increase the pressure on the basin resources.

The adequate daily food consumption, i.e., implies the absence of undernourishment in a country, is estimated to be 3000 Kilocalories (Kcal) as a rule of thumb. Figure 2.5.c shows the daily per capita food consumption in the Nile countries is currently below 2500 Kcal, below the threshold, except Egypt which is currently about 3600 Kcal, Figure 2.5.c. The demand for food is expected to increase under continued economic growth, urbanization and population growth in the Nile basin countries. These pressures are most likely to increase the pressure on the basin resources, e.g., land, water, etc. to meet the growing food demands.

The energy consumption in the Nile basin countries is very low, except Egypt. Also, the energy consumption in the Nile countries is among the lowest in the world. The Nile countries depend on the hydropower at varying levels, for example, in Burundi, Congo (DRC), Ethiopia and Uganda, the hydropower generation contributes over 80% in their electricity generation. The electricity supply is inadequate, expensive and lacks reliable infrastructure across the basin except for Egypt. The electrification rate, population ratio with access to electricity, is also low in the Nile countries. The electrification rate in the Nile countries, in 2017, ranged from 9% in Burundi to 100% in Egypt (The World Bank 2019), with an average electrification rate of about 41% in the basin. The rural areas are the most regions without access to electricity, approximately 80%. However, the basin has a hydropower potential of more than 20 GW and 26% is currently exploited. The power demands in the basin are likely to increase as a result of increased socio-economic developments in the Nile countries. Planned hydropower projects are promising and economically attractive for most of the Nile countries however, such projects are likely to impact the basin resources. Also, a high level of coordination and cooperation among the riparian countries is urgent to gain wide-basin benefits from the planned projects.

2.3.5 The Nile Basin Existing Infrastructure

Across history, the Nile River is considered a vital resource for the living communities and livelihoods in the basin. Several control and storage works were constructed across the basin for utilising the Nile waters for different uses, e.g., hydropower generation and irrigation development, Figure 2.6 and Table 2.2. The Old Aswan Dam, Egypt was constructed (1902) to provide annual storage for irrigation and was heightened two times in 1912 and 1934. The completion of Sennar Dam (1925) on the Blue Nile allowed Sudan to develop the Gezira irrigation scheme - the largest irrigation scheme in the world. While Jebel Aulia Dam (1937) was built on the White Nile, just South Khartoum, to store the White Nile flows and provide “timely flows” for Egypt during the high demand season (i.e., in the summer) and when the Blue Nile flows are low. However, the timely flows are no longer significant to Egypt after the construction of HAD and the Jebel Aulia Dam is currently operated for Sudan exclusively.

In Uganda, the Owen Falls Dam (1953) – currently known as Nalubaale power station – was constructed for hydropower generation and provide additional storage to Lake Victoria. Following the negotiations between Egypt and the British government (on behalf of Uganda, Kenya and Tanzania) it was concluded that the dam would be operated according to the so-called “Agreed Curve”. The Agreed Curve was derived from the natural relationship between the lake levels and outflows, thus allowing the dam to release flows analogous to the natural flows of Lake Victoria on a monthly basis at least (Howell and Allan 1994; Sutcliffe and Parks 1999).

The 1959 Agreement for full utilisation of the Nile waters between Egypt and Sudan resulted in the construction of: the Roseires Dam (1966) on the Blue Nile, Khashm El Girba Dam (1964) on Atbara River in Sudan and the High Aswan Dam (1971) in Egypt. The 1959 Agreement was based on the long-term average annual Nile flows (84 km^3) at Aswan. According to the agreements the Nile water was allocated as follows: (55.5 km^3) for Egypt, (18.5 km^3) for Sudan and (10 km^3) were assumed to be lost by evaporation and seepage from Lake Nasser (Shahin 1985; Howell and Allan 1994). Also, additional water from upstream conservation projects should be equally shared between Egypt and Sudan. The construction of the Roseires Dam allowed Sudan to further expand the Gezira scheme. It is worth mentioning here the idea of HAD arose from the Equatorial Nile Project that aimed at storing water in the East African lakes to reduce the effect of low flow years and provide “timely flows” (i.e., over year storage) (Sutcliffe and Parks 1999). However, the wide-basin agreement was required for this project. The construction of HAD offered an alternative to the Equatorial Nile Project and provided over-year storage capabilities to Egypt.

Figure 2.6 Existing infrastructure in the Nile basin adapted from NBI (2012)

In Ethiopia, Fincha Dam (1971) was built for hydropower generation and irrigation supply. Recently, Alwero Dam (1995) in the Sobat River basin and Koga Dam (2012) in Lake Tana basin were built for irrigation purposes. Amerti-Neshe Dam (2012) in the Blue Nile basin was also built for hydropower generation and irrigation supply. Chara-Chara weir (2000) on Lake Tana outlet, Tis Abay hydropower plant on the Blue Nile (2001), Tana Beles diversion (2010), and TK5 (2009) on Atbara River were constructed for hydropower generation. Recently in Sudan, Merowe Dam (2009) on the Main Nile was built for hydropower generation while Upper Atbara and Setit Dam Complex (2016) on Atbara River was built for hydropower generation, domestic and irrigation water supply. In Uganda, Bujagali (2012), Ismba (2019) hydropower plants were commissioned recently.

A number of ongoing projects are also under construction in the basin. The Grand Ethiopian Renaissance Dam (GERD) is under construction in Ethiopia, located on the Blue Nile near the Ethiopian-Sudanese borders and is expected to be operational by the end of 2020. The GERD with 6450 MW will be the largest hydropower plant in Africa once comes online. The Rusumo Falls Hydroelectric Project (RRFP) is a regional hydropower project to increase the power supply to Rwanda, Tanzania and Burundi. The construction started in March 2017 and the project is expected to be commissioned in 2020. The power plant has an 80 MW capacity and the generated power will be equally shared among the three nations (NBI 2016b). In Uganda, Karuma hydropower plant is currently under construction and was expected to be completed in 2019 but subjected to delays. The project is located on Victoria Nile, just downstream Lake Kyoga, with an installed capacity of 600 MW.

Table 2.2 Existing reservoirs and hydropower plants in the Nile basin

Country	Dam	Location	Construction period	Storage capacity km^3		Purpose
Egypt	Old Aswan Dam (OAD)	Main Nile	1898 – 1902	1.06	Run-of-the River (RoR) now	Annual storage in the past & now for HP[1]
			1st heightening in 1912	2.30		
			2nd heightening in 1934	5.10		
	High Aswan Dam (HAD)	Main Nile	1960 – 1972	169.00		Century storage[2] & HP[1] (2100 MW)
Ethiopia	Fincha Dam	Fincha	commissioned in 1971	2.40		Irrigation & HP[1] (130 MW)
	Chara Chara weir	Lake Tana outlet	Commissioned in 1996	9.10		Lake Tana regulation
	Tis Abay	Blue Nile	commissioned in 2001	-		HP[1] (73 MW)
	Tana Beles	Beles	Commissioned in 2010	-		HP[1] (460 MW)
	Amerti Neshe Dam	Amerti Neshe	Commissioned in 2012	0.13		Irrigation & HP[1] (97 MW)
	Alwero Dam	Sobat River	commissioned in 1995	0.07		Irrigation
	Tk-5 Dam	Atbara River	commissioned in 2009	9.30		HP[1] (300 MW)
	Koga Dam	Koga, Lake Tana Basin	commissioned in 2012	0.77		Irrigation
	GERD	Blue Nile	Under construction	74.00		HP[1] (6450MW)

Kenya	Sondu Miriu Dam	Lake Victoria basin	commissioned in 2003	RoR	HP[1] (60 MW)
	Sang'oro	Lake Victoria basin	commissioned in 2013	RoR	HP[1] (21 MW)
Rwanda	Rusumo Falls power station	Kagera	Under construction	RoR	HP[1] (80 MW)
Sudan	Sennar Dam	Blue Nile	commissioned in 1925	0.52	Irrigation & HP[1] (15 MW)
	Jebel Al-Aulia Dam	White Nile	1934 – 1937	3.50	Irrigation & HP[1] (30 MW)
	Khasm El-Girba Dam	Atbara River	1960 – 1964	1.30 in 1964 0.97 in 1971	Irrigation & HP[1] (17.8 MW)
	Roseires Dam	Blue Nile	1961 – 1966	6.4 at 490m (a.m.s.l.)	Irrigation & HP[1] (280 MW)
	Merowe Dam	Main Nile	2003 – 2009	12.45	HP[1] (1250 MW)
	Upper Atbara and Setit Dam Complex	Atbara River	Commissioned in 2016	2.70	Irrigation & HP[1] (230 MW)
Uganda	Nalubaale power plant (formerly Owen Falls Dam)	Lake Victoria Outlet	1948 – 1950	-	HP[1] (180 MW)
	Bujagali power plant	Victoria Nile	commissioned in 2012	RoR	HP[1] (250 MW)

	Kiira power plant		commissioned in 2003	RoR	HP[1] (200 MW)
	Ismba power plant		commissioned in 2019	RoR	HP[1] (188 MW)
	Karuma power plant		Under construction	RoR	HP[1] (600 MW)

Note: [1]HP stands for hydropower generation

[2] Century storage refers to a reservoir storage that is sufficient to guarantee water supply equal to the average inflow over a period of 100 years (Sutcliffe and Parks 1999)

2.3.6 Future Development Plans in the Nile Basin

Population growth, economic growth and urbanization in the Nile countries are increasing demands for water, food and energy. Various development plans, e.g., hydropower projects, irrigation expansions and aquacultures projects are set by the riparian countries to tap the resources potential within the Nile basin. The riparian countries have developed master plans with ambitious irrigation expansion schemes to meet their growing demands for food, raw materials for industry and animal feeding in the basin (Awulachew 2012).

Irrigated agriculture is currently predominant in Egypt and Sudan, while, rain-fed agriculture is the dominant practice outside Egypt. However, rain-fed agriculture has low productivity and vulnerable to high risks of crops failure due to rainfall variability and climate change impacts. The current estimates for irrigated agriculture in the basin is approximately about 5.8 million ha. The arable land in the basin that suitable for irrigated agriculture is estimated to be approximately (10-11) million ha. Irrigation expansion plans will increase the agricultural water demand in the basin. These plans will increase the pressure on the Nile water and could even limit planned developments (Awulachew 2012; Digna et al. 2018b). Previous studies suggest that the White Nile irrigation developments have insignificant downstream impacts, unlike the Blue Nile and Main Nile irrigation development plans. Also, upstream irrigation developments are feasible with implementing adequate water supplies. The existing and potential irrigated and rain-fed agriculture in the riparian countries are shown below in Table 2.3.

Table 2.3 Existing and potential rain-fed and irrigated agriculture in the basin

Country	Rainfed area (1000 ha)[1]	Irrigated area (1000 ha)[2]	Potential irrigation area (1000 ha)[1]	Potential rainfed area (1000 ha)[1]
Egypt	0.0	3823.5	4420.0	0.0
Sudan	14044.8	1764.6	2750.0	18067.6
Eritrea	58.7	4.0	150.0	73.9
Ethiopia	2978.3	91.0	2220.0	4715.5
Uganda	8188.6	9.7	202.0	14111.2
Kenya	2204.9	47.8	180.0	2499.4
Tanzania	1971.0	19.8	30.0	2503.6
Rwanda	1159.2	7.0	150.0	1441.4
Burundi	562.1	15.3	80.0	948.6
Congo (DRC)	0.0	0.0	0.0	0.0
Total	31167.7	5782.7	10182.0	44361.3
Note: [1]Hilhorst et al. (2011b) , [2] NBI (2016b)				

The hydropower potential in the Nile basin is enormous (over 20 GW) and the hydropower is the most attractive energy source for most of the riparian countries (NBI 2016b). The energy demands will continue to grow under the rapid population growth and economic growth. Several multi-purpose dams are proposed in the national master plans of the riparian countries – e.g., Ethiopia, Tanzania, Kenya, but to name a few – to tap the hydropower potential in the Nile basin. Prefeasibility and feasibility studies for a number of hydropower projects in the basin are also considered by the Nile countries (Cervigni et al. 2015). Furthermore, there are a number of ongoing hydropower projects across the basin, e.g., GERD in Ethiopia, Rusumo Falls hydropower project in Uganda. On the other hand, the NBI conducted several studies for power developments and regional power trade opportunities in the basin, e.g., the Eastern Nile Power Trade Project that covers Egypt, Ethiopia, and Sudan (NBI 2007). The planned hydropower projects in the Nile basin are summarised in Table 2.4. The table compiled from different sources including Awulachew et al. 2007; Ministry of Energy and Mineral Development 2011; MEWNR 2013; Cervigni et al. 2015; MEDIWR 2015; NBI 2016a.

Table 2.4 Planned hydropower projects in the Nile basin

Country	Project	River	Installed capacity (MW)
Ethiopia	Baro 1	Baro river	180
	Baro 2		500
	Genji		214
	Geba A		105
	Geba 2		66
	Geba R		310
	Birbir R		465
	Tams		1060
	Karadobe	Blue Nile	1600
	Mabil		N/A
	Beko-Abo		1940
	Mendaya		2200
	Chemoga/Yeda	Chemoga/Yeda river	278
	Lower Didessa	Didessa	300
	TK7	Atbara river	321
Kenya	Nandi Forest	Yala river	50
	Magwagwa	Sondu Mirri river	115
	Nzoia (34B)	Nzioa river	16
	Nzoia (42A)		25
Rwanda	Kikagate	Kagera river	16
	Nyabarongo II		43

South Sudan	Fula Dam	Bahr Eljebel	890
	Shukoli Dam		235
	Lakki Dam		410
	Bedden Dam		570
Sudan	Dagash	Main Nile	320
	Shereiq		420
	Kajbar		360
	Low Dal		620
	Sabloka		120
Tanzania	Kakono	Kagera river	53
	Rusumo Falls		84
Uganda	Kalagala	Victoria Nile	330
	Murchison falls		648
	Ayago		612
	Oriang		392
	Kiba		288
	15 small RoR[1]	Kagera river	N/A
Note: [1]RoR: Run of the River			

2.4 Previous Studies in the Nile Basin

Various studies have been conducted to assess and evaluate the water resources and future development plans in the Nile basin. These investigations are varied according to the study area, hydrological time-series, model type (e.g., water resources model, economic model, hydro-economic model, etc.) and the planned projects in the basin. The review is organised based on the modelling approach and reviews tools developed for the Nile basin, followed by a review of current WFE nexus studies for the Nile basin.

2.4.1 River Basin Simulation Models of the Nile

The Water Evaluation And Planning (WEAP) tool was utilised in several studies across the basin. Awulachew (2012) simulated the current and future demands scenarios for the entire Nile basin in the short and long term. It was found that the water availability in the short and long term would not be sufficient to meet the future irrigation demands compared to the current demand levels. While McCartney et al. (2012) analysed the current and full development plans (irrigation and hydropower) in the upper Blue Nile basin (i.e., Ethiopia and Sudan). A linear programming optimization algorithm was applied to optimise water use in the basin. It was concluded that the river flow regime will be altered and the monthly average Blue Nile flows will be reduced as a result of increased water storages (i.e., evaporation increase) and withdrawals in the upper Blue Nile. Another study conducted by Omar and Moussa (2016) to evaluate future water management in Egypt by 2025. Future scenarios were considered with and without the continuation of current water management policies. A number of policy measures were tested (e.g., improving irrigation efficiency, increase groundwater supply). The annual water deficit was estimated at 26.0 km^3 under the continuation of current policies, while applying policy measures would likely reduce the annual water shortages to 5.20 km^3. The above-described models are deterministic models and the long term uncertainty in the future river flows were not considered. Furthermore, the climate change were not addressed in these studies.

Digna et al. (2018b) assessed the impacts of future developments in the Eastern Nile basin on water availability for hydropower generation and irrigation. A RIBASIM model was developed and applied to evaluate different development scenarios with and without basin-wide cooperation. They concluded that the hydropower generation will be boosted in Ethiopia by up to 1500%, while would increase in Sudan by about 17% and slightly decrease in Egypt by 1% when GERD is operational but without irrigation expansion in the basin. Also, the irrigation expansions in the basin would reduce the hydropower potentials in riparians by about 15%. However, the model did not consider the increased water demands in Egypt, climate change impacts on the river flows. Furthermore, the uncertainty in the future river flows was not fully addressed as the model applies one historical time-series (1900-2002).

Levy and Baecher (1999) developed NileSim tool for the entire Nile basin. NileSim was developed as an educational tool to assist non-technical people, e.g., policymakers, to understand the natural complex behaviour of the Nile and the water management in the basin. The tool is a real-time simulator based on the physical hydrology of the river and runs under historical river flows. However, the tool addresses the existing water management in the basin and did not consider future development plans across the basin.

Belachew and Mekonen (2014) built a model for the Eastern Nile basin in HEC-ResSim environment to simulate the current water management and evaluate the impacts of the future development plans in the basin. The model was developed under the Eastern Nile Planning Model (ENPM) project to provide the eastern Nile countries with improved decision support modelling frameworks. The model is a public domain and allows the user to: carry out any combinations of management options in the basin, modify the operation rules of the dams, consider climate change impacts, improve the input data, and add new planned projects. The model was applied for different combinations of planned projects in the basin but only considers one historical flow record (1960-2002).

Another group of studies were conducted in response to the announcement of GERD construction, Ethiopia in 2011. These studies investigated the impacts of GERD filling and operation on the water resources in the basin and to some extent hydropower generation and irrigation in Egypt, Ethiopia and Sudan. Mulat and Moges (2014) assessed the impacts of GERD on HAD during the filling and operation phases using MIKE River Simulation model. They concluded that the hydropower generation from HAD would be reduced by 12%, 7% during GERD filling and operation, respectively. However, the main Sudanese reservoirs on the Blue Nile were not included. Also, deterministic hydrological flow scenarios (i.e., dry, average, wet flow years) were used in the study. Abdelhaleem and Helal (2015) studied the impacts of the reduction of the Nile flows during GERD filling on different water uses in Upper Egypt. A hydrodynamic 1-D SOBEK model was developed using a daily time step for a one-year horizon. They concluded that the intakes of domestic, irrigation pump stations and the safe navigation draft would be significantly affected if the annual reduction to Egypt's water share is more than 15%, 10%, and 5%, respectively. However, the study assumed a range of flow reductions (0-40%) to Egypt's annual Nile water share (55.50 km^3).

Furthermore, the model is an annual model and the over year storage of HAD was not considered together with GERD and other significant reservoirs in Sudan.

Wheeler et al. (2016) analysed strategies for filling GERD using a wide range of agreed annual release from GERD and their downstream impacts using a river basin planning model, RiverWare. The study covered the Eastern Nile basin and investigated the coordination among the three co-riparians to minimise the risks of meeting their demands under different hydrological conditions. It was found that GERD filling unilaterally would likely cause positive benefits and negative impacts (e.g., improved hydropower generation in Sudan, and reduced water supplies to Egypt). While coordination among reservoirs in the eastern Nile countries would likely reduce the risks associated with water supplies and hydropower generation in downstream countries. However, the study used the Index Sequential method (Ouarda et al. 1997) for generating synthetic flow series and the method has well-known limitations. For example, it only generates sequences observed in the historical data that limits the possible variability of future flows. Also needs extensive historical records.

Zhang et al. (2015) applied an integrated model to investigate the impacts of GERD filling on downstream countries using stochastic analysis and considering possible climate change impacts. The model includes three modules: (a) soil moisture, (b) evapotranspiration and (c) reservoir storage. Two filling approaches considered: (a) percentage of the incoming GERD flows (5%, 10%, 25%), and (b) threshold (storing flows above the annual historical average flows and 90% of this amount). It was concluded that the reduction in river flows in the downstream would largely depend on the filling policy, climate variability, and projected climate change. However, the model is simple and only includes four flow inputs, it was limited to GERD and did not consider other significant downstream infrastructure. Keith et al. (2017) evaluated a wide range of GERD filling rates (5-100%) under plausible climate change scenarios. A System Dynamics (SD) model for the entire Nile basin was developed using precipitation and temperatures as inputs. It was concluded that filling rates above 15% of the incoming flows are likely to cause detrimental impacts on downstream flows. However, the model does not consider all significant infrastructure across the basin, assumes that climate change impacts will be incrementally monotonic i.e., the model cannot capture extremes volatilities, e.g., droughts. Moreover, the model does not consider increased water demands in the co-riparians.

2.4.2 The DST for the Nile Basin

The Decision Support Tool (DST) for planning and managing the water resources in the Nile basin was developed by Georgakakos (2006). The tool was developed under the auspicious of the Food and Agriculture Organization (FAO) and the Italian government. The DST has a river simulation and management and agricultural planning modules, hydrologic and remote sensing modelling components which are provided to facilitate regional assessment. The tool enables “cost/benefit assessments for new agricultural and hydropower projects, environmental assessments, public health warning and intervention systems for water and vector-borne diseases, and socio-economic assessments”. However, it is difficult to make changes in the tool, i.e., adding a new project.

Blackmore and Whittington (2008) evaluated the water resources developments and opportunities for cooperation in the eastern Nile countries Egypt, Ethiopia, and Sudan. A modified version of the DST was used to investigate future development scenarios and potential pathways for cooperation in the future. The study concluded that regional cooperation and coordination are strongly recommended to achieve basin-wide benefits from planned projects in the basin and effectively mitigate the associated risks (e.g., water shortage during drought periods). Also, the study showed that the continuation of unilateral developments, growing demands in the basin, together with climate change are most likely to increase the pressure on the water resources in the Nile basin. However, the study did not fully consider the uncertainty in the future river flows as the study was limited to the use of one historical time series (1913-1976). Also, it is difficult to include new projects in the DST.

2.4.3 The NB DSS Framework for the Nile Basin

The Nile Basin Decision Support System (NBDSS) is an analytical tool developed by the Nile Basin Initiative, (NBI 2016a). The tool includes three main modules: (a) database, (b) analytical tools that include simulation and optimization tools and (c) multi-criteria analysis. Modelling tools incorporated in the DSS cover different aspects of river basin planning and management such hydrological modelling, catchment sedimentation and management, water resources planning and management and flood and drought management together with optimization and multi-criteria decision making tools. Tools include different DHI products such as MIKE HYDRO, NAM and MIKE SHE. The NB DSS facilitates linking different modelling tools together (e.g., rainfall-runoff model with water allocation model) to perform an integrated analysis. Furthermore, it offers multi-sector water resources planning and management at national and basin level. The NB DSS can be used to support water resources planning and investment decisions. The tool can be also used to evaluate different water management and development options in the basin.

A pilot application of the NBDSS has been conducted to assess the potential impacts of development and management plans for the entire basin by Aurecon (2012). The study concluded that the low flows would be improved as a result of river flow regulation caused by new reservoirs, while the water availability downstream HAD is likely to reduce by 11% under the full development scenario. Also, the total GDP across the basin could increase by 6.70 billion USD. Sileet et al. (2014) applied the NBDSS to evaluate the impacts of the planned projects in the Upper Blue Nile basin on the downstream countries under different scenarios using multi-criteria analysis. It was concluded that the hydropower development scenario in the Blue Nile basin favours the irrigation development scenarios either with or without hydropower development.

2.4.4 Hydro-Economic Models Developed for the Nile Basin

The impacts of the long-term planned four reservoirs on the Blue Nile River, in Ethiopia, on Egypt and Sudan were evaluated by Guariso and Whittington (1987). A classical multi-objective programming model was developed to maximise the hydropower generation in Ethiopia while maximizing water supply for irrigation in Egypt and Sudan. It was concluded that for an average flow year, there would not be a conflict between the operation of the Ethiopian hydropower reservoirs and the agricultural water supply in Egypt and Sudan. However, the model is deterministic model and considers many simplified assumptions, e.g., the head on the turbine was not considered and hydropower generation depends only on water released from reservoirs. Also, the four planned reservoirs were replaced by a single reservoir with a capacity equal to the combined capacity of the four reservoirs.

Whittington et al. (2005) studied the economic value of cooperation in the Nile basin. A non-linear, constrained optimization algorithm was developed for the entire Nile basin with a monthly time step for an average annual river flow. The model maximises the total annual economic benefits from irrigation and hydropower generation with and without different levels of cooperation. It was concluded that the total annual direct economic benefits from irrigation and hydropower in the basin are estimated to be 7-11 billion USD without considering the capital cost of the infrastructure. Also, the hydropower benefits are mainly generated from Ethiopia and to less extent Uganda, while the irrigation benefits are mostly generated from Egypt and Sudan. However, the model is deterministic and the future uncertainty in the river flows was not addressed and considers simplified assumptions to solve the optimization algorithm. The model is an annual model and did not address the complexity of the over year storages in the basin.

Block (2007) analysed the filling stages and the subsequent operation of the planned four main reservoirs on the main stem of the Blue Nile River, Ethiopia. The study also considered different economic conditions, reservoir fill policies, and climate change in the Blue Nile basin. An optimisation algorithm was developed and called the Investment Model for Planning Ethiopian Nile Development (IMPEND). The study concluded that scenarios that consider filling stages of the reservoirs had a benefit-cost (b/c) ratio less than those ignore the reservoir filling stages of about (0.2-0.8) or (1-6) $ billion. Climate change results suggest a little increase in the b/c ratio but also reveal potential significant reductions to the b/c. Block and Strzepek (2010) applied the same model to assess the impacts of the filling stages and dams' construction sequencing on the economic benefits and costs of the planned hydropower and irrigation projects. It was found that excluding the reservoirs filling stage and dams' construction staggering would overestimate the projects benefit by 6.4 Billion USD and downstream flows by 170%. However, the model assumes that Egypt, Ethiopia, Sudan agree to fill and operate the dams and the study was limited to the Blue Nile basin in Ethiopia.

Goor et al. (2010) assessed the impacts of the planned irrigation and hydropower projects in the Blue Nile basin, in Ethiopia and Sudan, on the operation strategies of dams in Egypt, Ethiopia and Sudan. A stochastic hydro-economic model that maximises benefits from hydropower and irrigation in the three countries was developed and applied to the Eastern Nile. It was found that the annual Ethiopian hydropower would be boosted by about 40 TWh once the planned reservoirs come online. While the Sudanese irrigation withdrawals are likely to increase by 5.5% due to river flow regulation caused by the Ethiopian reservoirs. Also, HAD inflows would be reduced and HAD will be operated at low levels. However, the model assumes the riparian countries are in cooperation and the basin reservoirs are coordinated.

Arjoon et al. (2014) analysed the hydrological and economic impacts of GERD, when GERD becomes operational, on Egypt and Sudan. A stochastic hydro-economic optimisation model for the eastern Nile was developed with 10 years planning horizon and runs at monthly time-step. The algorithm maximises the economic returns from water allocation over a specified horizon. The study concluded that the downstream countries would largely benefit from the GERD especially during the dry periods. Also, the study stressed for cooperation among riparian countries to realise the wide-basin benefits, similar to conclusions from earlier studies, e.g., Whittington and McClelland 1992; Whittington et al. 2005. However, the model uses simplified demand curves, could not address the inter-annual variability, and assumed that the riparian countries are in full cooperation.

Siderius et al. (2016) investigated the impacts of cooperation forms on the water, land and investment allocation to maximise food production and food self-sufficiency in the Nile basin. A hydro-economic algorithm that optimises the water allocation between hydropower generation and agriculture production (irrigated and rainfed) in the entire basin was developed. It was concluded that rainfed agriculture, with supplemental irrigation where need, offers a great potential opportunity to increase food production and approximately meet 75% of the growing food demand in the basin by 2025. However, the model relies on simplified assumptions, e.g., the hydropower generation assumes a static head over the reservoir together with stationary flows during the considered period, also simple cropping patterns in the riparian countries were used. The model failed to address the inter-annual and inter-seasonal variability of the river flows and their wide impacts on agriculture sustainability especially the rainfed agriculture (i.e., deterministic model). Moreover, climate change effects were not considered in the study.

Another group of studies assessed the impacts of climate change on water resources planning and management in the Nile basin. Jeuland (2010) developed a modelling framework to assess the impacts of climate change and physical conditions on the net present value of the planned infrastructure in the Nile basin. The model covers the entire Nile basin and includes three modules: (a) stochastic streamflow generator, (b) hydrological simulation and (b) an economic appraisal model. It was found that the planned dams on the Blue Nile in Ethiopia could provide higher benefits under climate change compared to historical flow conditions. However, the model assumes that the planned infrastructure maximise hydropower generation only. The hydrological model is a simple model that includes 11 river flow inputs and the irrigation expansion occurs only in Ethiopia and Sudan.

Booij et al. (2011) developed the Nile Hydrological Simulation Model (NHSM) to simulate the current and future Nile flows using three General Circulation Models (GCMs) with two SRES emission scenarios (B1 and A2). NHSM is an integrated model that combines a rainfall-runoff model with a water resources allocation model (RIBASIM). NHSM simulations during calibration and validation stages, showed an acceptable to a good performance at the catchment level. Future simulations under different GCMs showed contrasting trends and differences in the river flows during future periods (2046-2065) and (2081-2100). However, the model did not perform well at the sub-catchment level, for example, overestimates the peaks of the river flows.

The precipitation and river flow trends across the river Nile showed great variability and inconsistencies among the studies conducted to investigate the climate change in the Nile basin (Barnes 2017). Elshamy et al. (2009) applied the

Nile Forecasting System (NFS), a real-time distributed hydro-meteorological model, to the upper Blue Nile catchment using 17 downscaled GCMs outputs for the period 2081-2098 under SRES scenario A1B. It was concluded that the average annual river flows at El Diem station would reduce by 15% for the ensemble mean with a range of -60 to +40% of change. Another study conducted by Kim and Kaluarachchi (2009) to assess the impacts of climate change and dams operation on the water resources in the Blue Nile in Ethiopia. The study utilised the outcomes of 6 GCMs under SRES emission scenario A2 until the year 2050 and used to drive a water balance model with two soil layers. The study considered the two planned reservoirs Karadobi and Border (GERD now) on the Blue Nile with two different operation policies, single and joint operation. Simulation results suggest that hydrological variables, e.g., average precipitation and average runoff would slightly increase across the study area. The joint operation of the two dams showed improvement to the flow characteristics and robustness of the water supply, i.e., storing the excess water during flooding season and provide supplementary flows during dry periods. However, the study was limited to the Blue Nile in Ethiopia, irrigation expansions were not included and only the two dams of Karadobi and Border were considered in the study.

Beyene et al. (2010) investigated the climate change impacts on the river hydrology and the water resources for the entire Nile basin. They developed a water resources model that considers the management of the existing infrastructure and water use in the basin and called Lake Nasser Reservoir Model (LNRM). LNRM is driven by stream flows generated by a hydrological model that utilises the outcomes of downscaled 11 GCMs with two SRES scenarios A2 and B1 till the year 2100. It was concluded that the river flows will increase during the first period of 21st century (2010-2039), while will decrease by mid and late periods of 21st century, i.e., (2040-2069) and (2070-2099) compared to the historical river flows. Simulation results from LNRM showed that changes in HAD hydropower generation and irrigation water supplies in Egypt were similar to the changes in river flows. The average annual hydropower generation from HAD will be gradually reduced during the mid and late periods of the 21st century, unlike the first period of the century HAD hydropower will not be affected. On the other hand, the irrigation water supplies in Egypt are likely to be more impacted during the mid and late periods of the 21st century than HAD hydropower generation. However, LNRM is a simple model that mainly considers HAD and assumes that the current Sudanese water demands as a single water user upstream Lake Nasser. Also, future developments in the basin were not considered in LNRM.

The above-discussed studies applied systems approach and developed various modelling methods, tools, gave insights into the current and future of water management across the Nile basin and their implications at national and regional levels. While to some extent those studies addressed various aspects of the water, food and energy in the basin, there is a lack of comprehensive nexus study for the entire Nile basin. Some of these studies are limited to exploring the historical Nile river flow records and applying deterministic approaches that failed to adequately address the long-term uncertainty in future river flows and HAD over-year storage capabilities. Moreover, these studies did not explicitly consider interdependencies and feedback among the WFE nexus and did not adequately take into account socio-economic dynamics, with different studies focusing on different parts of the Nile basin.

2.4.5 The Water, Food and Energy Nexus Analysis in the Nile Basin

Despite the limitations to the above-mentioned studies, this does not mean that different aspects of the nexus have not been investigated (e.g., Al-Riffai et al. 2017; El Gafy et al. 2017; Keith et al. 2017; Tan et al. 2017; Basheer et al. 2018; Allam and Eltahir 2019).

Tan et al. (2017) investigated the different operating policies of the GERD in the context of the nexus in the basin using an SD model. The SD model was linked to an optimization algorithm that maximises hydropower generation from GERD and minimises water supply deficits in irrigation and municipal sectors. The study results suggest that the cooperation among the riparian countries is more likely to achieve the hydropower potentials from GERD and reduce the downstream water deficits at the same time. In their analysis, the GERD was only considered, while other significant infrastructure in Egypt and Sudan were not considered, together with food production and the inter-annual flow variability were not included. The investigation mainly focused on the water sector in the three countries and hydropower generation from the GERD. Al-Riffai et al. (2017) developed a conceptual framework for the WFE nexus analysis and the impacts on the economies of the Eastern Nile countries (Egypt, Ethiopia, and Sudan).

Basheer et al. (2018) analysed the cooperation levels and the economic gains in the Blue Nile basin in the context of the WFE nexus. An integrated model was developed for this purpose and incorporated the main hydrological processes, irrigation demands, water allocation module, and hydropower generation within the study area. Results suggest that increasing the cooperation level between Ethiopia and Sudan is more likely to increase the regional economic benefits from the water, food and energy in the basin. However, the analysis was limited to GERD in Ethiopia and the Blue Nile in Sudan and applied the index sequential method which is well-known for its limitations. El Gafy et al. (2017) built an SD model for the WFE nexus by focusing on food consumption and production in Egypt. The study developed a WFE Nexus Index (WFENI) that incorporates different aspects of the water, food and energy management and strategies. For example, the WFENI can be applied to determine the optimal cropping pattern to minimise water and energy consumption and maximise water and energy productivity. However, the water resources and the hydropower generation were not either considered or analysed.

Allam and Eltahir (2019) developed an optimization model for optimal allocation of land and water resources in the upper Blue Nile basin. The model has two optimization modules: (a) land and water resources module that optimally allocates the resources to rain-fed and irrigated agriculture, (b) GERD operation module that maximises hydropower generation from GERD. Results suggest that the rain-fed agriculture expansion has a potential for approximately 30-50% of the basin area. Moreover, this optimum agricultural expansion is more likely to reduce the annual Blue Nile flow by 7.6 km^3. On the other hand, optimal operation of the GERD suggests a relatively uniform monthly release of about 3-4 km^3. The exploration offers a platform to investigate the cooperation and future developments in the Nile basin. However, the study was limited to the Blue Nile basin in Ethiopia and the downstream countries have not been included. Also, the long-term uncertainty associated with future river flows together with climate change impacts have not been addressed.

Passell et al. (2016) investigated the potential impacts of GERD filling and operation on food production, hydropower generation, social unrest and human ecology in Egypt using an integrated SD model. The integrated model incorporates agriculture, economy, human ecology and behaviour in Egypt together with the Nile basin hydrology. Results suggest that population and economic growth combined with climate change are likely to have greater impacts on Egypt's water scarcity and food production than GERD impacts. During the GERD filling period, food production in Egypt could be reduced by 25% in the worst case, but proper coordination to slowly fill the GERD is likely to reduce these impacts. While the GERD subsequent filling period showed that GERD has negligible impacts on food production. Also increasing groundwater abstraction and improving irrigation efficiency indicated promising results to mitigate Egypt's water shortage in the short and the long term, despite associated high costs. However, while GERD and HAD were only included in this work, the uncertainty in the climate change projections was not included, for example, the GERD filling process considered only the dry climate projections.

The above-reviewed studies provide various approaches to better understand the WFE nexus interdependencies and their complex nature in the Nile basin. However, the causal feedbacks, the interactions among the WFE nexus, and the socio-economic dynamics were not considered in most of these studies and none of them considered water resources of the entire Nile basin.

2.5 Modelling Approaches

The scientific water community, in particular, has developed various systems-based approaches to tackle complex water-related challenges with planning and management of water resources. Early attempts back to the Harvard water program (Brown et al. 2015; Cai et al. 2018), which induced interdisciplinary approaches to better understand and manage water resources systems and their interactions with human, environmental and economic systems. System approaches and tools based on simulation and optimization techniques have been widely employed in water policy, planning and management (Brown et al. 2015). Examples include urban water systems, water resources systems, water infrastructure operations, and flood and drought management. Systems analysis techniques include system dynamics, agent-based modelling and mathematical programming. System Dynamics (SD) (Forrester 1997; Sterman 2000) is a Systems Thinking approach that considers the interactions and feedbacks between the subsystems to better understand the dynamic behaviour of complex systems. The method has been widely applied in analysing water resources management and coupled human-water problems. Agent-based modelling (ABM) is an integrated framework where the system is modelled as a set of autonomous agents. Each agent interacts with other agents in shared environment and behaves based on its own interests and rules (Bonabeau 2002; Khan et al. 2017). Mathematical programming includes optimization-based techniques that seek to characterize trade-offs among conflicting objectives while achieving system goal(s).

Simulation-based tools are common in addressing water-related problems. Simulation models may include hydrological process, water inflows and inputs or allow for coupling human actions. Tools include but not limited to SWAT (Gassman et al. 2007), WEAP (Sieber 2006), RiverWare (Zagona et al. 2001), Agent-based modelling (Crooks and Heppenstall 2012) and System Dynamics-based tools, e.g., Vensim (Ventana Systems (2019)) and Simile (Simulistics 2019). Application of simulation techniques covers areas of urban water systems (see Djordjević et al. 1999; Zarghami and Akbariyeh 2012; Behzadian et al. 2014; El Hattab et al. 2020), water resources planning and management (e.g., Savic and Simonovic 1991; Lévite et al. 2003; Jayakrishnan et al. 2005; Sehlke and Jacobson 2005; Schuol et al. 2008; Khan et al. 2017), flood management (see Hilly et al. 2018; Webber et al. 2018; Pyatkova et al. 2019) and drought management (see Garrote et al. 2007; Schuol et al. 2008) and policy analysis (e.g., Simonovic and Fahmy 1999; Fulp and Harkins 2001; Ahmad and Prashar 2010; Dai et al. 2013; Kotir et al. 2016).

Optimization methods have been widely applied in planning and management problems. Single and multi-objective optimization techniques, such as linear programming, computational general equilibrium models, and genetic algorithms are widely applied in planning and management water problems. To list just a few, in water distribution networks (see Savic and Walters 1997; Farmani et al. 2005; Kapelan et al. 2005a; Kollat et al. 2008), in reservoir operations (see

Bessler et al. 2003; Reis et al. 2006; Xu et al. 2014; Zarghami et al. 2016), in watershed management (see Duckstein and Opricovic 1980; Andreu et al. 1996; Kollat et al. 2008; Tilmant et al. 2012; Digna et al. 2018a) and water policy analysis (see Cai et al. 2006; Null and Lund 2006).

System Dynamics (SD) (Forrester 1997; Sterman 2000) is a Systems Thinking approach that considers the interactions and feedbacks between the subsystems to better understand the dynamic behaviour of complex systems. The method has been widely applied in analysing water resources management and coupled human-water problems. At the river basin level, SD was employed to analyse the interaction between population, water resources and agricultural development plans in the Volta river basin (Kotir et al. 2016). Qin et al. (2011) investigated the interactions between the socio-economic and water management in the Shenzhen river, China that has a rapidly urbanizing development. Xu et al. (2002) studied the sustainability of water resources in the Yellow River, China using an SD model. Madani and Mariño (2009) developed an SD model to investigate the impacts of water management policies on the socio-economic dynamics in the Zayandeh-Rud watershed, Iran. Sehlke and Jacobson (2005) developed an SD model to explore the interactions between surface water and groundwater resources in the Bear River system, the largest tributary of the Great Salt Lake, USA. Keith et al. (2013) employed an SD model to explore the limits to population growth due to water availability in the Nile system.

Also, Simonovic and Rajasekaram (2004) developed an integrated model that allows for investigating policy options in water resources, food production, population and energy sectors in Canada. Tidwell et al. (2004) integrated the physical and social dimensions using an SD approach to assess water management strategies and allow for public engagement in the planning process. SD approach is also applied in reservoir operations problems (e.g., Ahmad and Simonovic 2000; Teegavarapu and Simonovic 2014; Mereu et al. 2016; Zarghami et al. 2016). SD is a generic method and can address the interactions among disparate but interconnected subsystems (Mirchi et al. 2012), thus offering a promising opportunity to address the interactions between the WFE nexus and other related critical dimensions (Cai et al. 2018; Zhang et al. 2018). The SD approach will be explained in detail in the next chapter.

River basin management, planning and operation studies may involve generation of streamflow sequences and other hydrologic variables (e.g., rainfall, evaporation, etc.) and at multiple sites across the basin as well. Stochastic analysis allows for considering uncertainty and large variability in the hydrologic regime by generating large samples beyond the historical records of the same process. Synthetic flow series serve as useful inputs in areas like reservoir planning and operation, assessment of risk and reliability of water supply systems, determining risk of failure of hydropower systems, drought assessment, water quality, etc. (Salas 1980; Sharma and O'Neill 2002; Borgomeo et al. 2015). The generation of multisite synthetic streamflow series should maintain the statistical characteristics of the historical records, the marginal distributions at various temporal scales at each location and the mutual-dependencies among the sites as well (Srinivas and Srinivasan 2005). Arguably, an important aspect of such approaches is to employ a stochastic model that is able to reproduce the main characteristics of hydrological processes, such as non-Gaussianity, intermittency (at fine time scales), dependence (temporal or spatial) and periodicity (Koutsoyiannis 2005; Tsoukalas et al. 2019).

Early attempts to reproduce multivariate synthetic hydrologic time series employed parametric methods e.g., (Fiering 1964; Matalas and Wallis 1971b; Mejia 1972; Valencia and Schakke 1973) as discussed by Salas et al. (1985). The multivariate autoregressive (AR & ARMA) models have long been applied in multisite stochastic time series problems because of their practical nature (Salas 1980).The use of synthetic time series has been widely adopted in several studies in water resources, such hydro-systems studies (e.g., Salas 1980; Salas et al. 1985; Savic et al. 1989; Koutsoyiannis and Economou 2003; Kapelan et al. 2005b; Celeste and Billib 2009; Hilhorst et al. 2011b; Tsoukalas and Makropoulos 2015b; Tsoukalas and Makropoulos 2015a; Tsoukalas et al. 2016), and risk analysis of floods or drought (Wheater et al. 2005; Haberlandt et al. 2011; Sun et al. 2011; Sun et al. 2012; Nazemi et al. 2013; Stagge and Moglen 2013; Borgomeo et al. 2015; Herman et al. 2016).

2.6 Discussion

In this chapter, the WFE nexus in transboundary river basins was critically reviewed. Various approaches have been adopted to better understand and address inter-sectoral interdependencies in river basins. Systems-based approaches have a promising potential to adequately address the nexus complexity while considering critical issues such as climate change and population growth. Despite the progress in nexus modelling approaches and tools, yet there is no unified framework to analyse and evaluate the nexus interlinkages. Existing nexus modelling tools have commonly applied loose coupling approaches that are well known for their limitation to fully capture inter-sectoral feedbacks and links. Previous nexus studies have been mostly adopted deterministic approaches, e.g., the use of average historical flow records that fail to capture the inherent uncertainty associated with the hydrological river flow regime. Critical issues such the use of simplified assumptions, overlooking population growth and climate change are other limitations to the literature.

The Nile river basin is introduced in this chapter to explore the WFE nexus in the basin as a case study. The basin is challenged by rapid population growth, economic development activities in different parts in the basin and climate change. Despite the extensive advancement in modelling approaches to address various aspects of water, food and energy in the Nile basin, there is no comprehensive WFE nexus study for the entire basin. Previous studies in the Nile basin were limited to specific sub-basins, critical infrastructure in riparian countries were not all commonly considered and deterministic approaches were often applied. Therefore, a comprehensive framework is required to address the nexus interlinkages together with related issues including: (1) population growth, (2) climate change, (3) planned infrastructure projects, economic development, (4) long-term uncertainty in river flow regime and (5) policy options. Together with the above-discussed gaps in the literature, this thesis builds upon the nexus approach and develops an integrated framework that considers the above-listed issues and gaps in the literature. A systems-based modelling approach is considered here to better understand the complex nature of the nexus in the river basin. SD approach is adopted here, and the model development and application will be discussed in the coming chapters. An integrated simulation model will be developed to explore the future of the nexus in the Nile basin regarding four main issues, i.e., (a) GERD development, (b) policy options at the national level in Egypt, (c) cooperation over GERD and (d) climate change and wide-basin planned infrastructure.

CHAPTER THREE: MODELLING METHODOLOGY

3.1 WFE Nexus Framework in a River Basin

This chapter develops a modelling framework that integrates the water, food, energy and key socio-economic drivers in a river basin. The framework shown in Figure 3.1, considers the interlinkages among the water, food and energy sectors as well as external factors that affect the three domains: (a) population, (b) economy, (c) policy options, (d) planned developments, and (e) climate change. Basin-wide synthetic streamflow series are generated to account for the inherent uncertainty of the streamflow regime, significant natural variability embedded in the historical time series and to a large extent 'uncertainty-proof' the analysis. The framework allows for investigating the trade-offs and synergies that may result from planned projects, (e.g., new dam or applying new policy measures such as using efficient irrigation methods) and impacts of the socio-economic dynamics on the WFE nexus, represented here by population and living standards. The water component is a water balance model for the entire Nile basin and includes key hydrological features, activities that affect water availability e.g., water abstractions and water management infrastructure such as

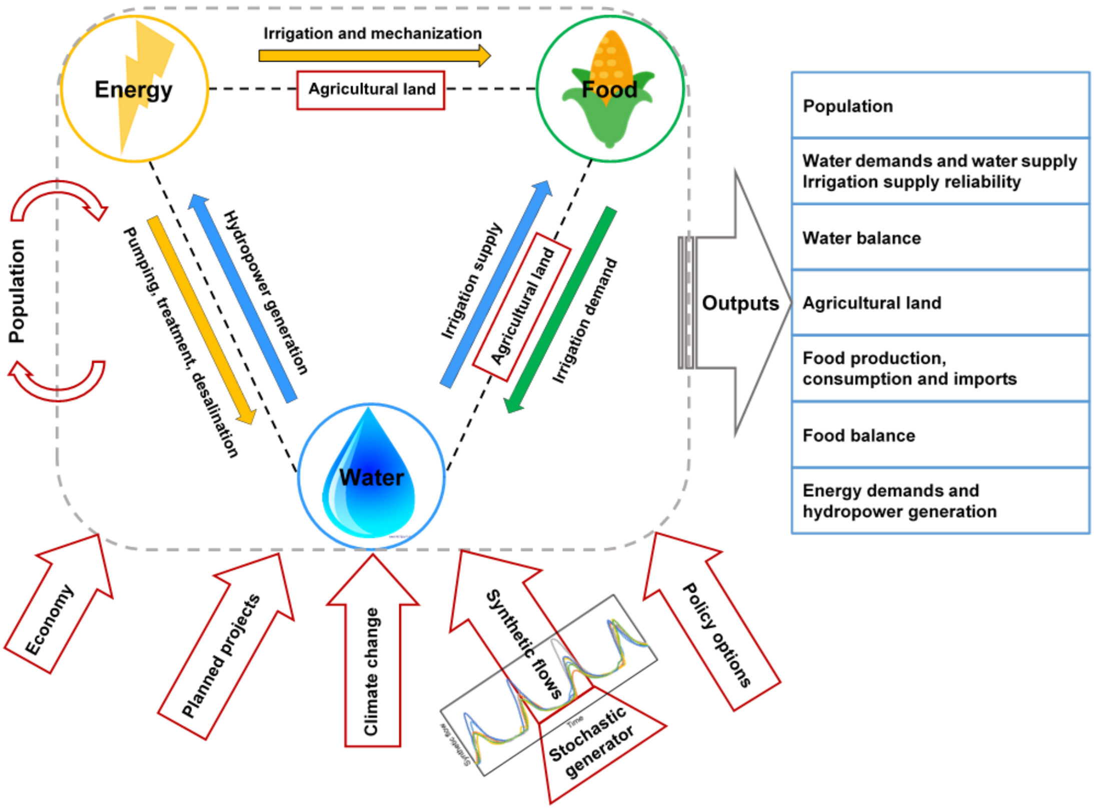


Figure 3.1 WFE nexus modelling framework

dams and water diversions. The energy component considers the hydropower generation and energy demands for different water uses, such as water treatment, and in food production, e.g., machinery use. It should be noted that an energy balance was not considered in this study, but this was beyond the scope of current work. The food component represents the agricultural land, food production, food consumption and food imports. The external factors complete the framework and allow for analysing their impacts as well as changes in one sector on the broader WFE nexus interdependencies.

The framework produces a wide range of results from the different sectors, e.g., water balance, food balance, population, Figure 3.1. Results from the water sector include water supply and demands for different water users (e.g., domestic, agriculture, and hydropower) and energy demand in the different water activities. Food sector outcomes include food supply and demands for different crops, food imports, agricultural land, and energy demand in the agricultural sector. The outputs from the energy sector include hydropower generation from different dams and hydropower plants across the basin and the energy demands in the water sector (e.g., water treatment and desalination) and food sector (pumping water for irrigation). A System Dynamics (SD) approach is adopted here as the method: (a) provides an integrated platform to combine different system components into one model, (b) can capture the interrelationships and the dynamic feedback between the system components, (c) is able to break the system down into interconnected sub-systems, and (d) can assist in understanding and managing a dynamic system (Sterman 2000). These make SD a relevant approach to address the broader interdependencies among the nexus sectors and managing the water, food and energy in a holistic manner (Bazilian et al. 2011).

3.1.1 System Dynamics

SD is a rigorous systems analysis method that is based on nonlinear dynamics theory and feedback control theory. It was originally developed to understand the dynamics and the underlying structure of industrial processes and urban systems by Forrester and his colleagues (Mirchi et al. 2012, Sterman 2000). However, the method is generic and can be applied to any dynamic system with any temporal and spatial scale. It has been widely applied to various problems in economics, ecology, engineering, health and education (Sušnik et al. 2013, Sterman 2000; Simonovic and Rajasekaram 2004). Furthermore, SD was applied to understand the underlying structure and the feedback process among the system components (Sterman 2000; Mirchi et al. 2012). Unlike the event-oriented approach, SD provides closed-loop thinking to the system as shown in Figure 3.2. Linear thinking approaches often used to solve a problem, define the problem based on the gap between the current situation and the desired goal. Linear approaches fail to consider the roots of the problem, decisions to solve the problem may result in unintended consequences and today's solution becomes a problem in the future (Sterman 2000).

Closed loop thinking instead provides a better understanding of the system by considering the whole system as a series of interconnected feedback loops, Figure 3.2.b. Current decisions reshape the environment and in turn, our decisions are affected by the newly modified situation i.e., humans alter their decisions to reach the anticipated goals (Sterman 2000; Mirchi et al. 2012). Any action has effects that could be either intended or unintended. Unintended effects arise due to our limited understanding of the system (Sterman 2000). In this sense, Systems Thinking approaches are preferable to linear thinking approaches when addressing complex problems. SD modelling offers a qualitative and quantitative platform to understand and investigate the dynamic behaviour of complex systems (Mirchi et al., 2012) through Causal Loop and Stock and Flow Diagrams.

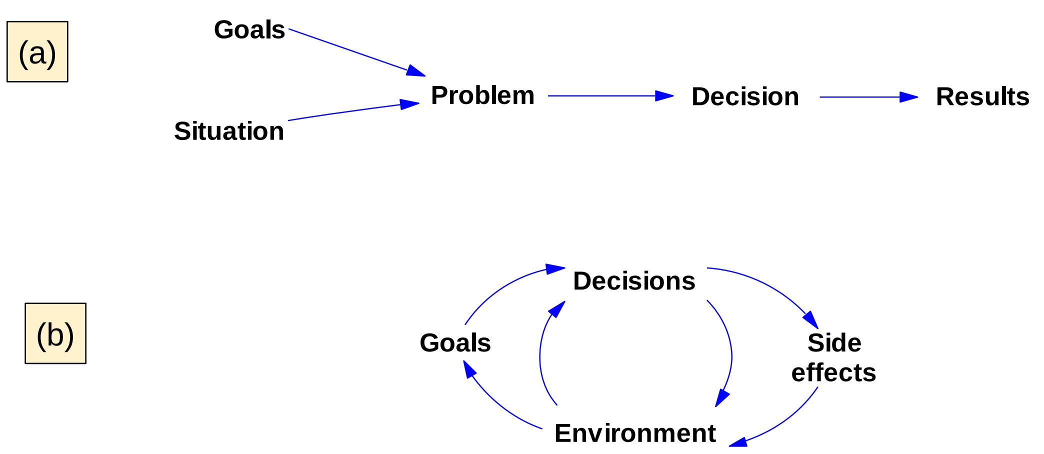


Figure 3.2 (a) Event-oriented problem thinking VS (b) Closed-loop problem thinking, adapted from Sterman (2000)

3.1.1.1 Causal Loops Diagrams

Causal Loop Diagrams (CLDs) capture the main interactions between the system variables qualitatively (Mirchi et al. 2012; Kotir et al. 2016). The diagrams offer an interactive tool to describe the main feedback loops of the system, loop dominance, and time delays (Sterman 2000). CLDs consists of variables connected by arrows and headed by positive/negative signs to represent the causal relationship between the system variables. Positive causal relationship means that a decrease/increase in variable A would result in a decrease/increase in variable B, i.e. the change is in the same direction for the two variables. In contrast, negative causal relationship means that a decrease/increase in variable A would lead to an increase/decrease in variable B, i.e. the change is in the opposite direction. The causal links describe the underlying structure of the system but cannot determine the actual behaviour of the variables. In other words, “they describe what would happen if there were a change”, (Sterman 2000). The combination of positive and negative relationships might form feedback loops, (Mirchi et al. 2012).

The dynamics arise from two types of feedback loops: (a) reinforcing feedback loop and (b) balancing feedback loop. A reinforcing feedback loop is characterised by the continuation of growth or decline within the system state. In contrast a balancing loop seeks to reduce the difference between the current system state and the desired state. The main loops are indicated by a loop identifier that shows the loop is either reinforcing (R) or balancing loop (B). The loop identifier spins in the same direction of the corresponding loop. The best way to determine the loop polarity is to trace the change in one variable through the loop. If the loop reinforces the original change, it is a reinforcing loop and if it opposes the loop then it is balancing loop (Sterman 2000).

The population can be used as an example to illustrate the CLDs, Figure 3.3. The births loop is a reinforcing loop (R) in which the increase in the births number increases the population. Meanwhile, the increase in population together with the birth rate leads to an increase in the births number. In the same manner, the deaths loop is a balancing loop (B), in which the increase in the death numbers decreases the population. The increase in population along with the death rate leads to an increase in the death numbers. CLDs are provisional and evolve as our understanding of the system improves (Sterman 2000). These diagrams are useful in mapping the feedback loops within the system (Sterman 2000). However, they cannot allow us to quantify the dynamic behaviour of complex systems (Sterman 2000). Therefore, Stock and Flow Diagrams (SFDs) are employed to quantify the dynamics of the system based on the CLDs of a system of interest. It can be argued that CLDs highlight the underlying feedback loops of the system, while SFDs emphasise the arithmetic relationships of the underlying system (Zhuang 2014).

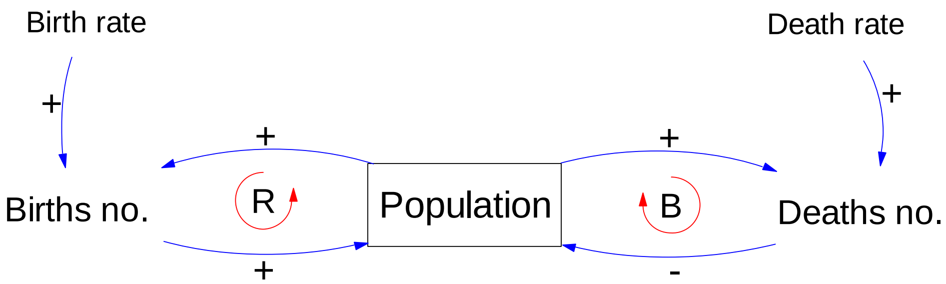


Figure 3.3 Causal Loop Diagrams of population

3.1.1.2 Stock and Flow Diagrams

As stated above SFDs represent the mathematical relationships between the system variables. SFDs comprise: (a) Stocks, which represent anything that accumulates (e.g., reservoir), (b) Flows, which are activities that fill or deplete the stocks (e.g., inflow and outflow), (c) Connectors, which link model elements and transfer information among the elements of the system, and (d) Convertors, which include arithmetic operations that can be performed on flows and logical functions that operate the system (e.g., operating rules of a reservoir). The SFDs of the above-described population example is shown in Figure 3.4. Stocks are important elements to the dynamics of the system, as they are responsible for defining the

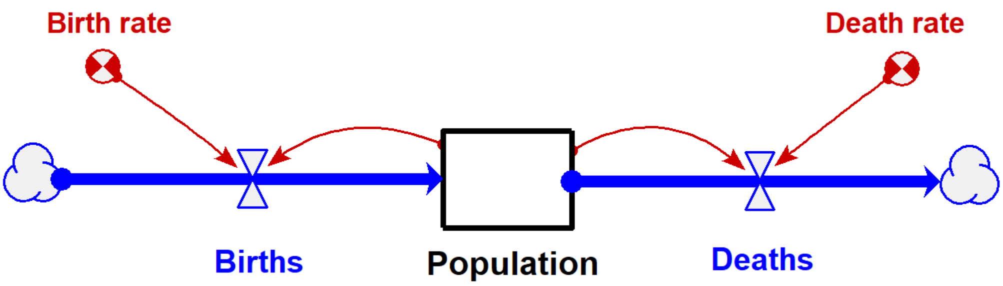


Figure 3.4 Stock and Flow Diagrams of population

state of the system and provide information that affects decisions. They also provide the system with memory and inertia, create delays and cause disequilibrium by decoupling rates of the flows (Sterman 2000). The change in a stock state is equal to the difference between inflows and outflows. Therefore, stock and flows are equivalent to a system of differential equations, however, SFDs are easier to understand, explain and modify (Sterman 2000). Stock can be represented as follows:

$$\text{Stock}(t) = \text{Stock}(t_o) + \int_{t_o}^{t} [\text{Inflow}(s)\text{-Outflow}(s)]ds \tag{3.1}$$

Or

$$\frac{d_{Stock}}{dt} = \text{Inflow}_t\text{-Outflow}_t \tag{3.2}$$

The Simile software environment is employed in this study (Muetzelfeldt and Massheder 2003; Simulistics 2019). The software is based on a set of differential equations like other SD simulation software tools, e.g., Vensim (Ventana Systems 2019) and Stella Architect (isee systems 2019). Simile was primarily developed for agro-ecological systems, however, it has been successfully applied to water management problems, e.g., (Sušnik et al. 2012; Sušnik et al. 2013) and sea-level rise and climate change impacts, e.g., (Sušnik et al. 2015). The different system sectors will be explained in detail below.

3.2 Integrated Model Structure

The integrated model developed here can be divided into two main components as follows (a) an integrated model for the entire Nile river basin, (b) comprehensive nexus model for Egypt. A physically-based water balance model for the Nile river system was built first, including basin-wide river stream flows, natural lakes, wetlands, man-made reservoirs, hydropower plants and water withdrawals activities. The model simulates the river flow regime and management activities (e.g., water withdrawals and reservoir operations) and can be driven by either historical or synthetic streamflow series. Irrigated areas and land productivity across the basin are also included in the model and accounts for food production in the basin from irrigated agriculture. Hydropower generation from hydropower plants in is an important outcome from the integrated model.

The integrated model covers the entire Nile basin to HAD. Downstream HAD, the model is linked to a comprehensive nexus model for Egypt. A water balance in Egypt is considered considering Nile water supply from HAD and other available water resources in the country (e.g., groundwater, agricultural drainage water reuse). Water demands covers different water users, e.g., municipalities and irrigation. The food sector includes food production and food imports, i.e., food balance, considering different crops. A detailed energy use and interactions with food and water sectors is also considered, while energy production accounts for hydropower generation from HAD. The two main models are linked and run together in the same interface in Simile environment. The integrated model can be driven by either historical river flows or basin-wide stochastically generated river flows with and without climate change. Figure 3.5 shows a layout of the integrated model indicating main elements of the WFE nexus and their interlinkages in the Nile basin at a coarse-scale. The structure and development of each component are explained in detail below.

3.3 The Nile Water Resource Model Structure

A water balance model for the entire Nile basin was developed to simulate the key hydrological features and different activities that affect the surface water availability (e.g., water withdrawals) and management of water infrastructure (e.g., dams and irrigation water diversions). For this purpose, two generic structures were considered in building the water resources model: (a) river reach, and (b) reservoir (Sehlke and Jacobson 2005). The former structure captures the flows within a given reach and includes runoff from different tributaries, upstream inflows, different water abstractions, losses within the reach (e.g. seepage and evaporation) and return flows from water users. The latter structure considers the upstream inflows, evaporation, rainfall rates for a reservoir together with reservoir operation rules, and releases from the reservoir. The CLDs of the two generic structures were firstly developed using Vensim (Ventana Systems 2019) to illustrate the causal relationship between the system elements as shown in Figure 3.6. For example, the increase in the evaporation and water released from a res-

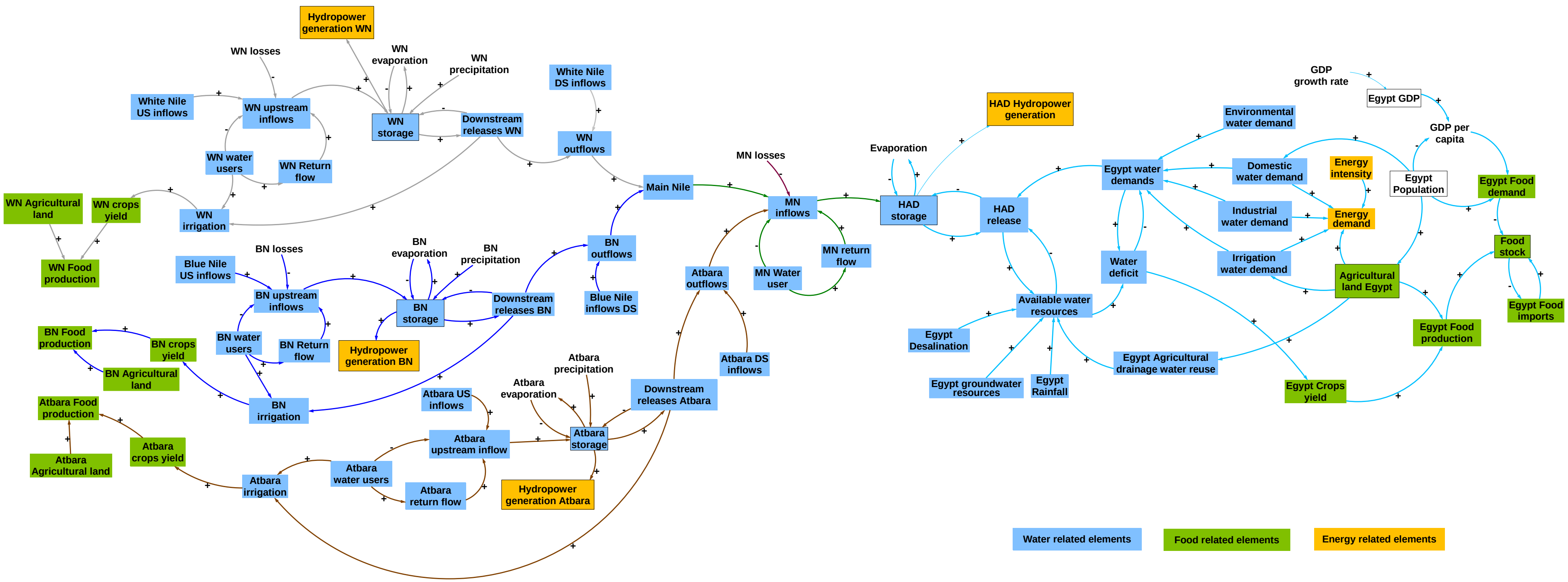


Figure 3.5 Water, food and energy interactions in the Nile river basin

-ervoir reduces the stored water volume in the reservoir (negative relationship), while the increase in upstream inflows and precipitation over the reservoir increases the stored water volume (positive relationship).

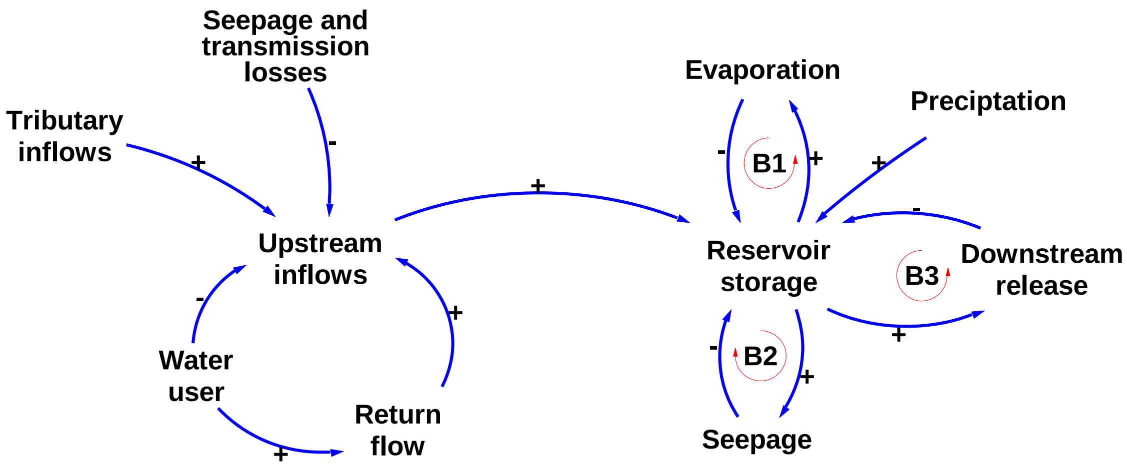


Figure 3.6 CLDs of the river reach and reservoir

The proposed CLDs are quantified through SFDs, as shown in Figure 3.7. The rectangles denote stocks which represent water storage in reservoirs and lakes. The stocks are connected by lines with valves, which represent the water inflows and outflows from a reservoir. The other variables are converters that control the inflows, outflows and stocks. The storage in a reservoir can be mathematically represented by a mass balance equation as follows:

$$S_{t+1} = S_t + I_t + P_t - O_t - E_t - SP_t \quad (3.3)$$

where,

S_{t+1}: Reservoir storage at time (*t+1*), S_t: Storage in the reservoir at time (*t*),

I_t: Reservoir inflow at time (*t*), P_t: Precipitation over the reservoir at time (*t*),

O_t: Reservoir outflow at time (*t*), E_t: Evaporation from the reservoir at time (*t*),

SP_t: Spill from the reservoir at time (*t*)

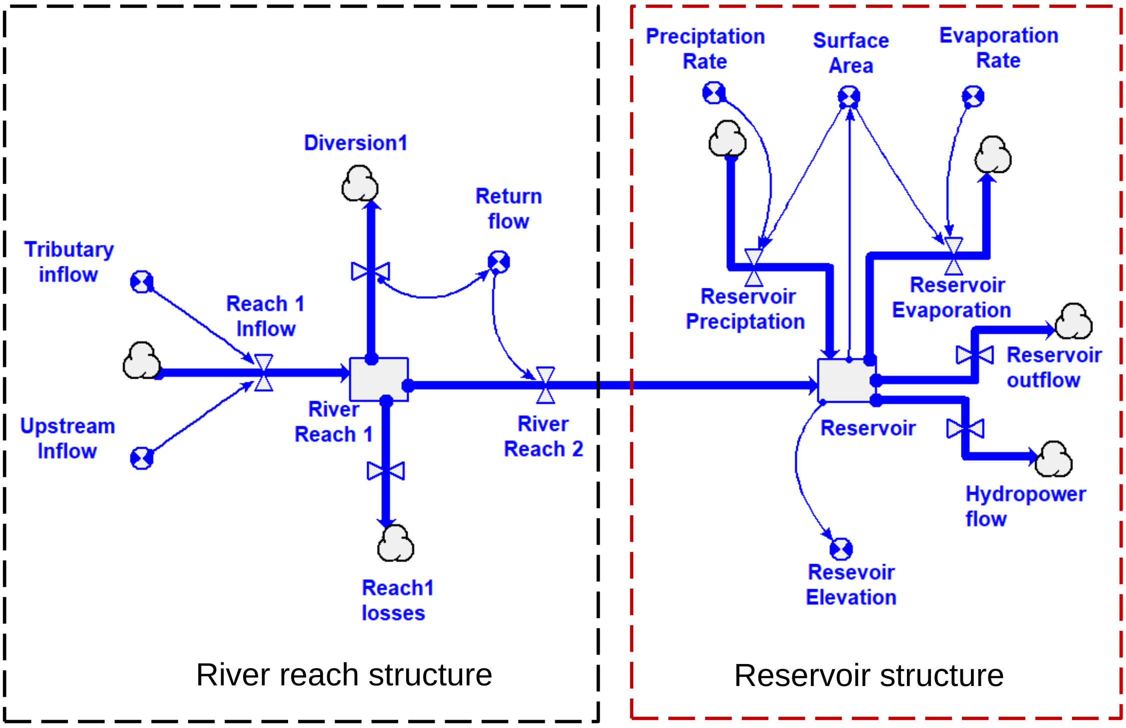


Figure 3.7 The combination of the river reach and reservoir structure

It should be noted that, the catchment hydrology was not considered here as it is beyond the scope of this work. The reservoir inflows include inflows from upstream tributaries, releases from the upstream reservoir(s), and return flows from upstream water users and water diversions. The precipitation/evaporation from a reservoir was calculated as the product of the rainfall rate (R_{rate})/evaporation rate (E_{rate}) at the reservoir site and the surface area (*SA*) for each reservoir at each time step as follows: $P = R_{rate} \times SA$, and $E = E_{rate} \times SA$. The Surfacearea_Elevation_Storage relationship was used to estimate the surface area for the reservoir at each time step. The outflow from the reservoir can be determined based on the reservoir's operation rules (see appendix A) and downstream demands (e.g., irrigation and hydropower demands) and their priorities. Demand reduction factors for irrigation and hydropower users are applied where they exist. It can be subjected to the following general conditions:

$$O_t = \begin{cases} \textit{Downstream demands} & \text{if } (S_t - S_d) \geq \textit{Downstream demands} \\ (S_t - S_d) & \text{if } (S_t - S_d) < \textit{Downstream demands} \\ 0 & \text{if } S_t \leq S_d \end{cases} \quad (3.4)$$

where: S_d is the reservoir dead storage

In a similar manner, the spill from reservoir is calculated based on its maximum storage capacity:

$$SP_t = \begin{cases} (S_t + I_t + P_t\text{-}E_t\text{-}S_{max}) & \text{if } (S_t + I_t + P_t\text{-}E_t\text{-}S_{max}) > 0 \\ 0 & \text{if } (S_t + I_t + P_t\text{-}E_t\text{-}S_{max}) < 0 \end{cases} \quad (3.5)$$

where: S_{max} is the maximum reservoir storage

The prioritised operation rules for single and multipurpose dams through the year were written using conditional statements (IF-THEN-ELSE). The hydropower flows (i.e., turbine flows) in the case of a multipurpose dam were estimated iteratively. Normally 3-4 iterations were sufficient to determine the actual hydropower flows with acceptable accuracy. The continuity equation was also applied to the river/reservoir reach to avoid negative values. It can be represented by the following form:

$$I_t - O_t + \Delta S_t = 0 \quad (3.6)$$

Where: I_t represents inflows to the river reach/reservoir (e.g., upstream flow), O_t stands for flows that leave the reach/reservoir (e.g., water diversion) and ΔS_t is the change in storage.

It is worth mentioning here, the wetlands and marshes across the basin are modelled as a single reservoir. Evaporation, precipitation, and flooding processes are represented by a Surface area_Elevation_Storage relationship. The above-described conditions (i.e., equations 3.3-3.6) were also applied to these assumed reservoirs.

The monthly hydropower generated for each hydropower plant is calculated during the simulation at each time step. The annual hydropower generation (AHP) from a hydropower plant can be calculated as follows:

$$AHP = \sum_{i=1}^{12} \frac{\gamma \times Q_i \times H_i \times \eta}{10^9} \quad (3.7)$$

where, AHP is the annual hydropower generated (GWh/yr), γ the specific weight of water (N/m^3), Q_i the turbine discharge in month i (m^3/s), H_i the turbine water head in month i (m), and η the turbine efficiency.

3.3.1 The Nile River Water Resources Model

The water resources model represents the key hydrological features and simulates different activities that affect the surface water availability (e.g., water withdrawals) and management of water infrastructure (e.g., dams and diversions). The entire model was developed in Simile environment by linking the river reach/reservoir to the relevant elements sequentially until the whole basin's hydrology, water management and abstraction activities were represented. The model is divided into three main sub-models: (a) the White Nile sub-model, (b) the Blue Nile sub-model, and (c) the Main Nile in Egypt. Each sub-model is composed of interlinked sub-model groups, which is an SD feature that enables breaking a complex system down into smaller subsystems (Simulistics 2019). Figure 3.8 shows a schematic of the entire Nile basin including main rivers with their tributaries, natural lakes, reservoirs, and major irrigation schemes across the basin.

Main natural lakes considered here are Equatorial lakes (Lake Victoria, Lake Kyoga, Lake Albert), and Lake Tana in Ethiopia. Wetlands include Sudd wetlands, Bahr El-Ghazal wetlands, and Machar marshes in the Sobat basin. Existing dams considered here are Nalubaale power plant (formerly Owen Falls Dam), Kiira Dam, and Bujagali Dam in Uganda together with Gogo Dam, Sondu Mirriu Dam, and Sang'oro Dam in Kenya. Also, Lake Tana outlet, Koga Dam, Tana Beles diversion, Tis Abay power plant, Fincha Dam, Amertie Neshie Dam, Alwero Dam, TK5 Dam in Ethiopia. Sudanese dams included are El-Roseires Dam, Sennar Dam, Jebel Aulia Dam, Khashm El-Girba Dam, and Merowe Dam. While HAD in Egypt is the last major dam considered in the model. Table 3.1 presents the main existing infrastructure considered and their main characteristics. The National water balance in Egypt is considered and linked to the Nile water resources model. This model is described in detail in section 3.3.1.

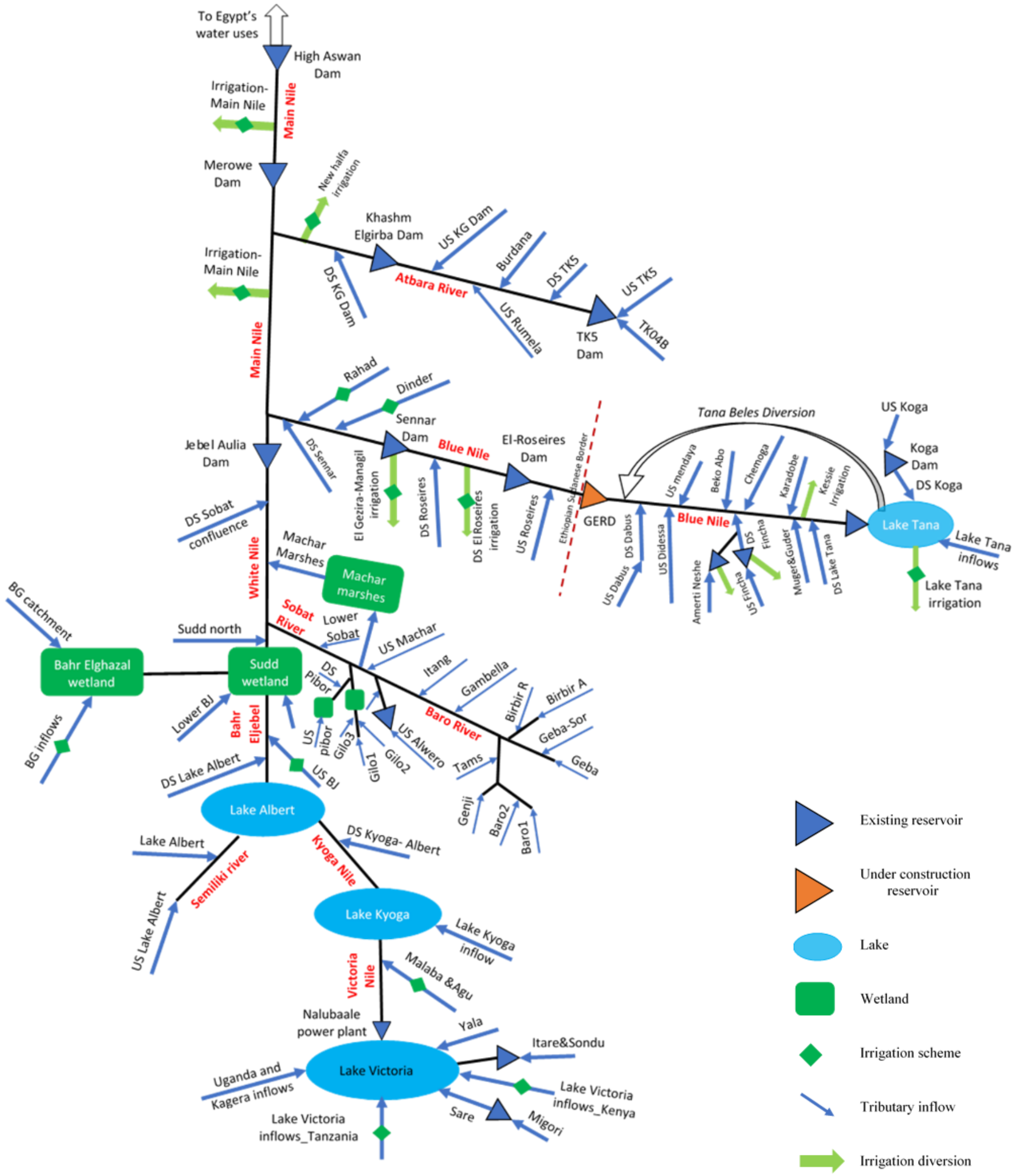


Figure 3.8 Schematic of the entire Nile basin

Table 3.1 Main infrastructure across the basin, location, purpose and installed hydropower capacity

Reservoir	Location	Purpose	Installed capacity (MW)
Gogo falls RoR	Migori tributary, Lake Victoria basin	Hydropower generation	2.0
Sondu Mirriu RoR	Sondu and Mirriu, Lake Victoria basin	Hydropower generation	60.0
Sang'oro RoR		Hydropower generation	21.0
Kiira power plant	Lake Victoria outlet	Hydropower generation	200.0
Nalubaale power plant	Lake Victoria outlet	Hydropower generation	180.0
Bujagali RoR	Victoria Nile	Hydropower generation and regulate Lake Victoria outflows	250.0
Alwero Dam	Alwero, Sobat catchment	Irrigation	-
Jebel Aulia Dam	White Nile	Hydropower generation and Irrigation	28.8
Tana Beles	Beles	Hydropower generation	460.0
Koga Dam	Koga	Irrigation	-
Tis Abay Dam	Blue Nile	Hydropower generation	73.0
Fincha Dam	Fincha	Hydropower generation and Irrigation	130.0
Amerti Neshe Dam	Amerti Neshi	Hydropower generation and Irrigation	97.0
El Roseires Dam	Blue Nile	Hydropower generation and Irrigation	280.0
Sennar Dam	Blue Nile	Hydropower generation and Irrigation	15.0
TK5 Dam	Tekeze River	Hydropower generation	300.0
Khasm ElGirba Dam	Atbara River	Hydropower generation and Irrigation	17.8
Merowe Dam	Main Nile	Hydropower generation and Irrigation	1250.0
High Aswan Dam	Main Nile	Hydropower generation and Irrigation	2100.0

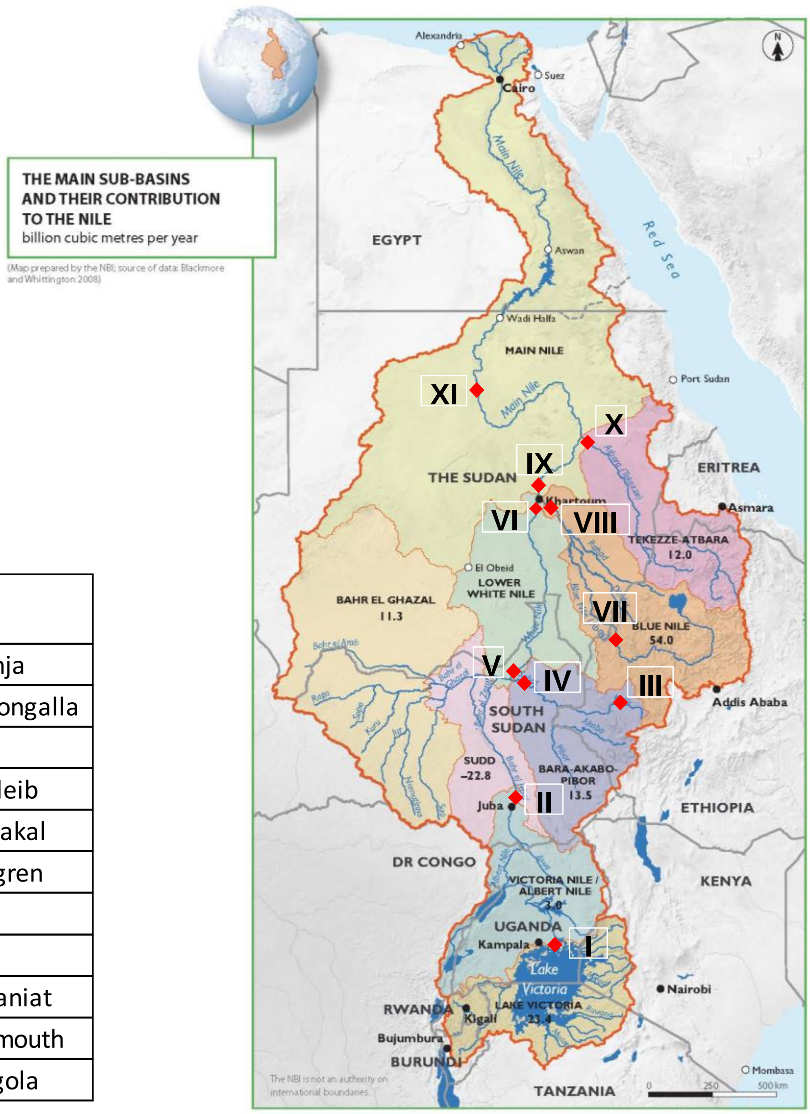
3.3.2 Water Resources Model Data Requirements

The main data source for the basin hydrology, infrastructure, and main water users across the basin is the Nile Basin Decision Support System (NB DSS), (NBI 2016a). The NB DSS was developed by the Nile Secretariat (Nile-SEC) department, Nile Basin Initiative (NBI) and obtained by direct contact with Dr Abdulkarim H. Seid, Head of the Water Resources Management Department, ENRTO, NBI. Basin-wide hydrologic inputs were available for the period (1950-2014) from a rainfall-runoff MIKE RIVER model embodied in the NB DSS. The existing water demands (irrigation, municipal and industrial demands) were also available for the riparian countries, while for Egypt the demands were calculated and will be explained later in a separate section. The irrigation water demands for planned irrigation schemes across the basin were also available from the NB DSS database. The NB DSS also provides access to existing and planned reservoirs information (e.g., operation rules, Surface area_Elevation_Storage relationship, rainfall and evaporation rates at the dam site, and storage zones). In addition to hydropower plants' data (e.g., installed hydropower capacity and power plant efficiency).

In Simile, the reservoir data were written in the form of (IF-THEN-ELSE) statement, constraints, and lookup tables. For example, (IF-THEN-ELSE) statement was used to write the operation rules and the prioritised operation rules for a multipurpose dam as mentioned above (i.e., equation 3.3-3.5). While constraints were added to reservoir dead storage to avoid negative values, flood control levels to avoid excess storage, and demand reduction levels if they exist. In the same manner, the storage zones and prioritised rules for the natural lakes and the assumed reservoirs (i.e., wetlands) were established. Actual starting operation date of the existing reservoirs was derived from different sources (Wheeler et al. 2016; Basheer et al. 2018) and embedded into the simulation. Existing and planned projects data are provided in appendix (A).

3.3.3 Water Resources Model Testing

After the model was built in Simile environment and the inputs uploaded to the model, the model is now ready for the simulation. The model runs at a monthly time step and simulates the basin-wide water management during the period (1950-2014). The model was calibrated at key gauge stations, Figure 3.9, for the period (1950-1969) followed by validation for the period (1970-1989). Basin-wide inputs, e.g., dam operation rules, actual commission dam dates, tributaries inflows, water diversions and evaporation and rainfall rates over dams and natural lakes, are used to drive the simulations. Calibration parameters include flow and time dependent stream gain and losses, hydrologic routing (e.g., time-lag and storage routing) and river channel losses such as seepage and evaporations.



ID	gage station
I	Victoria Nile at Jinja
II	Bahr elJebel at Mongalla
III	Baro at Gambella
IV	Sobat at Hillel Doleib
V	White Nile at Malakal
VI	White Nile at Mogren
VII	Blue Nile at Deim
VIII	Blue Nile at Soba
IX	Main Nile at Tamaniat
X	Atbara at Atbara mouth
XI	Main Nile at Dongola

Figure 3.9 Locations of gauge stations across the Nile basin, NBI (2016b)

Model validation at gauge stations where there was no sufficient historical data was conducted at the next gauge station located downstream the missing gauge. Table 3.2 shows the performance indicators of the model calibration and validation according to the recommended criteria by Moriasi et al. (2007). According to these criteria, model simulation results showed satisfactory performance and the regional model is fit for the purpose for which it is developed.

Table 3.2 Calibration and validation results at key gauge stations calculated according to criteria found in Moriasi et al. (2007)

ID	Gauge station	Calibration			Validation		
		NSE[1]	RSR[2]	PBIAS[3]	NSE[1]	RSR[2]	PBIAS[3]
I	Victoria Nile at Jinja	0.95	0.22	-1.28	0.52	0.69	0.18
		(1950-1969)			(1970-1979)		
II	Bahr elJebel at Mongalla	0.81	0.44	-3.96	0.24	0.87	-0.91
		(1950-1969)			(1970-1982)		
III	Baro at Gambella	0.78	0.46	4.88	n/a[4]		
		(1950-1969)					
IV	Sobat at Hill Doleib	0.73	0.52	-2.59	0.81	0.43	-3.25
		(1950-1969)			(1970-1988)		
V	White Nile at Malakal	0.73	0.52	-2.01	0.82	0.43	0.97
		(1950-1969)			(1970-1988)		
VI	White Nile at Mogren	0.61	0.63	-0.57	0.64	0.60	4.67
		(1950-1969)			(1970-1988)		
VII	Blue Nile at Deim	0.92	0.29	1.39	0.90	0.32	-1.96
		(1951-1969)			(1970-1989)		
VIII	Blue Nile at Soba	0.86	0.37	2.01	0.68	0.57	-0.65
		(1950-1969)			(1970-1989)		
IX	Main Nile at Tamaniat	0.84	0.40	3.73	0.60	0.63	1.91
		(1950-1969)			(1970-1989)		
X	Atbara at Atbara mouth	-0.19	1.09	-48.53	0.76	0.49	34.89
		(1950-1969)			(1970-1972)		
XI	Main Nile at Dongola	0.89	0.34	3.66	0.67	0.58	3.37
		(1962-1969)			(1970-1989)		

Note:

[1]NSE: Nash-Sutcliffe efficiency, [2]RSR: Ratio of the root mean square error to the standard deviation of measured data, [3]PBIAS: Percent bias and [4]n/a: not available data at the gauge station
Desired values: RSR < 0.50, NSE >0.75 and PBIAS < ±10

Figure 3.10 shows the comparison between the historical and the simulated monthly river flows at three gauge locations: (a) Malakal on the White Nile, (b) El Diem on the Blue Nile and (c) Dongola on the Main Nile. The rest of gauge stations are provided in appendix (B). Results that can be obtained from the simulation include river flow at particular location in the basin, water levels in a reservoir, reservoir storage, downstream releases from a reservoir, water diversions and water withdrawals at a particular time-step (e.g., monthly, yearly). Also, the monthly and annual hydropower generated from power plants, supply to demand ratio for water users, e.g., irrigation, and water shortages at monthly or annual intervals.

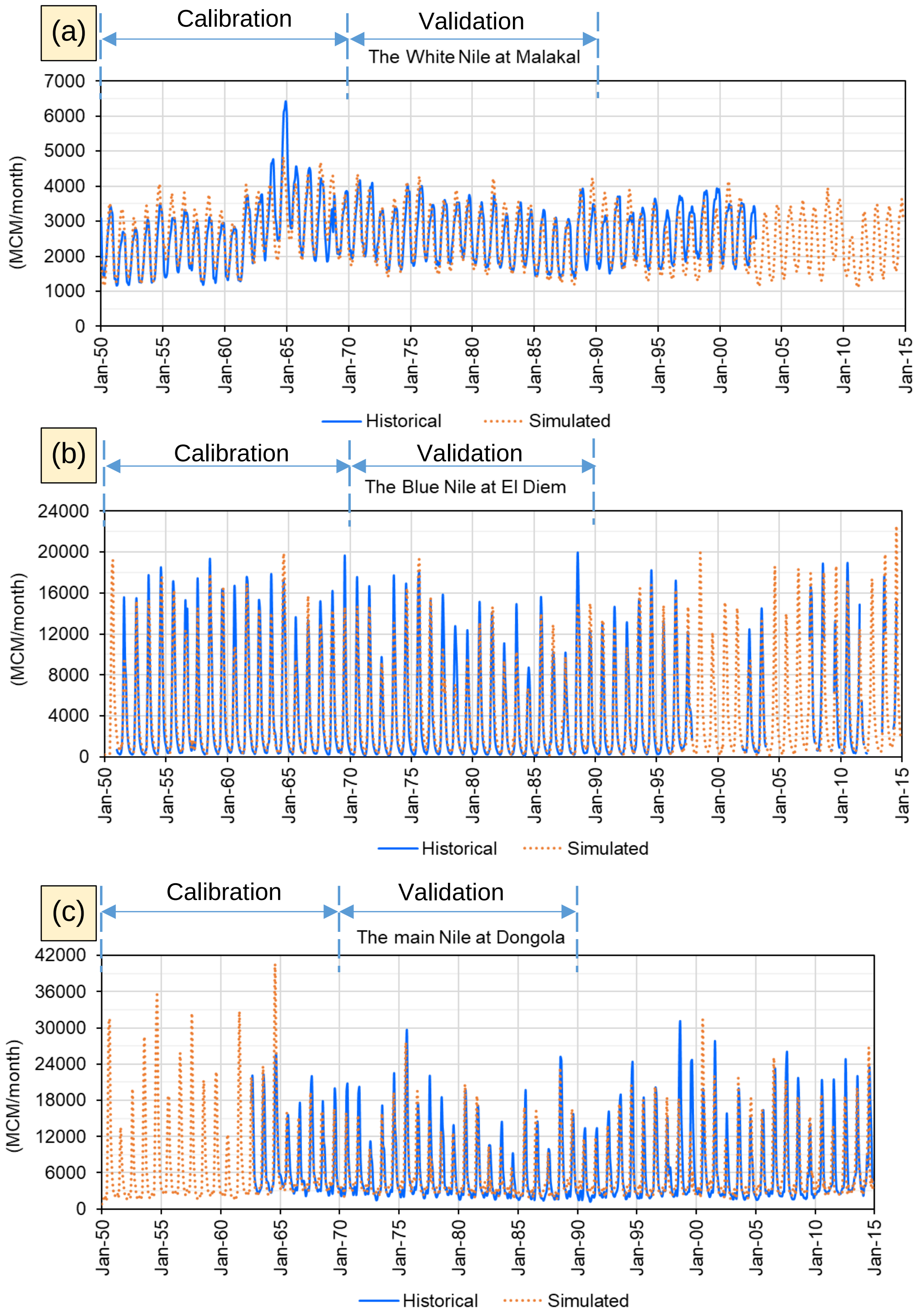


Figure 3.10 Historical VS Simulated monthly river flows of: (a) the White Nile at Malakal, (b) the Blue Nile at El Diem and (c) the Main Nile at Dongola

3.4 Egypt Sub-Models

3.4.1 Egypt Water Sub-Model

The water sub-model for Egypt at the national level is considered and shown in Figure 3.11. The supply side includes: HAD releases, shallow groundwater supply, deep groundwater supply, agricultural drainage water reuse, effective rainfall, desalination, and treated wastewater. The water demands side includes agricultural water demand, domestic water demand, industrial water demand, and navigation and regulation requirements in addition to the evaporative losses from the main Nile course and canals network. The CLDs of the water resources in Egypt is also shown in Figure 3.12 and will be explained in the coming paragraphs along with each related component. It represents the structure of the water system in Egypt at the national level as described in the consecutive water policies, published reports and literature (see, Abu-Zeid 1992; Aboelata 1998; Abu-Zeid 2003; ICID 2004; MWRI 2005; MWRI 2011).

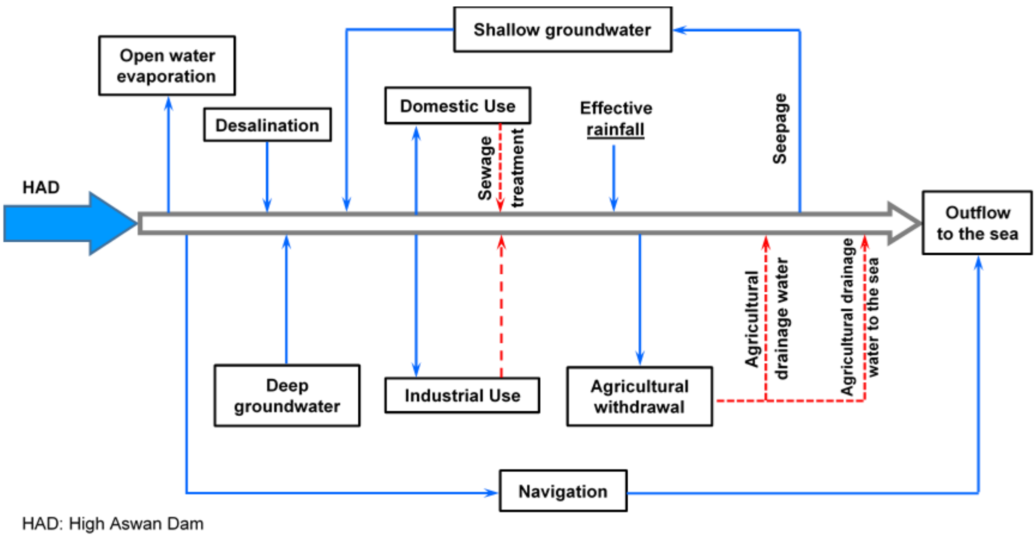


Figure 3.11 Egypt water balance at the national level

3.4.1.1 Egypt Water Supply Sub-Model

The considered water supplies at the national level in Egypt are the water released from HAD, shallow and deep groundwater, effective rainfall, the agricultural drainage water reuse, treated wastewater, and water desalination. The sub-model is linked to the Nile water resources model via HAD. Nile inflows arriving and stored in HAD, while the water is released from HAD to meet different water demands in Egypt. Water is released based on the different downstream

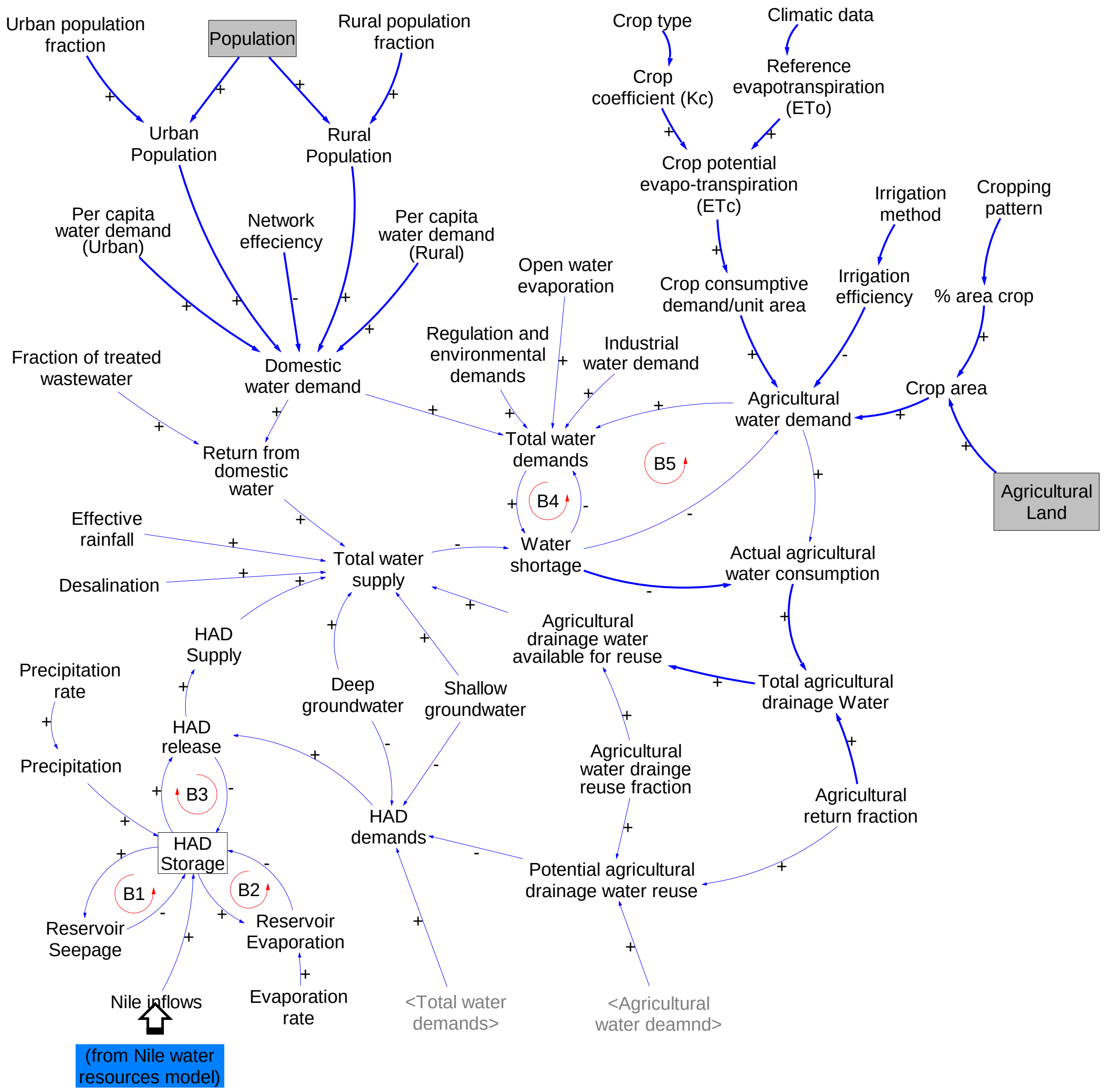


Figure 3.12 CLDs of the water resources system in Egypt

water demands, the reservoir storage conditions, and other available water resources (groundwater, agricultural drainage reuse, etc.). Historical deep groundwater and shallow groundwater data were used in the simulation as exogenous inputs. Historical data were collected from literature, national reports (Abu-Zeid 1992; Hefny et al. 1992; Abu-Zeid 2003; Allam and Allam 2007; El Tahlawi et al. 2008; MacAlister et al. 2012; CAPMAS Various years-d), while missing data were linearly interpolated. The safe yield values for the groundwater are considered and will be investigated in the coming chapters (MWRI 2005; MWRI 2011; ENHC 2013). Currently, shallow groundwater estimated at 7.0 km^3/year while deep groundwater yield is estimated to be 2.1 km^3/year, according to the national water balance of Egypt (El-Din 2013; CAPMAS Various years-d).

Agricultural drainage water reuse was considered as a fraction of the irrigation water. Two parameters were used to estimate the amount of the agricultural drainage water: (a) the agricultural drainage return fraction, which represents the fraction of agricultural drainage water returned to drains, and (b) agricultural drainage water reuse fraction that represents the amount of the agricultural drainage water available for reuse. The agricultural drainage return fraction reported in the literature is found to be between 0.25-0.40 (ICID 2004; MWRI 2005; MWRI 2006; Hilhorst et al. 2011a). The agricultural water return fraction in this work was estimated to be 0.30 from model calibration and found to be consistent with the observed data for agricultural drainage water return fraction. The agricultural drainage water reuse fraction was used as a dynamic input parameter and estimated from the ratio of actual agricultural drainage water to the total agricultural drainage water. The current level of agricultural drainage water reuse was estimated to be 11.0 km^3/year according to the national water balance (CAPMAS Various years-d).

Rainfall in Egypt is very low, erratic and unpredictable and occurs along the northern coastal strip. The effective rainfall utilised for water use is estimated to be between 1-1.5 km^3/year and a constant value of 1.0 km^3 was used in the model simulation. From the sensitivity analysis, the model was found to be insensitive to that value and will not affect the model results. Desalination of seawater will become a significant water resource in the future as indicated in MWRI’s 2050 strategy. Desalination is included in the model simulation from the year 2003 and currently is estimated at 0.05 km^3/year (CAPMAS Various years-d). Treated wastewater is being considered in previous national water policies and is considered as a potential resource will utilized as a result of increased demands from different water sectors (ICARDA&AUSAID 2011; MWRI 2011). Therefore, treated wastewater is used as a fraction of the domestic water withdrawal. This fraction is estimated to be 13-20% of the domestic water withdrawal (CAPMAS Various years-d). A value of 13% was used in the model simulation and the sensitivity of this parameter to the model will be shown in the sensitivity analysis section (3.3.7.1).

The demands from HAD were determined iteratively during the simulation. First, the model assumes that there is no water shortage and estimates the potential water reuse in this case (i.e., full water supply). After that, the model balances the water supply and demand and if no water shortage is expected, the model continues the simulation. In the event of a water shortage is expected, the model allocates it to the agricultural sector (Loop B5, Figure 3.12). Following on from that, the model determines the actual agricultural water withdrawal and adjusts the agricultural water reuse.

3.4.1.2 Egypt Water Demands Sub-Model

Water demands from different sectors in Egypt and their dynamics are discussed in the coming paragraphs together with their underlying structure and assumptions. It should be noted that the domestic and industrial water demands are given priority over agricultural water demands as reported in MWRI (2005) and MWRI (2011) therefore, water shortages will be allocated first to the agricultural sector. The hydropower is considered a by-product of HAD releases.

3.4.1.2.A Agricultural Water Demand

The agriculture sector in Egypt is a source of economic growth in the country, contributing to about 11.2% of the country GDP in 2018 (The World Bank 2019). The agricultural sector is considered the largest water user and consumer in Egypt, accounting for approximately 80% of the total water demands (ICARDA&AUSAID 2011; MWRI 2011). Irrigated agriculture is dominant in Egypt due to the arid and hyper-arid climate conditions, while rainfed agriculture is limited to the narrow strip along the north coast and the red sea coast. There are three cropping seasons in Egypt: (a) winter (November-May), (b) summer (April-October) and (c) Nili season (July-October). Dominant crops in each season are: (a) wheat, sugar beet, and clover for the winter season, (b) maize, sorghum, rice, cotton, and sugar cane for the summer season, and (c) maize for the Nili season. Vegetables (e.g., tomatoes, potatoes, etc.) are also cultivated in the three seasons, together with fruits (e.g., citrus, mango, banana, etc.).

The agricultural land in Egypt can be divided into two main types according to the irrigation method; (a) Old lands, (b) New lands (ICARDA&AUSAID 2011). Since the cultivated land and agricultural land are sometimes confusing terms, it should be noted that agricultural land refers to the physical land suitable for agricultural production. The old lands are the largest irrigated areas and are the most fertile lands, located in the Nile Valley and Delta. Surface irrigation systems are commonly practised in the old lands. The New lands are the newly reclaimed lands from the desert since 1952 in which modern irrigation systems (e.g. drip and sprinkler irrigation) are practised by the law (Allam and Allam 2007). A distinction between the old lands and the new lands is therefore considered in the model. Estimates for the irrigation efficiency at the national level showed large variations (0.44-0.66) in the literature (e.g., ICARDA&AUSAID 2011; MWRI 2011; Molle et al. 2013; Abdelkader et al. 2018). The irrigation application efficiency in the old lands was estimated to be 0.60 from model calibration. In contrast, half of the new lands are assumed to apply modern irrigation methods as reported in the MWRI's 2050 strategy (MWRI 2011). Therefore, two irrigation methods were assumed in the New lands that apply efficient methods as follows: (a) sprinkler irrigation with an application efficiency 0.70 and (b) drip irrigation with an application efficiency 0.90 (Allen et al. 1998).

The monthly crop water requirements ($\mathrm{ET_C}$) were calculated based on the FAO guidelines, irrigation and drainage paper No. 56 (Allen et al. 1998). A single crop coefficient approach is adopted here to calculate the crop evapotranspiration ($\mathrm{ET_C}$). It can be calculated for crop i as follows:

$$\mathrm{ET_{Ci}} = \mathrm{K_{Ci}} \times \mathrm{ET_O} \tag{3.8}$$

Where, $\mathrm{ET_{Ci}}$ stands for crop i evapotranspiration (mm/month), $\mathrm{k_{Ci}}$ is the crop factor of crop i, and $\mathrm{ET_o}$ is the reference evapotranspiration (mm/month),

The reference evapotranspiration ($\mathrm{ET_o}$) was calculated by the CROPWAT 8.0 model, (Muñoz and Grieser 2006) according to FAO Penman-Monteith equation, (Allen et al. 1998). CROPWAT requires spatial data (e.g. altitude, longitude) together with climatic data of the zone of interest (e.g., temperature, humidity, wind speed and sunshine hours) to calculate ($\mathrm{ET_o}$). Average monthly climatic data for different meteorological stations across Egypt were available from the CLIMWAT database, (Muñoz and Grieser 2006) for the period (1971-2000). The crop factor ($\mathrm{K_{Ci}}$) is a coefficient used to adjust the reference grass evapotranspiration to the specific crop evapotranspiration characteristics. The single crop coefficient integrates the soil evaporation and the crop transpiration rate into one coefficient. The four crop growth stages (i.e., initial stage, crop development, mid-season, and late-season) were also considered when calculating the crop water demands, Figure 3.13.

The crop factor for the initial ($K_{c\ ini}$) , mid ($K_{c\ mid}$) and late-season ($K_{c\ end}$) was obtained from FAO tables (Allen et al. 1998), while local data from the literature (e.g., Ouda et al. 2016a) was used when it was available. The crop factor for the development and late-season stages was linearly interpolated. The sowing, harvest dates and length of each crop growth stage were obtained from different sources (e.g., Allen et al. 1998; NWRP 2000; Ouda et al. 2016a; CAAES 2017). Moreover, the crop coefficient (K_{ci}) was adjusted to reflect the frequency of wetting and climatic conditions during the initial stage according to Allen et al. (1998). The crop coefficient (K_{ci}) can be calculated for any stage and time interval once the crop coefficient curve is constructed, Figure 3.13. The calculation procedure of the crop evapotranspiration (ET_{ci}) is summarised in Figure 3.14.

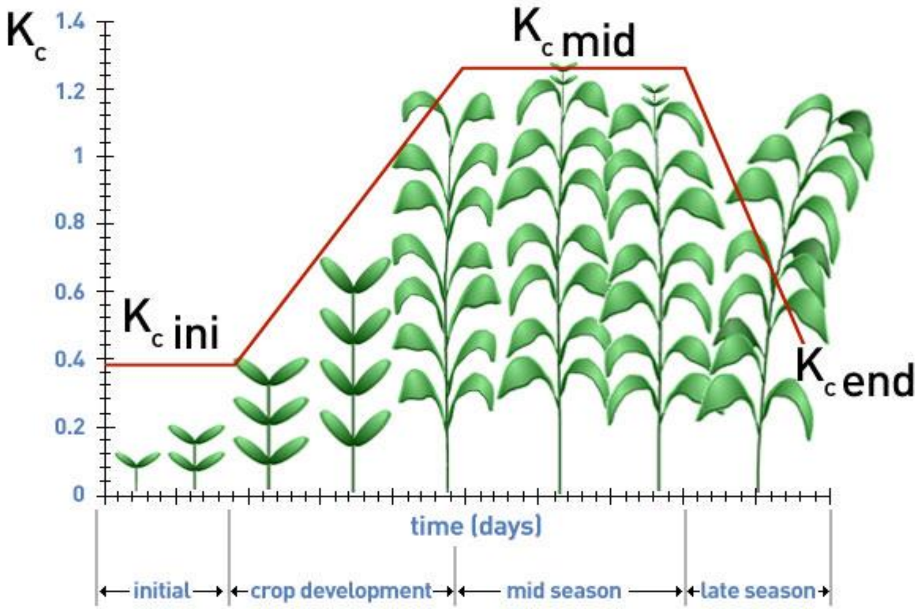


Figure 3.13 Generalized crop coefficient curve (FAO 2020)

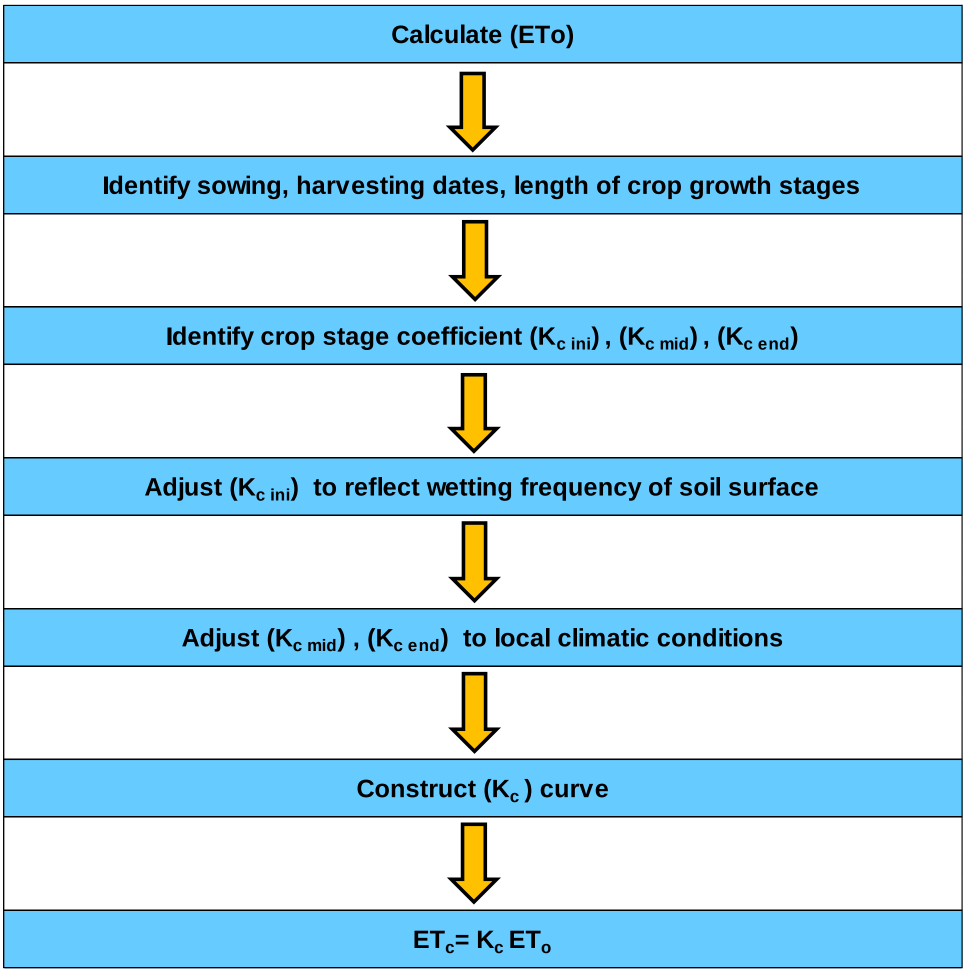


Figure 3.14 General procedure to calculate ET_{ci}

By considering the effective rainfall, the monthly crop consumptive water requirements ($\mathrm{CWR_i}$) per unit area (1feddan=4200.82 m^2) can be calculated as follows:

$$\mathrm{CWR_i} = (\mathrm{ET_{ci}}\text{-}\mathrm{P_e}) \times (4200.84/10^3) \tag{3.9}$$

where, $\mathrm{CWR_i}$ denotes the consumptive water requirement of crop i (m^3/feddan/month), $\mathrm{P_e}$ the effective rainfall (mm/month) and is calculated as follows:

($\mathrm{P_e} = 0.6\ \mathrm{P}\text{-}10 \quad \text{for } \mathrm{P} \le 70\ \mathrm{mm}$), or ($\mathrm{P_e} = 0.8\ \mathrm{P}\text{-}24 \quad \text{for } \mathrm{P} > 70\ \mathrm{mm}$), P is the rainfall, and 4200.84 is a conversion factor used to calculate the crop water requirements per feddan (1feddan=4200.84 m^2).

Dominant crops in each season were considered: (a) wheat, sugar beet, and clover for the winter season, (b) maize, sorghum, rice, and sugar cane for the summer season, and (c) maize for the Nili season. Vegetables were also considered in the three seasons, together with fruits. The considered crops represent over 80% of the total cultivated crop area. Also, other crops were aggregated and considered as one component for their irrigation demands. Also, the monthly water requirement for each crop was calculated for the three main climatic zones in Egypt (i.e., Upper Egypt, Middle Egypt and Lower Egypt). The average monthly water requirement of the three regions was calculated for each crop and used as the crop consumptive water demand at the national level. The crop-related data that required to calculate ($\mathrm{ET_{ci}}$) and crop consumptive water demands for each climatic zone and at the national level are summarised in appendix (C). A comparison between the calculated crop water requirements in this study and the crop water requirements estimates from the ministry of water resources and irrigation in Egypt is also shown in appendix (C).

The irrigated area of crops together with the crop water demands are used to estimate the water demands for the agricultural sector. The ratio of crop (i) area to the agricultural land ($\mathrm{C_i}$) was estimated from the FAOSTAT database (FAO 2020) and the annual bulletins for crop areas from the Central Agency for Public Mobilization and Statistics (CAPMAS), Egypt, (CAPMAS Various years-c). The crop ratio of crop (i) together with the total agricultural land (calculated from the agricultural land sub-model) were used to calculate the irrigated area of crop (i) as shown in the CLDs, Figure 3.12. The monthly agricultural water demand (AWD) can be calculated from the following equations:

$$\mathrm{A_i = Agr_{land} \times C_i}, \tag{3.10}$$

Where, $\mathrm{A_i}$ denotes the area of crop i (feddan), $\mathrm{Agr_{land}}$ is the agricultural land (feddans) and $\mathrm{C_i}$ the agricultural land percentage of the crop (i).

$$\mathrm{AWD} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{\mathrm{CWR_i}}{\eta_{\mathrm{irr}}} \mathrm{A_i} \tag{3.11}$$

Where, $\mathrm{CWR_i}$ denotes the consumptive water demand of crop (i) (m^3/feddan) and η_{irr} stands for the irrigation method efficiency.

In the event of water shortage, the water shortage would be allocated to the agricultural sector as mentioned above. This is shown through the balancing loop B5, Figure 3.12. In the case that the water demands exceeds the water supply (i.e., water shortage condition), the model calculates the water shortage and allocates it to the agricultural sector. The reduction in agricultural water withdrawal affects food production and will be explained in the food production sub-model (3.3.2). It is worth mentioning that the model did not fully consider the on-farm management skills of farmers, e.g., excess irrigation water application, but this was beyond the current work scope.

3.4.1.2.B Domestic and Industrial Water Demands

The domestic water demand at the national level is calculated as a function of the population size and per capita water demand, Figure 3.12. The population levels were calculated from the population sub-model (3.3.3). The population estimates were divided into the urban and rural population with their associated consumption rates. According to urban and rural population estimates available from The World Bank (2019), it was assumed that urban and rural population percentages (% of the total population) are 43% and 57%, respectively, Figure 3.15. The Egyptian Code of practice for drinking water supply (MHUUC 2010) gives the daily demand rate for different regions, Table 3.3. From model calibration, the water demand rate for the urban populations is estimated at 270 litres/capita/day (l/c/d), and 130 (l/c/d) for the rural populations. Also, the water

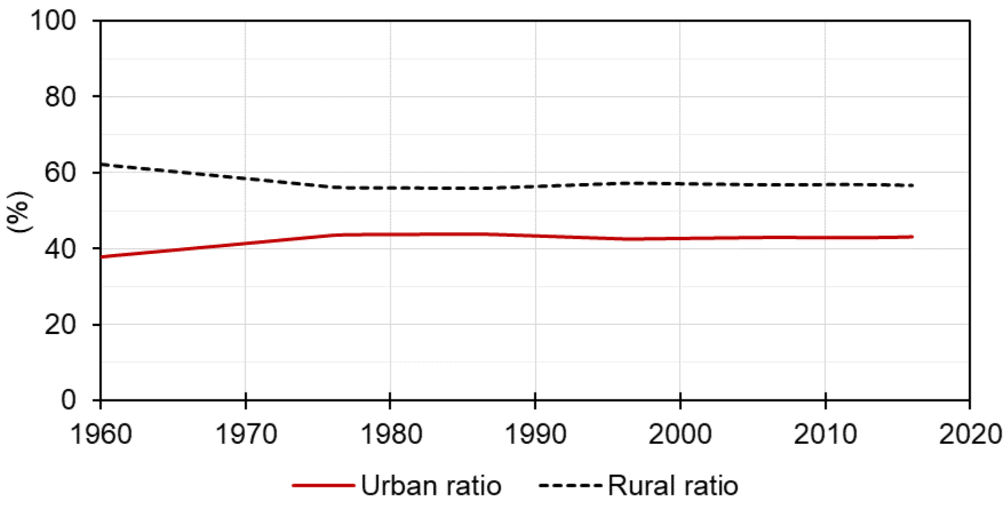


Figure 3.15 Percentage of urban and rural populations in Egypt (The World Bank 2019)

distribution network efficiency is estimated at 0.70 and is found to be similar to reported values in the literature (e.g., CEDARE 2011; Abdelkader et al. 2018).

Table 3.3 Domestic water demand by region, (MHUUC 2010)

Service area	Population (1000)	Demand rate (l/c/d)
Villages	≤ 50	100-150
Markaz	50-500	150-200
Small city	500-1000	200-250
Metropolitan	>1000	250-280
New cities	-	280-320
Touristic	-	350-400

The monthly domestic water demand (DWD) at the national level can be calculated as follows:

$$\mathrm{DWD} = \frac{(\mathrm{U_{pop}} \times \mathrm{D_{urban}} + \mathrm{R_{pop}} \times \mathrm{D_{rural}}) \times \mathrm{N_{d/month}}}{1000 \times \eta_{\mathrm{net}}} \quad (3.12)$$

Where, $\mathrm{U_{pop}}$: urban population, $\mathrm{D_{urban}}$: daily per capita urban water demand (l/c/d), $\mathrm{R_{pop}}$: rural population, $\mathrm{D_{rural}}$: daily per capita rural water demand (l/c/d), $\mathrm{N_{d/month}}$: Number of days per month, and η_{net}: drinking water network efficiency.

Industrial water is supplied from the drinking water network and also directly from the Nile River, canals and groundwater wells. Therefore, the domestic water demand estimated above includes some water for the industry. Based on recent national water balances from CAPMAS (CAPMAS Various years-d), the industrial water demand was assumed to be 1.20 km^3/year and is similar to estimates reported in the MWRI's Strategy 2050 (MWRI 2011).

3.4.1.2.C Navigation, Environmental and Hydropower Water Demands

The main course of the Nile River and parts of the irrigation network are used for navigation. The demand for navigational purposes coincides with the low flows period (i.e. winter closure). Recently, water releases for navigation are insignificant and estimated at 0.20 km^3/year, (CAPMAS Various years-d). There is however a guaranteed minimum release from the HAD, which is also required for some drinking water intakes along the Nile. Since the 1988 drought, no additional water is exclusively released for hydropower generation i.e., HAD hydropower is a by-product of downstream water releases (ICID 2004). Successive national water policies set different measures to manage the system, meet growing water demands and achieve national goals (e.g. agricultural land expansions). One of these measures is to reduce the water allocated to navigation, regulation, and hydropower generation. These annual water requirements were reduced from 4.0 km^3 in 1980 water policy, to only 0.30 km^3 in 1990 water policy. This gradual reduction is considered in agricultural land development and will be explained in the food sub-model.

3.4.1.2.D Open Water Evaporation

The evaporative losses from open water surfaces can be calculated as the product of surface area and evaporative rate. The open water surfaces include the surface area of: (a) the Main River and (b) the irrigation canals network. The surface area of the main Nile and irrigation network in the Nile Valley and Delta was provided by NWRP (2000). The corresponding evaporation rate is calculated according to Penman's formula for open water surfaces (Allen et al. 1998). The annual open water evaporation from open water surfaces is estimated at 2.04 km^3. The estimated value is found to be within the reported range 2.00-2.50 (national water balance, CAPMAS Various years-d) and close to the reported value 2.40 in NWRP (2000).

3.4.2 Egypt Food Sub-Model

The food sub-model considers the food demand and supply at the national level, with a focus on food from arable land cultivation since other food sources (e.g., fisheries and livestock) are small, (Meadows et al. 1974). The food sub-model interacts with the other sectors e.g., water, energy and socio-economic dynamics as shown in the CLDs in Figure 3.16. The interaction between the water and food domains can be traced through the two main loops R2 and B3. The agricultural land acts as a moderator and links the two loops. The loop R2 is a reinforcing loop, i.e., as the population increase, the food demand increases and puts pressure on the agricultural land, leading to an expansion in the agricultural land.

The increase in agricultural land leads to an increase in food production and the domestic food supply as well. The increase in the food domestic supply leads to better population nutrition (i.e., fewer deaths due to undernourishment which lead to overall population growth).

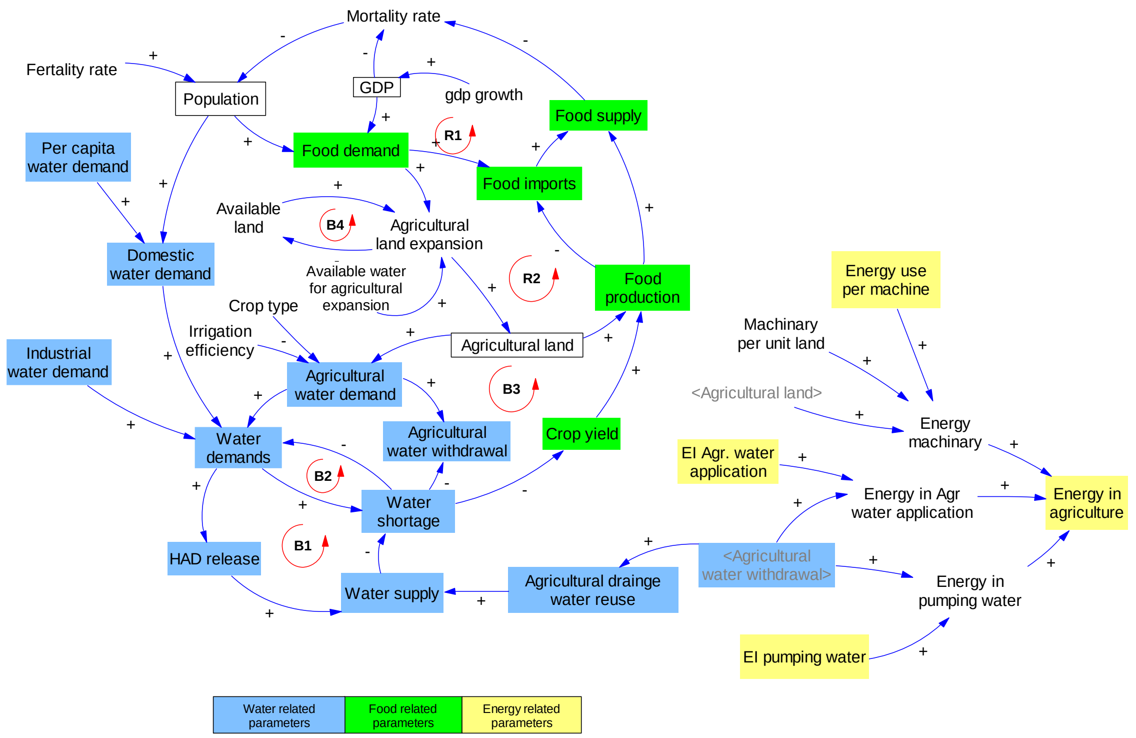


Figure 3.16 Egypt's CLDs for WFE nexus and socio-economic interactions

Loop B3 is a balancing loop and shows the interactions among the different sectors of population, food, water and agricultural land. As the agricultural land increases following population growth, the agricultural water demands increase and lead to an increase in water shortages. Reduced water availability (i.e., increased water shortages) reduces crops yield and domestic food production. Reduction in food production reduces food supply and results in higher mortalities (i.e., reduced population). The two reinforcing loops R1 and R2 demonstrate the interaction between the food sector and the socio-economic conditions (i.e., population and Gross Domestic Product (GDP) per capita). As the population increases the food demand increases and, in turn, the food imports are increased. The underlying structure of the food sub-model will be explained in the next paragraphs considering the food demand and supply (section 3.3.2.1). The interaction between the food and energy is shown through the energy demands in the different agricultural activities (e.g., pumping water for irrigation, machinery use in the agricultural sector, irrigation water application). The energy demand in the agricultural sector will be explained in the energy sub-model in Section 3.3.5.

3.4.2.1 Egypt Food Demand

The food demand is mainly driven by the population and the living standards represented here as GDP per capita. A common measure that represents human nutrition requirements is "kg food per capita or kilocalories (kcal) per capita". In this study, the kcal per capita per day was chosen to represent the average daily food consumption at the national level. The food balance sheets (FBS) from FAO (2020) provide information on patterns of different food supply and consumption within a country for a certain period e.g., food domestic production, food imports, food exports, humans' food, animal feed, seeds and losses. The trends in average food consumption (kcal/capita/day) and average annual income (GDP/capita) in Egypt are shown in Figure 3.17 and Figure 3.18, respectively. A relationship between food consumption and income at the national level is also shown in Figure 3.19. This relationship shows that food consumption increases with the income level, i.e., an increase in the income leads to an increase in the food consumption and vice-versa, similar to previous findings from the literature (e.g., Meadows et al. 1974). Not surprisingly, the relationship exhibits a saturation behaviour, i.e., the increase in food consumption will stabilise at a certain level regardless of the increase in income, due to human nutrition capacity. This is shown in Figure 3.17, as over the last decade there was an insignificant increase in average food consumption at the national level.

Based on the relation between food consumption and income, a lookup table was constructed and used in the model simulations to determine the demand for food based on the income level, Figure 3.19. Likewise, the demand for a specific food commodity (i) can be determined. A relationship between the income and the share of food commodity (i) in the food mix can be established. For example, the relationship between wheat share in daily food mix and the income is shown in Figure 3.20. The food commodities considered in this study are wheat, maize, sorghum, sugarcane, vegetables and fruits. They constitute about 75% of the total daily food intake in Egypt. The relationships for the income and the share of these food commodities in the food mix are provided in appendix (C). The impacts of seasonal variations, group income levels, and demographic factors (e.g., gender, age) on food demand were not considered in this work but that was beyond the scope of this study.

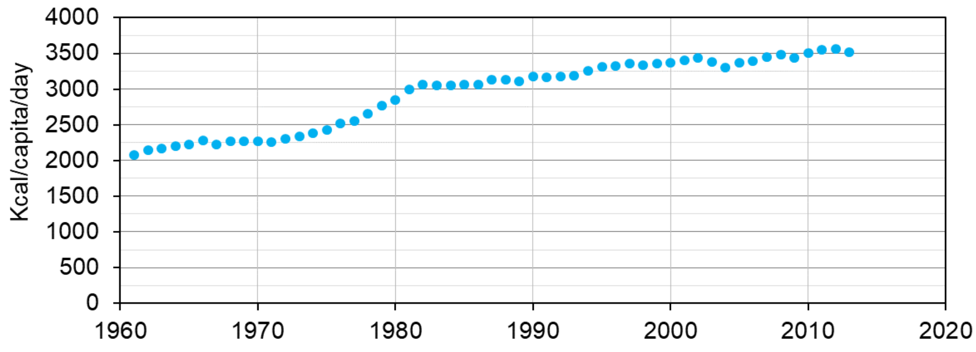


Figure 3.17 Average daily food consumption per capita, Egypt (FAO 2020)

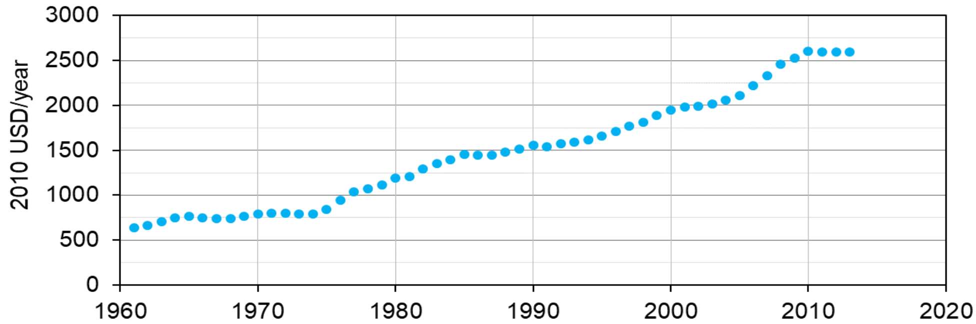


Figure 3.18 GDP per capita in Egypt (The World Bank 2019)

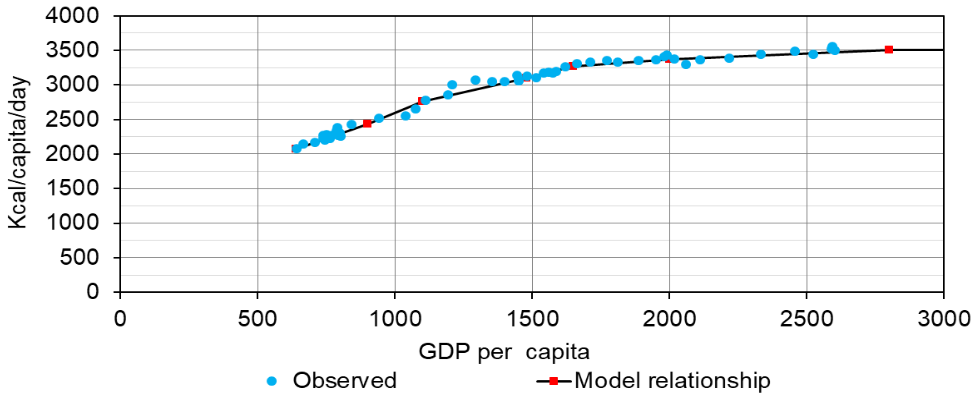


Figure 3.19 Daily kcal consumption-GDP per capita relationship

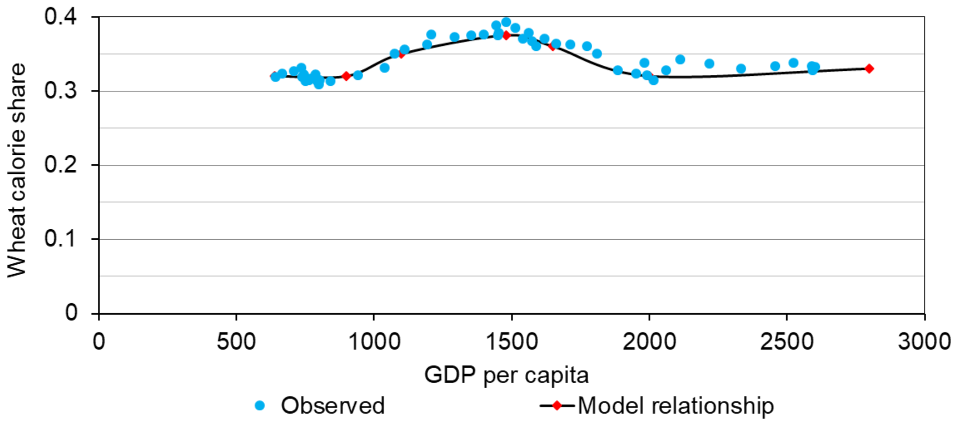


Figure 3.20 Wheat calorie share-GDP per capita relationship

The food demand is referred to be the desired food demand (either in kcal or kg) per capita per day. The CLDs of food demand is shown in Figure 3.21. The annual demand for food commodity (i) can be calculated based on an income level (GDP/capita) as follows:

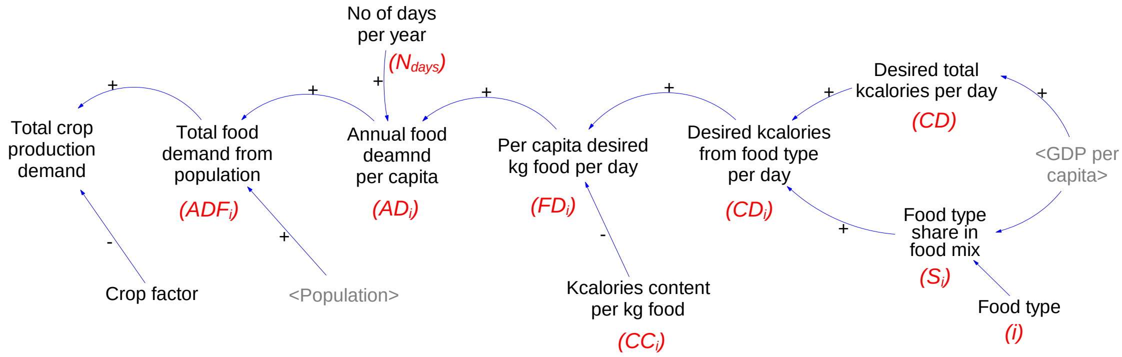


Figure 3.21 CLDs for food demand

(1) Estimate the desired kcal demand (CD) (kcal/capita/day) from the food consumption-income relationship,

(2) Estimate the share of food commodity (i), (S_i), in the food mix from the food commodity share-income relationship,

(3) Calculate the desired kcal demand from food commodity (i) ,(CD_i) (kcal/capita/day),

$$CD_i = CD \times S_i, \tag{3.13}$$

(4) Calculate the desired demand for food commodity (i), (FD_i) (kg/capita/day),

$$\mathrm{FD_i} = \frac{\mathrm{CD_i}}{\mathrm{CC_i}} \tag{3.14}$$

where, $\mathrm{CC_i}$ denotes the kcal content per 1.0 kg of food commodity (i) (kcal/kg)

(5) Calculate the desired annual demand for food commodity (i), $(\mathrm{AD_i})$ (kg/year)

$$\mathrm{AD_i} = \mathrm{FD_i} \times \mathrm{N_{d/year}} \tag{3.15}$$

where, $\mathrm{N_{d/year}}$ denotes the number of days in a year (i.e., 365)

(6) Calculate the desired annual demand for food commodity (i) from the population $(\mathrm{ADF_i})$ (1000 tons),

$$\mathrm{ADF_i} = \frac{\mathrm{AD_i} \times \mathrm{Pop}}{10^6} \tag{3.16}$$

where, Pop denotes the population size.

The above steps represent the demands from the population (i.e., food). To account for other demands of a certain crop (e.g., feed, seeds, etc.), a factor that incorporates these other demands was estimated from the FBS and named "crop factor". The annual production demand from crop (i) $(\mathrm{PD_i})$ (1000 tons/year) can be estimated as follows:

$$\mathrm{PD_i} = \frac{\mathrm{ADF_i}}{\mathrm{F_i}} \tag{3.17}$$

Where, $\mathrm{F_i}$ denotes the crop food factor of crop (i).

3.4.2.2 Egypt Food Supply

The food supply for the considered food commodities comes from domestic food production and food imports. Since domestic food production is produced from land cultivation. The structure of the agricultural land sub-model will be explained first followed by a description of food production and food imports sub-models.

3.4.2.2.A Agricultural Land Sub-Model

Egypt has limited agricultural land resources as currently about 3.8 % of the total country area is under cultivation. As mentioned earlier, the base of the agricultural land is located in the Nile Valley and Delta (i.e., Old lands), and the newly reclaimed land in the desert since 1952 (i.e., New lands). Land reclamation in Egypt has been practised throughout the history, and there has been a continuous effort from consecutive governments to reclaim new lands to face the growing food demands from population and the raw materials for the industry. The total reclaimed land since 1952 until now is estimated at 3.0 Million feddans (CAPMAS Various years-c). Currently, the total agricultural land is estimated at 9.10 Million feddans (6.16 Old lands and 2.94 New lands), (CAPMAS Various years-c).

The consecutive national water resources policies set different measures to secure water for the newly reclaimed lands as well as meeting demands from the other sectors (ICID 2004). These measures can be summarised as follows: (a) expansion in agricultural drainage water reuse, (b) expansion in groundwater abstraction in the Nile valley and Delta (shallow groundwater) and desert areas (deep groundwater), (c) reduction in navigational and hydropower generation water requirements and (d) irrigation system improvements.

Table 3.4 presents the main measures from successive national water policies to secure water for the newly reclaimed lands (ICID 2004; MWRI 2005; MWRI 2011). The current agricultural development strategy (SADS 2030) estimates that the total agricultural land will be 11.50 million feddans by 2030 (with 3.10 million feddans to be reclaimed) (MALR 2009). Additional water required for land reclamation is assumed to come from improving the irrigation systems (e.g., introducing efficient irrigation methods in old lands) and reducing the use of water-intensive crops (namely rice and sugarcane) (MALR 2009; MWRI 2011), together with increased groundwater abstraction and agricultural drainage water reuse. In contrast, the ministry of the water resources expects the total agricultural land to reach 11.80 million feddans by 2050 (MWRI 2011). This difference between the two strategies is considered and will be discussed in chapter (5).

Table 3.4 Policy measures for securing water for land development in water policies

Policy	Measures	Conclusions	Note
1975	Expansion in agricultural drainage water reuse (12.16 km^3) Implementing upper Nile conservation projects (e.g. Jongeli canal project would add 9.0 km^3)	- Estimated additional water to be saved (16.76 km^3), - Estimated land to be reclaimed (2.50 million feddans)	Groundwater resources were given little attention
1980	Irrigation improvement program (IIP) would save (5.00 km^3) Jongeli canal project would add (2.00 km^3) Expansion in agricultural drainage water reuse (6.30 km^3 in 1985 and 10.00 km^3 in 1990) Expansion in groundwater abstraction (4.90 km^3 in 2000) Water savings from IIP was not considered until 2000	- Estimated additional water to be saved (7.90 km^3), - Estimated land to be reclaimed (1.58 million feddans)	The water resources would be updated every five years during (1980-2000)
1986	Jongeli canal project would be operational by 1992/1993 and add (2.00 km^3) Expansion in groundwater abstraction (4.00 km^3 in 1992, 4.90 km^3 by 2000) Expansion in agricultural drainage water reuse in Delta	- Estimated additional water to be saved by 1992/1993 (7.70 km^3/year), by 2000 (9.30 km^3/year) - Estimated land to be reclaimed by	Annual water saved was 2.30 km^3 only

	(3.40 km^3 by 1987, 6.30 km^3 by 1993 and 7.00 km^3 by 2000)	2000 (1.70 million feddans)	
	Storing water in the northern lakes during the winter closure (1.50 km^3)		
	Implementing IIP for 2.50 million feddans (2.00 km^3 would be saved by 2000)		
	Reducing water requirements of navigation and power generation (2.50 km^3 by 1993 and 1.50 km^3 by 2000)		
1990	Implementing Jongeli canal project by 2000	- Estimated additional water to be saved by (10.2 km^3), - Estimated land to be reclaimed (1.60 million feddans)	
	Expansion in agricultural drainage water reuse (7.00 km^3 by 2000)		
	Reducing water requirements of navigation and power generation (from 1.80 km^3 in 1990 to 0.30 km^3 in 2000)		
	Implementing IIP (would save 1.00 km^3 by 2000)		
	Improving the efficiency of the pipe network (an increase from 50% to 80%), i.e., no increase in domestic demand		
	Expansion in treated wastewater (1.10 km^3 in 2000)		
	Expansion in groundwater abstraction (up to 7.40 km^3/year)		

2017	Continue IIP, improve irrigation system efficiency, setting up water user associations	- Estimated land to be reclaimed (2.89 million feddans) in Facing the Challenge (FtC) strategy, while in the reference case was 3.04 million feddans	FtC strategy is the core of the water resources plan, includes measures for better water management by 2017
	Expansion in agricultural drainage water reuse (8.90 km^3 by 2017)		
	Expansion in groundwater abstraction (12.40 km^3 by 2017)		
	Rainfall and flash flood harvesting (1.30 km^3)		
	Expansion in treated wastewater (2.40 km^3 in 2017)		
	Expand desalination in coastal areas		
2050	Increase cooperation with Nile countries	Total irrigated area is expected to be 11.80 Million feddans (i.e., 2.70 million feddans will be reclaimed)	Planning in progress
	Expansion in groundwater abstraction (safe yield)		
	Rainfall and flash flood harvesting (1.50 km^3)		
	Expansion in agricultural drainage water reuse (7.5-8 km^3 in Delta)		
	Expansion in treated wastewater Expand desalination in coastal areas		
	Limit crop intensive water use areas (Rice, Sugar cane, Banana)		
	Expand desalination		

In developing the model, agricultural land considered here is the land suitable for cultivation and food production at the national level. The CLDs of the agricultural land together with its interactions with other domains (e.g., water, energy) is shown in Figure 3.22. Expansion in the agricultural land is driven by the increased demands for crop production. The demand for agricultural land can be estimated based on the demand for crop production (calculated from the food demand sub-model) and the crop yield. The difference between the agricultural land under cultivation and the demand for the agricultural land determines the agricultural land required for expansion. As discussed above, the expansion in the agricultural land depends on the amount of saved water from different sources and measures and the available arable land. Also, agricultural land development is constrained to a maximum development rate of 150 thousand feddans per year (for economic considerations) (MWRI 2005; MALR 2009). Actual expansion in the agricultural land can be then estimated based on available water and the water requirements per unit area.

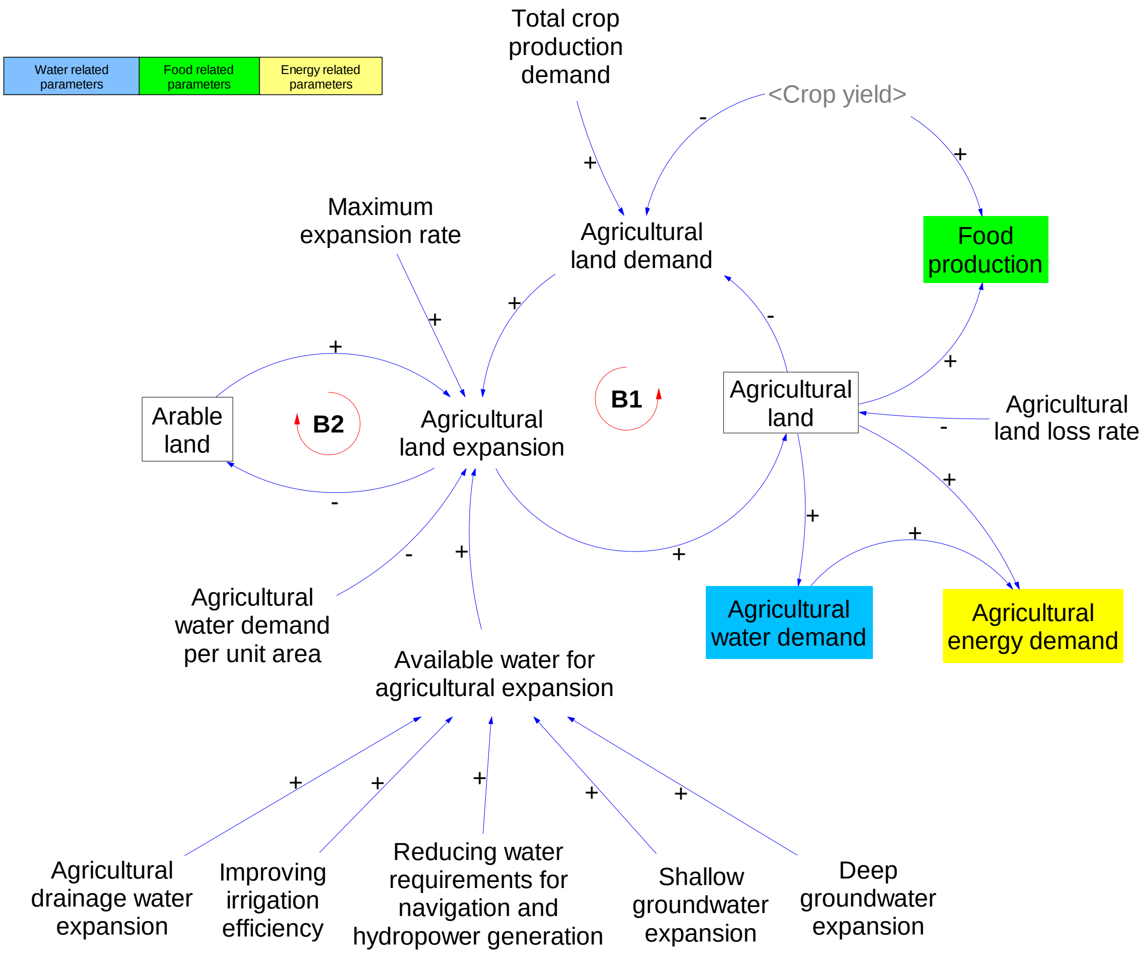


Figure 3.22 CLDs of the agricultural land in Egypt

In contrast, agricultural land is lost due to urbanization and soil degradation in Egypt. Several studies have been conducted to investigate the causes of agricultural land losses resources. The study conducted for the 1984 Water Master Plan project concluded that the agricultural land loss was between 10,000 and 75,000 feddans per year with an average estimate of 45,000 feddans per year (MWRI 2005). The Ministry of Agricultural Land and Reclamation carried out a study to investigate the loss in the agricultural land due to urbanization, land degradation and brick industry during the period 1983-1995. The average annual land loss was found to be 5.8 thousand feddans during the period of the study (MWRI 2005). El-Hefnawi (2005) discussed the loss of the agricultural land and the differences in agricultural land loss estimates in the literature. According to El-Hefnawi (2005), the agricultural land loss was found to be between 20,000 and 70,000 feddans per year and varied with time. In this study, a median value of 40,000 feddans per year was used and the sensitivity of the agricultural land loss will be shown in the sensitivity analysis section (3.3.7.1). The main parameters of the agricultural land sub-model are provided in Table 3.5.

Table 3.5 Agricultural land development parameters

Parameter	Value	Source
Agricultural land (in 1980)	5715 (thousand feddans)	CAPMAS (Various years-a)
Maximum reclamation rate	150 (thousand feddans/year)	MWRI (2005)
Delay in agricultural land development	3 years	Assumption
The agricultural land loss rate	40 (thousand feddans/year)	Assumption according to El-Hefnawi (2005)
Annual water requirements per unit area	5900 m^3/feddan	ICID (2004)

3.4.2.2.B Domestic Food Production

The food production considered here is the output from the cultivated land (i.e., domestic food production) for the considered food crops. The cultivated crops considered in this study covers more than 80% of the total cultivated crop area in Egypt. The CLDs of food production and its interactions with other sub-models are shown in Figure 3.23. The agricultural production of crop (i) can be estimated by multiplying the area of crop (i) by the yield of crop (i). The crops area are calculated based on the agricultural land and the adopted cropping pattern, as explained above in the agricultural water demand sub-model, Figure 3.23. The crop yield for the considered crops was taken from the FAO database (FAO 2020). The average yield for the vegetables group and the fruits group were estimated and used in the model.

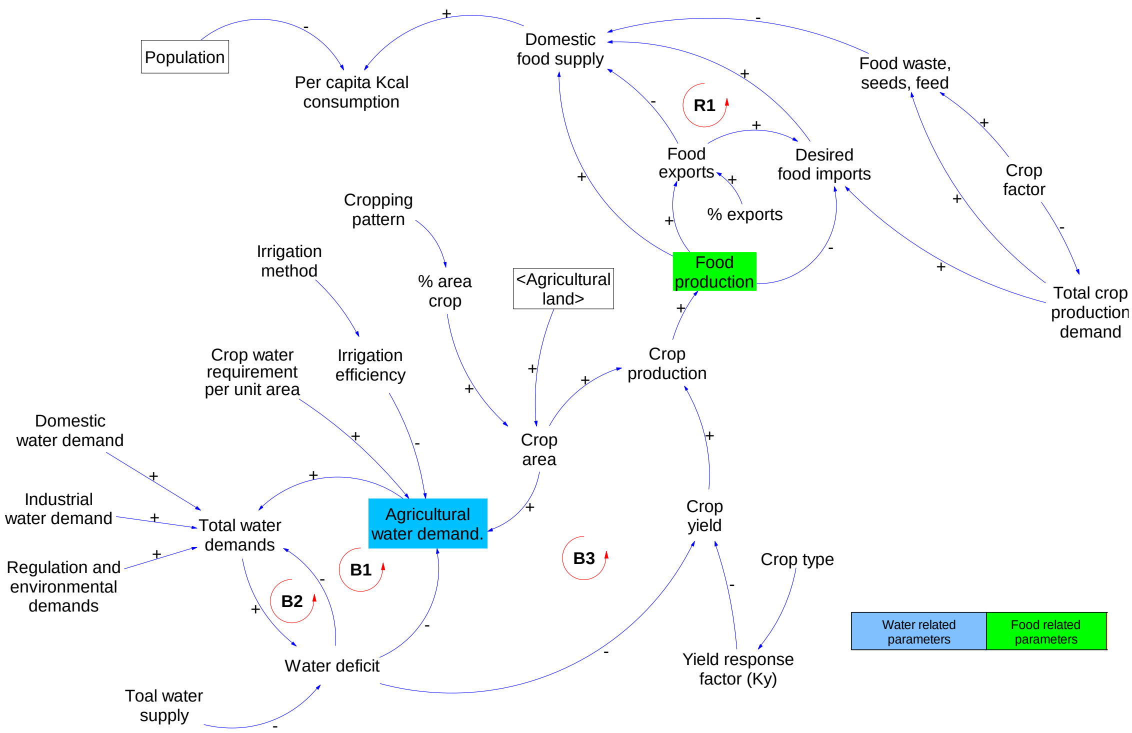


Figure 3.23 CLDs of the food supply sub-model

In the event of water shortages, as mentioned earlier, they would be allocated to the agricultural sector and eventually affect agricultural production. The reduction in crop yield due to water shortage is modelled using a simple form of the FAO "crop yield response to water" approach (Steduto et al. 2012). It is worth mentioning that in case that when a water shortage occurs, the shortage is evenly divided among the growing crops in the concerned season. The ratio of the actual crop water consumption to the crop water demand is considered as a proxy for the ET_a/ET_c ratio. This assumes the reduction in the crop evapotranspiration is equal to the reduction in the irrigation supply (i.e., ignoring water stored in the soil from previous irrigation application). This approach is considered to be suitable for the case of Egypt where irrigation is predominantly practised and effective rainfall is found to be insignificant at the national level.

However, this method could overestimate the reduction in food production. The sensitivity of this assumption was tested and showed negligible impacts (<1%) on food production (not shown here). The yield response factors for the considered crops were available from FAO irrigation and drainage paper no. 66, (Steduto et al. 2012). The food production (FP) in tonnes can be estimated as follows:

$$\mathrm{FP} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{A_i} \times \mathrm{Y_{ai}} \tag{3.18}$$

Where, $\mathrm{A_i}$ denotes the area of the crop i (feddan), and $\mathrm{Y_{ai}}$ the actual yield of crop i (ton/feddan).

The actual crop yield of crop i can be estimated as follows:

$$\mathrm{Y_{ai}} = \mathrm{Y_{mi}} \times \left(1\text{-}\mathrm{K_{yi}} \times (1\text{-}\frac{\mathrm{ET_{ai}}}{\mathrm{ET_{ci}}})\right) \tag{3.19}$$

Where, $\mathrm{Y_{mi}}$ stands for the maximum possible yield of crop i and considered here is the observed crop yield following previous studies (e.g., Siderius et al. 2016; Abdelkader et al. 2018). This is a simplified assumption that gives a fair estimate by accounting for the effects of water shortage on crop yield and food production, $\mathrm{K_{yi}}$ for the yield response factor of crop i where $\mathrm{ET_{ai}}/\mathrm{ET_{ci}}$ denotes the ratio of actual evapotranspiration of crop i ($\mathrm{ET_{ai}}$) to the maximum evapotranspiration of crop i ($\mathrm{ET_{ci}}$).

3.4.2.2.C Food Imports

The food imports are considered a part of the food supply within a country as shown in Figure 3.23. It was assumed that the country will have the capacity to import the necessary amounts of food commodities and the global markets and prices are stable. Giving the fact that the food subsidy system in Egypt covers approximately 77% of the population (Talaat 2018), it is difficult to capture the impact of food prices on supply and demand patterns from historical data (Abdelkader et al. 2018). In this regard, it was assumed that food imports can be estimated from the difference between the total demand and the domestic production of food commodities. The food production is calculated from the food production sub-model while the food demand is calculated from the food demand sub-model as explained above. For each food (crop) commodity, the food production, imports, and demand were calculated on an annual basis. Also, the changes in stocks were not considered here (i.e. the model did not assume equilibrium and no need for a stock as suggested by (Gerber 2015; Abdelkader et al. 2018) as the food commodities are assumed to be consumed with in the same year).

3.4.3 Egypt Population Sub-Model

The population sub-model simulates the population dynamics and their interactions with the resources. The CLDs of the population and their interactions with other domains is shown in Figure 3.24. The model in its simple form can be described by demographic relationships (Loops B1 and R1). The population is increased by an increase of the births rate, i.e., larger the population, the more fertile people and the more births, Loop (R1). In contrast, the population is decreased by an increase of the deaths rate, i.e., the more deaths there are the fewer population will be, loop (B1). The two loops are driven by the fertility rate and mortality rate, represented here as a function of the life expectancy for each age group. The fertility rate is considered as an exogenous variable to the model,

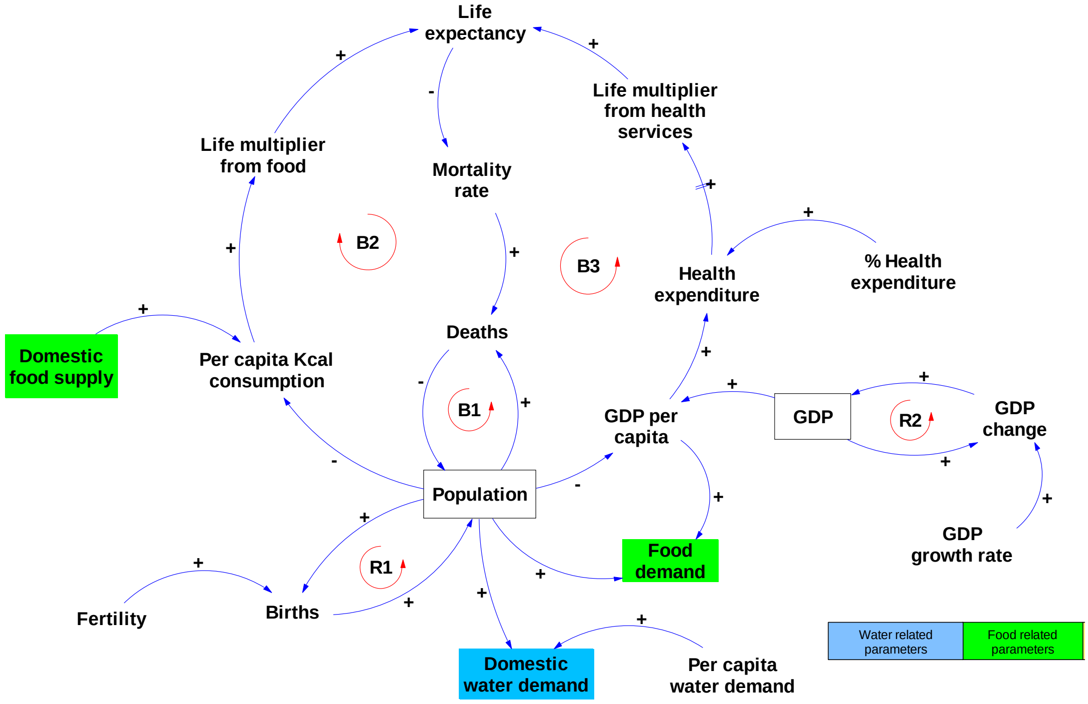


Figure 3.24 CLDs of population sub-model

while the life expectancy is influenced by the food consumption and health services via the balancing loops B2 and B3, Figure 3.24. The two loops tend to counteract the reinforcing loop R1. The causal relationships and the model structure were adapted from the world3-model (Meadows et al. 1974).

The structure of the population sub-model is composed of 15 age groups; each age group represents five years, except the youngest and oldest age groups, i.e., (0-1), (1-4) and (65 and above). However, the population model can be categorised into four main age groups: (0-14), (15-44). (45-64) and (65 and above). The population is increased by new births in the first age group (0-1), while the other age groups increase through the ageing of the younger age groups, i.e., maturation. The delay in maturation from each age-specific group to the next age group is assumed as a first-order delay by assuming that it will be equal to the average number of years each person stays in that group, e.g., 5 years. The number of births ($\mathrm{N_b}$) can be calculated from the following relationship:

$$\mathrm{N_b} = \frac{\mathrm{Pop_{(15\text{-}44)}} \times \mathrm{F} \times \mathrm{W_r}}{\mathrm{P_{time}}} \tag{3.20}$$

Where, $\mathrm{Pop_{(15\text{-}44)}}$ denotes the population in age group (15-44), F the fertility rate (number of children per woman), $\mathrm{W_r}$ women ratio in the age group (15-44) population (assumed to be 0.50) and $\mathrm{P_{time}}$ the woman's reproductive lifetime (assumed 30 years).

The population is decreased by deaths and ageing from the younger age group to the next older age group. The age-specific death rate for age groups (15-44), (45-64) and (65 and above) was assumed to be the same within each age group. Assuming the same death rate for the entire age group (0-14) was found to prevent correct model calibration. Therefore, the death rate of the age group (0-14) is separated between the younger age group (0-4), and the rest of the group (i.e., (5-9) and (10-14)). The number of deaths ($\mathrm{N_d}$) for a specific age group can be calculated as follows:

$$\mathrm{N_d} = \mathrm{Mor_{rate}} \times \mathrm{Pop_{group}} \tag{3.21}$$

Where $\mathrm{Mor_{rate}}$ stands for the mortality rate of each age-specific group and is a function of the life expectancy (Equation (3.22)) and $\mathrm{Pop_{group}}$ is the population in the age group.

$$\mathrm{Mor_{rate}} = \mathrm{f(LE)} \tag{3.22}$$

Where $\mathrm{Mor_{rate}}$ is the mortality rate of each age-specific group and is a function of the life expectancy (LE).

The total population (Pop) is the sum of the population size of each age group and can be estimated from equation (3.23). Crude birth rate (CBR) and crude death rate (CDR) can be also estimated from equations (3.24) and (3.25).

$$\mathrm{Pop} = \mathrm{Pop_{(0\text{-}14)}} + \mathrm{Pop_{(15\text{-}44)}} + \mathrm{Pop_{(45\text{-}64)}} + \mathrm{Pop_{(65+)}} \tag{3.23}$$

$$\mathrm{CBR} = \mathrm{N_b/Pop} \tag{3.24}$$

$$\mathrm{CDR} = \mathrm{N_d/Pop} \tag{3.25}$$

Key demographic data, e.g., the initial population level for each age group, fertility rate, life expectancy, female/male ratio and model life tables were obtained from the 2017 Revision of World Population Prospects, (United Nations 2017).

3.4.4 Egypt Economic Sub-Model

The economic model simulates GDP (constant 2010 $) at an aggregated level. The first-order accumulation of GDP is considered through a reinforcing loop (the growth rate in GDP), and the annual growth rate is an exogenous variable as shown in Figure 3.24. The per capita GDP ($\mathrm{GDP_{pc}}$) can be estimated by dividing the total GDP by the total population. The GDP and $\mathrm{GDP_{pc}}$ can be calculated as follows:

$$\mathrm{GDP_{t+1}} = \mathrm{GDP_t} \times (1 + \mathrm{r_{GDP}}) \tag{3.26}$$

$$\mathrm{GDP_{pc}} = \mathrm{GDP/Pop} \tag{3.27}$$

Where, $\mathrm{GDP_t}$ and $\mathrm{GDP_{t+1}}$ are the GDP at time t and $\mathrm{t+1}$ respectively, and $\mathrm{r_{GDP}}$ stands for the GDP growth rate.

3.4.5 Egypt Energy Sub-Model

The energy sub-model considers the energy use for the different activities in the water and food systems. Energy is required for pumping, distributing, treating and purifying water, and for desalination. Food production requires energy for machinery used in agriculture, fertiliser production, and irrigation practises. The CLDs of the energy demand in different activities (e.g., water pumping and irrigation) are shown in Figure 3.25 and Figure 3.26.

The approach adopted here considers the energy intensity of each activity to estimate the energy demands in the water and food sectors. Widely reported estimates for energy intensities from (Plappally and Lienhard V 2012; Napoli and Garcia-Tellez 2016) were used in this study with region-specific energy intensities for activities when available (Daccache et al. 2014; Ouda et al. 2016b). Energy for machinery was considered for tractors only since they predominate the machinery use in Egypt. The annual energy demands are estimated in GWh. The energy demand in a water activity can be estimated by multiplying the water quantity required for an activity by the energy intensity of the activity.

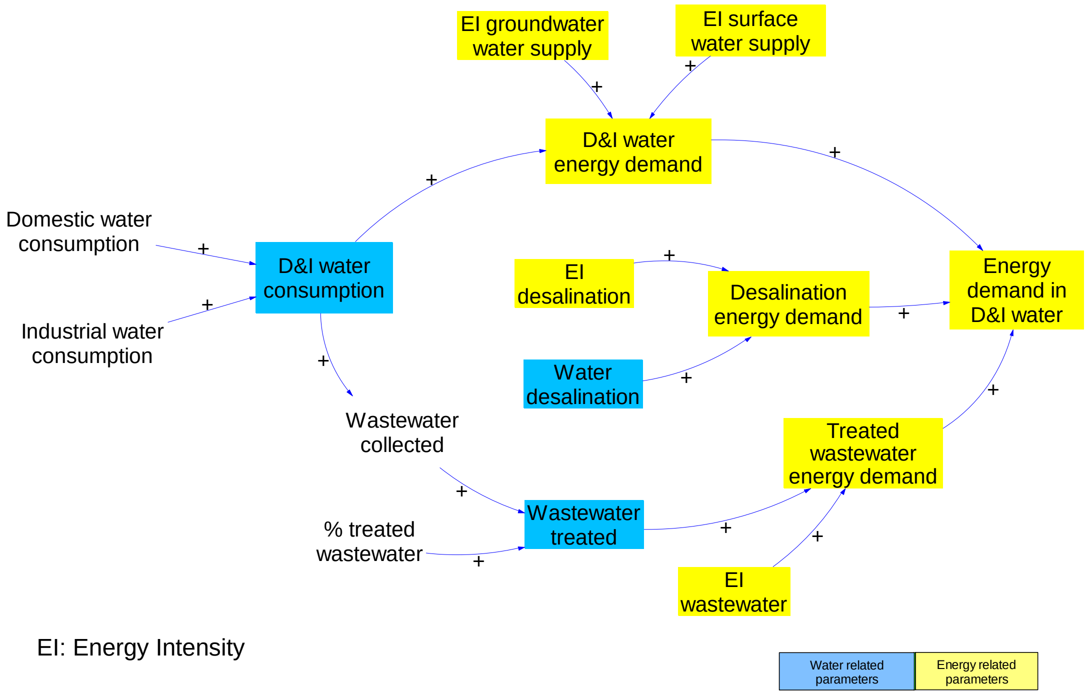


Figure 3.25 CLDs of energy demand in the domestic and industrial water

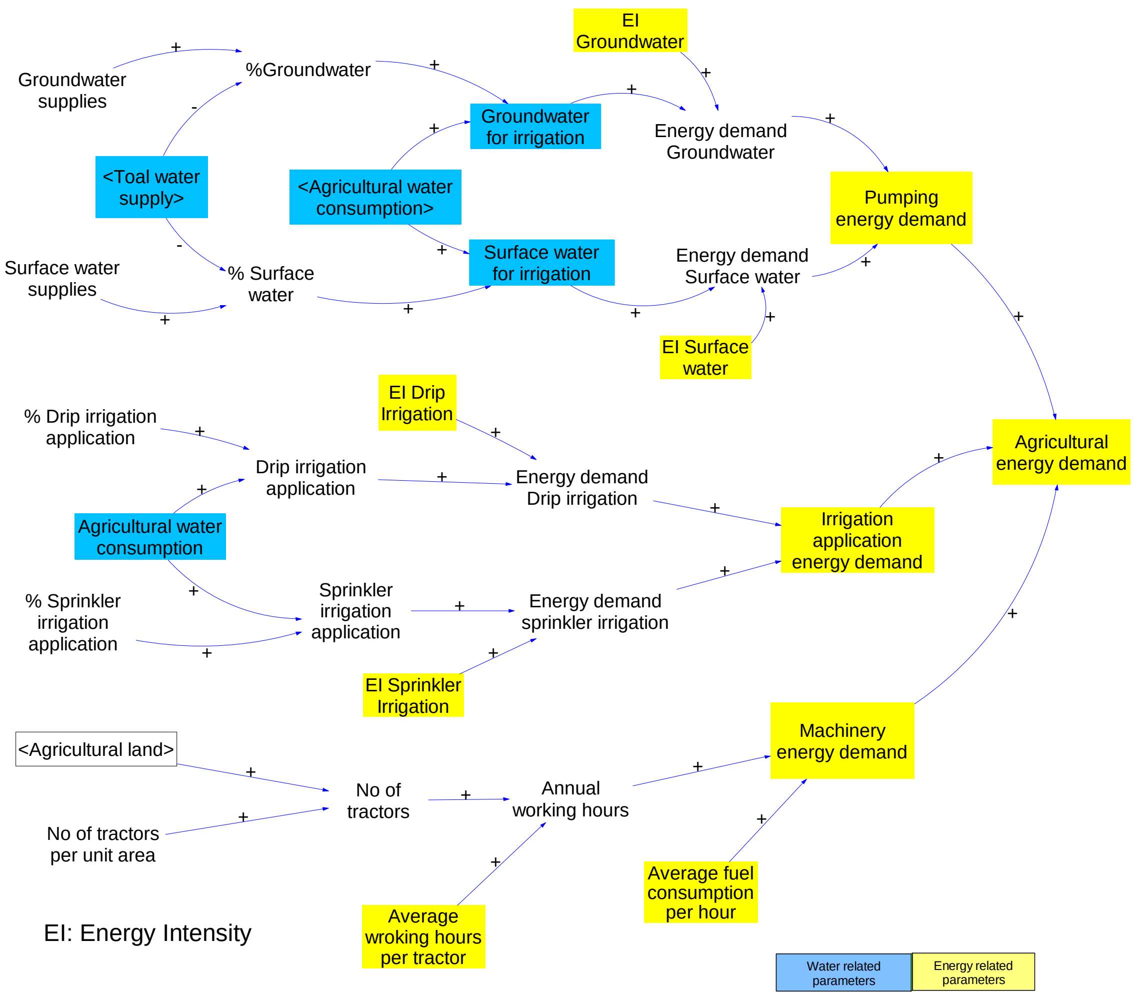


Figure 3.26 CLDs of energy demand in the agricultural sector

The annual energy demand in a water activity $\mathrm{AEDW_{activity}}$ can be estimated as follows:

$$\mathrm{AEDW_{activity}} = \sum_{i=1}^{12} \frac{\mathrm{EI_{activity}} \times \mathrm{Q_{water}}}{10^6} \tag{3.28}$$

Where, $\mathrm{EI_{activity}}$ denotes the energy intensity of water activity (KWh/m^3), and $\mathrm{Q_{water}}$ the water quantity in (m^3).

The annual energy demand for machinery (AEDM) (GWh/m^3) can be estimated as follows:

$$\mathrm{AEDM} = \frac{\mathrm{N_{tractors}} \times \mathrm{N_{hrs}} \times \mathrm{E_{rate}}}{10^6} \tag{3.29}$$

Where, $N_{tractors}$ denotes the number of tractors used in agricultural activities, N_{hrs} is the average working hours per tractor (hrs/year) and E_{rate} is the energy consumption rate per tractor (KW). Further to this, the following equations were used:

$$N_{tractors} = Agr_{land} \times N_l \tag{3.30}$$

$$E_{rate} = F_{rate} \times EC \tag{3.31}$$

Where, Agr_{land} denotes the agricultural land (feddans), and N_l is the number of tractors per unit land (tractor/feddan), F_{rate} is the fuel consumption rate per tractor (litre/hr) and EC is the energy content per unit volume of fuel (KWh/litre).

The hydropower generation was considered from HAD, and the monthly hydropower generated values were estimated during the simulation. Annual hydropower generation can be then estimated in GWh using Equation (3.7) in a similar way.

3.4.6 Egypt Sub-Models Data Requirements

Water resources (e.g., groundwater, agricultural drainage reuse, rainfall, desalination, and treated wastewater) in Egypt were obtained from various sources (Abu-Zeid 1992; Elarabawy et al. 1998; MWRI 2005; Allam and Allam 2007; Abdin and Gaafar 2009; El-Din 2013; ENHC 2013; Omar and Moussa 2016; CAPMAS Various years-b). Domestic water consumption rates were obtained from the Egyptian Code of practice for drinking water supply (MHUUC 2010). Data on agricultural land, crops yield, and cropping patterns were available from (FAO 2020; CAPMAS Various years-c). Food Balance Sheets were available from FAOSTAT database (FAO 2020). Demographic data (e.g., fertility rates and mortality rates) were obtained from the Population Division, Department of Economic and Social Affairs, (United Nations 2017). Economic data (e.g., GDP and GDP growth rates) were obtained from the World Bank Open Data, (The World Bank 2019). Data on machinery such as machinery numbers, average working hours per machine and fuel consumption rate were taken from (Soliman and Migahed 1994; CAPMAS Various years-a).

3.4.7 Egypt Sub-Models Testing

The sub-models are interconnected and communicate with each other via links. The model defines a set of differential equations that have to be solved by numerical integration methods available in Simile. The historical model for Egypt runs at a monthly time step from 1980 to 2014, unlike the water resources model runs at a monthly time-step from 1950 to 2014 due to limited data available for the different sub-models. The performance of the other sub-models, in Egypt, was evaluated by: (1) comparing the simulated and observed data, and (2) using the following statistical measures: Percent bias (PBIAS), Root Mean Square Percent Error (RMSPE), Theil Inequality Coefficient (TIC), and Theil Inequality Statistics. These statistical measures quantify the overall behaviour discrepancy of the model, (see appendix (C) for equations of these indicators). RMSPE provides a normalised measure for the error between the simulated and observed data, TIC has been shown to be the best summarizing measure (Barlas 1989). Theil Inequality Statistics breaks the error down into three components; bias (U^M), variance (U^S), and covariance (U^C) between the simulated and historical data, (Sterman, 2000).

The comparison of the model simulation results and observed data for population, domestic water consumption, agricultural land, food production and food imports shows that the simulated data fits the observed data and their historical trends, Figure 3.27. It should be noted that results are shown in an annual basis due to observed data format availability (i.e., available in annual basis). The statistical tests results are shown in Table 3.6. The PBIAS for the model variables are small (< 10%) the RMSE values are small (3-13%) except for food imports, and TIC has low values that ranged from 0.01 to 0.08. Based on the comparison of the simulated and observed data and the statistical indicators, the model was able to reproduce the observed data with a satisfactory accuracy (Stephan 1992; Sterman 2000) and capture the trends of the observed data.

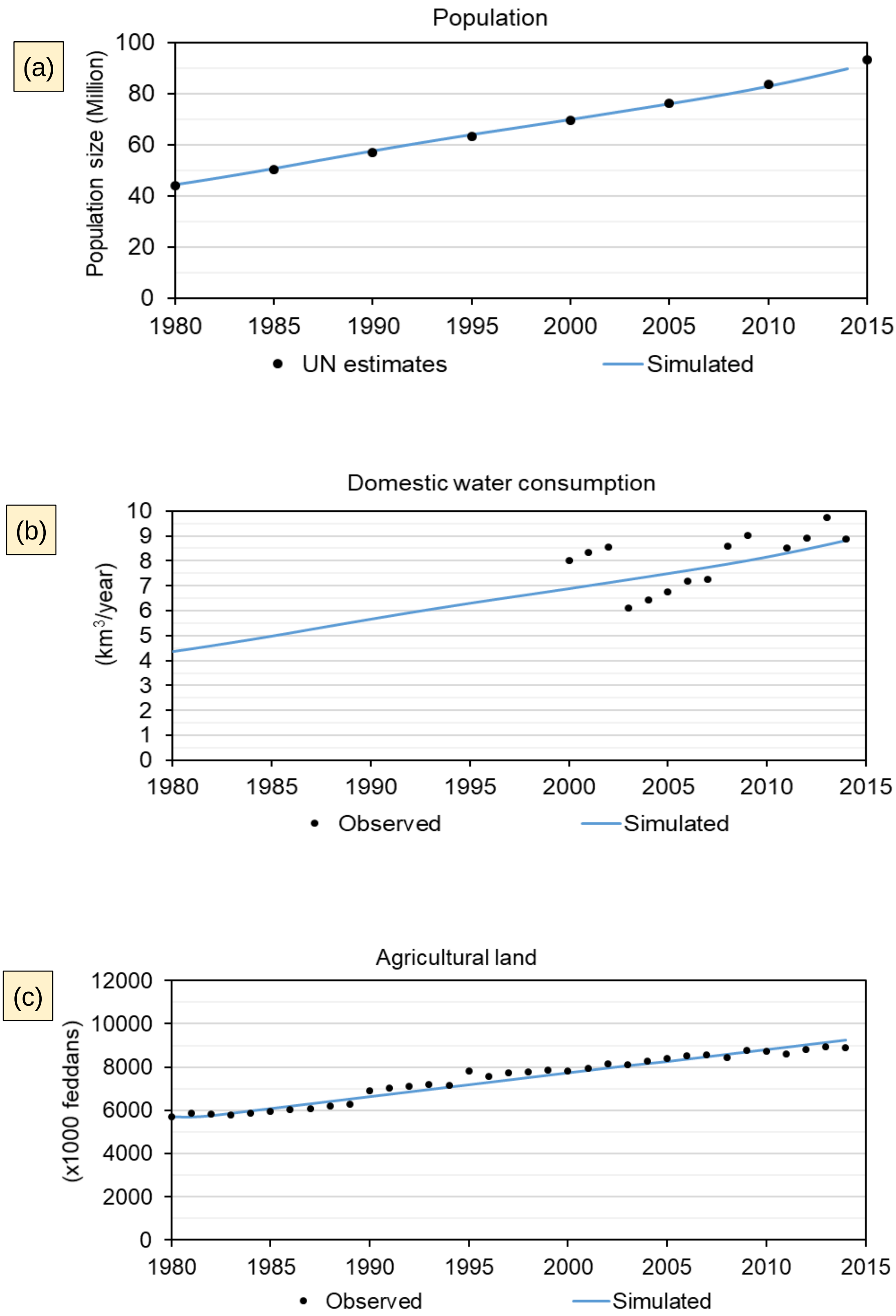
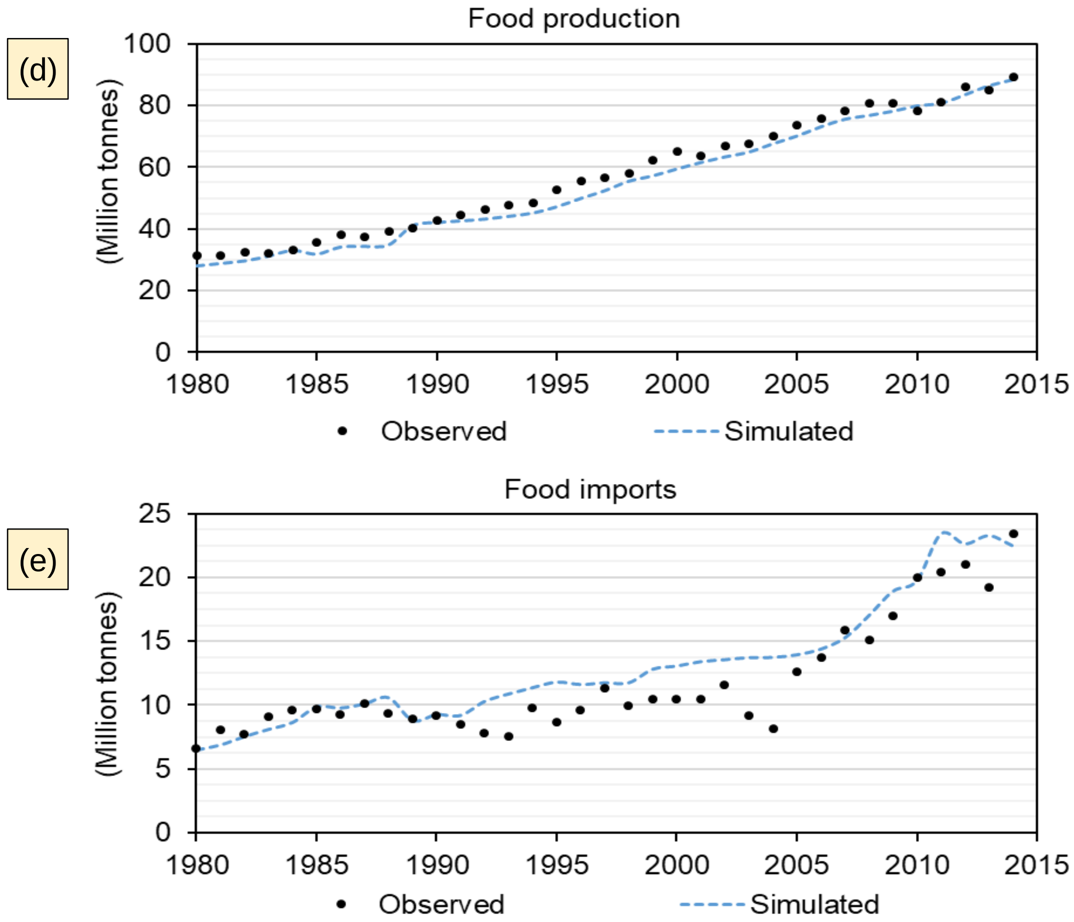


Figure 3.27 Observed VS Simulated data for: (a) Population, (b) Domestic water consumption, (c) Agricultural land, (d) Food production and (e) Food imports



Continued, Figure 3.27 Observed VS Simulated data for: (a) Population, (b) Domestic water consumption, (c) Agricultural land, (d) Food production and (e) Food imports

Table 3.6 Statistics of model parameters tests

Variable	PBIAS	RMSE (%)	TIC	Theil Inequality Statistics		
				U^M	U^S	U^C
Population	-3.70	4.0	0.02	0.97	0.03	0.00
Domestic water consumption	-4.70	13.0	0.07	0.13	0.33	0.54
Agricultural land	-0.53	3.0	0.01	0.03	0.00	0.97
Food production	-4.60	6.0	0.03	0.68	0.01	0.31
Food imports	11.40	22.0	0.08	0.39	0.02	0.59

Note:
$0 \leq TIC \leq 1.0$ (0 perfect prediction, 1.0 worst prediction),
TIC<0.40 very good/excellent model and TIC>0.70 poor model
$U^M+U^S+U^C=1.0$

RMSPE: 10% is an acceptable level of error

3.4.7.1 Sensitivity Analysis

The integrity and the robustness of the model were further tested through sensitivity analysis. Sensitivity analysis aims at evaluating the response of the model outputs to the uncertainties in the model parameters. It provides a means to identify the parameters that have a significant impact on the system and therefore provides possible improvements to the system e.g., policy guidance (Sušnik et al. 2013). Sensitivity analysis was conducted here through individual changes to the model parameters, i.e., only one parameter value was changed while the other model parameters were held at their calibrated values during the simulation period (1980-2014). Parameters that are believed to affect the dynamic behaviour of the model are selected and altered either by ±10% compared to their calibrated values or their reported range (i.e., uncertainty in parameter values). Tested ranges of the model parameters are shown in Table 3.7. The results of the sensitivity analysis at the end of the simulation are shown

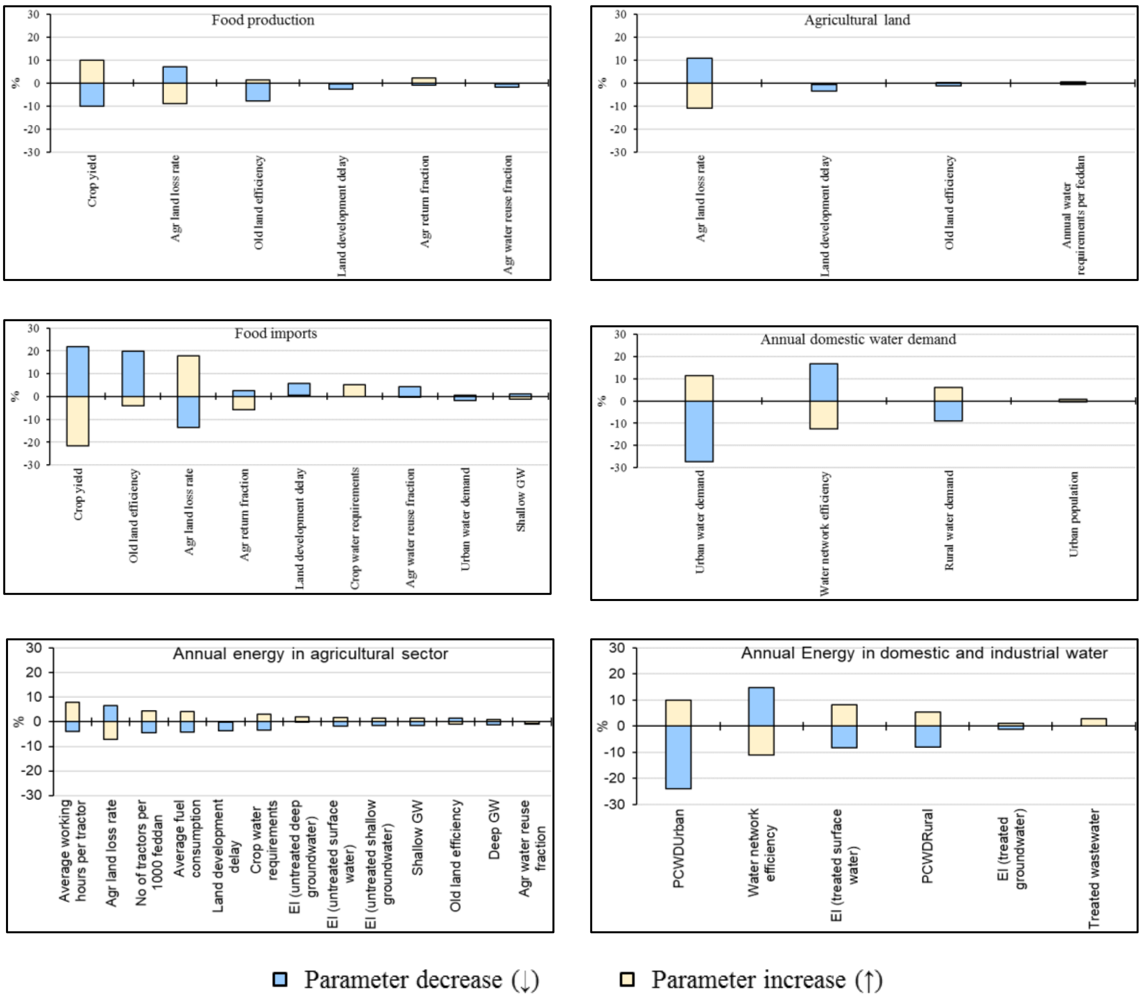


Figure 3.28 Sensitivity analysis results to the model

in Figure 3.28, where only parameters that cause a change to the model outputs of more than 1% are shown. Also, sensitivity analysis is shown here for variables that are not used in model testing (e.g., energy in agricultural sector) due to limited availability of observed data to compare with the simulated data during model testing.

Food production and imports were found to be more sensitive to the crop yield, agricultural land loss rate and the irrigation efficiency. The crop yield showed the greatest sensitivity to the food sector (food production and food imports). A ±10% change in the crop yield, compared to the base run, would result in (±10%) change in food production and (±21%) change in food imports.

The agricultural land loss rate directly impacts the agricultural land and in turn the food sector. Higher land loss rates would result in a reduction in agricultural land and food production while causing an increase in food imports. For example, higher land loss rate of 70x1000 feddans/year resulted in an 11% reduction in the agricultural land, a 9% reduction in food production, an 18% increase in food imports, while the energy demand in the agricultural sector would be reduced by 7%.

The irrigation efficiency also affects the food sector such that, for example, a decline in the irrigation efficiency increases the irrigation water demands. This results in water shortages in the agricultural sector which in turn impacts food production and imports as well. Changing the irrigation efficiency in the old lands from 0.61 (calibrated value) to 0.50, resulting in an 8% reduction in food production and a 20% increase in food imports.

Domestic water demand is directly impacted by the demand rates and pipe network efficiency. Per capita urban water demand showed higher sensitivity to the domestic water demand followed by the pipe network efficiency and per capita rural water demand. A decline of per capita urban water demand from 270 l/c/d (calibrated value) to 150 l/c/d (minimum demand rate, MHUUC 2010), i.e., a 44% reduction would result in a 30% reduction in the total domestic water demand. The energy demand in the agricultural sector is found to be sensitive to the machinery use, agricultural land loss rate, energy intensities of different water uses (e.g., pumping groundwater and surface water), and different water uses in the agricultural sector. The energy demand in the domestic water sector is found to be sensitive to per capita water demand rate, pipe network efficiency and the energy intensity of surface water supply. Machinery and agricultural land parameters were found to be the most sensitive parameters to the energy demand in the agricultural sector. For example, changing the average annual working hours per tractor from 1,100 hrs/year (base value) to 1,000 hrs/year, resulted in about a 4% reduction in the energy demand in the agricultural sector. Overall, results suggest that the model exhibits the expected sensitivity to key parameters, and provides reasonable results under these changes that do not affect the dynamic behaviour of the model.

Table 3.7 Tested range of Egypt's sub-model parameters for sensitivity analysis

Parameter tested	Range tested	Units
Agricultural land loss rate (feddan/year)	(10,000-70,000)	feddan/year
Agricultural drainage water return fraction	(0.25-0.45)	-
Agricultural drainage water reuse fraction	(0.40-0.54)	-
Annual water requirements per feddan	(4000-6700)	m^3/feddan
Average fuel consumption (litre/hr)	±10%	
Average working hours per tractor (hrs/year)	(1000-1300)	hrs/year
Crop water requirements (m^3/month/feddan)	±10%	-
Crop yield (ton/feddan)	±10%	-
Deep groundwater (km^3)	±10%	-
EI (treated groundwater) (KWh/m^3)	±10%	KWh/m^3
EI (treated surface water) (KWh/m^3)	±10%	KWh/m^3
EI (untreated deep groundwater) (KWh/m^3)	±10%	KWh/m^3
EI (untreated shallow groundwater) (KWh/m^3)	±10%	KWh/m^3
EI (untreated surface water) (KWh/m^3)	±10%	KWh/m^3
Land development delay (year)	(1-7)	years
No. of tractors (tractor/1000 feddan)	±10%	-
Old land efficiency	(0.50-0.60)	-
Shallow groundwater (km^3/yr)	±10%	-

Treated wastewater fraction	(0.115-0.20)	-
Urban water demand (litre/capita/day)	(150-320)	litre/capita/day
Rural water demand (litre/capita/day)	(100-150)	litre/capita/day
Water network efficiency	(0.60-0.80)	-

3.5 Discussion

This chapter presents an integrated modelling framework to address the WFE nexus interdependencies in the Nile River basin while considering other related themes such as population growth, economic growth, policy measures, planned developments and long-term uncertainties in future river flows with and without climate change. The developed framework was applied in full for Egypt while was partially applied to the rest of the Nile countries due to limited data available. An SD model was built for the entire the Nile river basin representing water management infrastructure, key hydrological features and water abstraction activities.

This model was linked to a complete WFE nexus model in Egypt. The development of each model, its sub-models and their interactions with each others are discussed and graphically represented. The integrated model runs at a monthly time-step and represents the river's management policies before the year 2015. The integrated model showed a satisfactory performance and was able to capture the river flow dynamics, water abstraction activities in the basin, basin's water management infrastructure and the WFE nexus in Egypt. The model is fit for the purpose for which it is developed and will be applied, in the following chapters, to investigate the WFE nexus in the basin while considering; planned developments in the basin, e.g., the GERD development on the Blue Nile, policy options and climate change in the basin. The simulation model recognizes hydropower generation in the basin together with energy demands in different water uses, e.g., pumping for water irrigation and in food production, e.g., machinery use. However, a complete energy model, i.e., energy balance, was not considered here by the model as it is beyond the scope of the thesis scope.

CHAPTER FOUR: WFE NEXUS IN THE NILE BASIN DURING GERD FILLING AND OPERATION

4.1 Introduction

This chapter explores the possible future of the WFE nexus in the basin with and without the GERD using the described integrated model for the entire Nile basin. The impact of the GERD development is investigated during the filling and operation stages of the dam by employing stochastic flow analysis and assuming that the current WFE nexus management policies in the basin stay unchanged.

4.2 The Grand Ethiopian Renaissance Dam Project (GERD)

The GERD is one of four major dams planned on the main stem of the Blue Nile River according to the initial study of the USBR in 1964 (Block 2006). The dam was originally named in the USBR study as the “Border Dam”. Investigations of the dam sites were carried out between 2009 and 2010, and the dam was known at this time as “Project X” (Water Technology. net 2014). In April 2011, the Government of Ethiopia announced the construction of the Grand Millennium Dam on the Blue Nile (Negm et al. 2018). Two weeks later, the project was renamed to the current name, i.e., the Grand Ethiopian Renaissance Dam. In terms of reservoir capacity, the reservoir storage has changed several times from its original design (11.1 km^3) to 62 km^3, then 67 km^3 and finally to the announced capacity of 74 km^3 (Negm et al. 2018). Regarding the hydropower generation capacity, the hydropower plant capacity has been upgraded from 5,250 MW (in 2011) to 6,000 MW (in 2012) with the final reported capacity of 6,450 MW (Hagos 2017).

The GERD is located at some 20 km above the Ethiopian-Sudanese borders. The GERD structure is composed of the main dam, the saddle dam, spillway and the hydropower plant, Figure 4.1. The Main dam is a roller-compacted concrete gravity type with a height of 145 m and 1,780 m length. The main dam is fitted with gated spillways and attached with two hydropower stations on each side. The hydropower plant is composed of 16 turbines with two turbines of 375 MW and the rest being 400 MW, according to final hydropower upgrade. The saddle dam is a rockfill dam with a length of 4,800 m, 45 m high and supporting the main

Figure 4.1 Main components of the GERD, adapted from Hagos (2017)

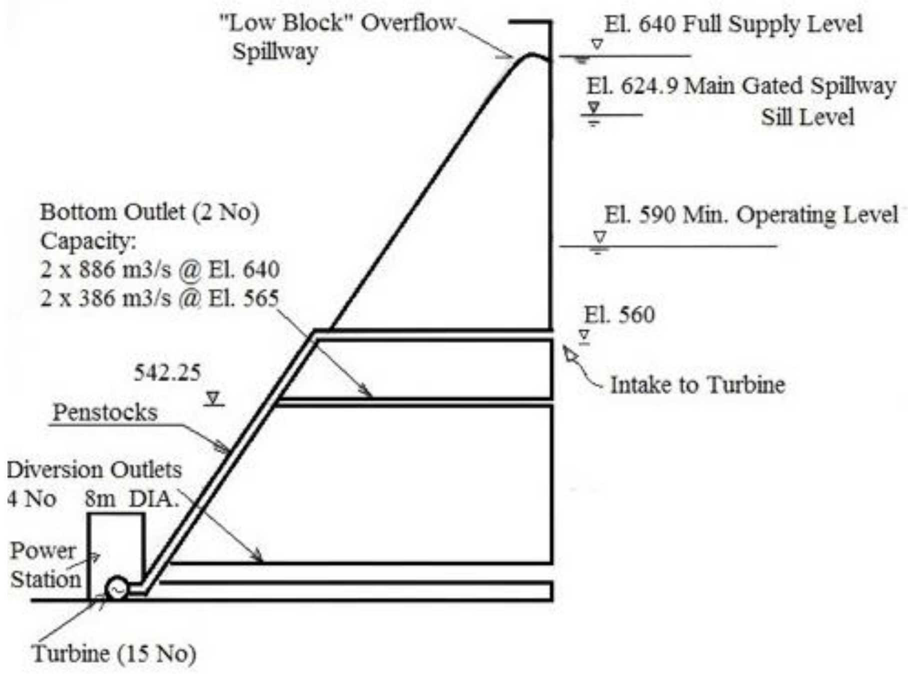


Figure 4.2 Vertical section of the main dam of the GERD, adapted from MIT (2014)

dam to form the reservoir. The reservoir capacity of 74 km^3 is about 1.5 times the average annual Blue Nile flows at the dam location. The Full Supply Level (FSL) of the reservoir is 640 m (a.m.s.l), and the Minimum Operating Level (MOL) is 590 m (a.m.s.l), Figure 4.2. The reservoir has a surface area of 1,874 km^2 at the FSL.

4.3 Stochastic Simulations

To assess the hydrological regime in the Nile basin, the input flows of the water resources sub-model for the period (1950-2014) were assumed representative of future Nile flows and no climate change impacts were considered in the present work. To cope with the inherent uncertainty of the streamflow regime, exploit the significant natural variability embedded in these long historical time series and to a large extent ‘uncertainty-proof’ the analysis, the notion of stochastic simulation is used. Historical hydrologic sequence is less likely to occur in the future and its use in river basins planning and management studies will be less representative of the system’s outcome in the future (Matalas 1967). Unlike the use of only one historical records sequence, the synthetic streamflow series provide large samples of a concerned process (i.e., generating hundreds or thousands of time series with any desired length). Thus allowing for evaluating a wide range of possible outcomes of the systems, probabilistic assessment of water related problems and aid in decision making regarding the system operation and management (Matalas 1967). The key concept is to generate a large number of synthetic streamflow time series (encapsulating the uncertainty of streamflow) and use them to drive the whole system and assess the response(s) of interest. Early attempts to generate single-site time series include Thomas and Fiering (1962b); Svanidze (1964), while multi-site time series have been considered in Fiering et al. (1971); Matalas and Wallis 1971a; Clarke (1973).

In this work, a novel stochastic simulation method was employed (Tsoukalas et al. 2017; Tsoukalas et al. 2018a) that is based on the notion of Nataf’s joint distribution model. The employed stochastic model can simulate multivariate cyclo-stationary processes with seasonally varying marginal distributions and correlation structure, such as monthly streamflow. It is also noticed that this approach is not exclusively designed for streamflow simulation (see, Kossieris et al. 2019 for simulation of fine time-scale water demand series) and it avoids the generation of un-realistic dependence patterns among consecutive time steps, a recently revealed problem (Tsoukalas et al. 2018b) associated with the seminal model of Thomas and Fiering (1962a).

In this vein, one hundred synthetic series of 72 river tributaries, see Figure 3.8, (i.e., 100 series x 72 tributaries) with a 65- year length were generated using the abovementioned synthetic streamflow generator, as implemented in the *anySim* R-package (Tsoukalas and Kossieris 2019). A comparison between simulated (i.e., stochastically generated) and historical statistical characteristics (mean, standard deviation, skewness, lag-1 month to month correlation and lag-0 cross correlation among each month) of the 72 streamflows of river tributaries is provided in Appendix (D). The basin-wide synthetic streamflows series are used to derive the previously-described integrated simulation model in chapter three. An automated R code was developed to run the simulation model under the basin-wide synthetic streamflow series and produces a set of different outputs, e.g., hydropower generation, irrigation supply to demand ratio, river discharges at gauge locations and time to fill GERD as in this case.

Future simulations run at monthly time step under the basin-wide synthetic flows from 2015 to 2080 to investigate the WFE nexus in the Nile basin during the filling and subsequent operation of the GERD. Various filling strategies and policies were investigated in the literature as discussed by Wheeler et al., (2016). Several filling rates (10%, 15%, 25%, 50%, and 100% - i.e., as a percentage of the monthly inflows upstream the GERD) are adopted here for filling of the reservoir. This filling strategy allows for sharing the risks and rewards associated with the variability of the flows (Zhang et al. 2016). Dynamic filling scenarios (i.e., by assigning high fill rates to wet months/years and low fill rates to dry months/season) can be also investigated. However, this is beyond the scope of the current work. Also, the 100% fill rate is a theoretical scenario that is considered for comparative purposes and to illustrate the impact of an extreme fill condition.

According to the recent announcement by the Ethiopian Minister of water and energy (Maasho 2019), “750 MW is the planned initial hydropower production with two turbines” by the end of 2020 and the GERD is expected to be fully operational by the end of 2022. Therefore, the model assumes the GERD will start filling in January 2020 with two turbines (375 MW) operating and will be fully operational by the end of 2022. Once the reservoir reaches the design level of 590 m, the electricity can be generated while the filling process continues until the reservoir water level reaches the FSL. For each filling scenario, once the reservoir reaches the FSL, the filling phase ends and the GERD operation phase proceeds till the end of the simulation. During the operation phase, the GERD is operated for hydropower generation only with the target hydropower level of 1,730 MW (NBI 2016a). This policy agrees with previous hydropower targets as discussed by Digna et al. (2018b).

The model allows the reservoir to reach the full hydropower capacity (6,000 MW) if the reservoir conditions allow (e.g., the reservoir is full along with high inflows). It should be noted that the 6,000 MW limit is considered here to compare the results of the present study with previous work that used the same value. The reservoir is not allowed to fall below the MOL. The current status of the system in terms of water management, water demands and withdrawals across the basin are kept the same. For the WFE nexus calculations in Egypt, the water demands were allowed to increase due to the projected population growth and agricultural land expansion.

4.4 Results and Discussion

4.4.1 Time to Fill the GERD

The time required to fill the GERD reservoir (i.e., reach the FSL) under different filling rates and including hydrologic variability, which is assessed using synthetic flows series, is shown in Figure 4.3. The average time to fill the reservoir and the variability in the average filling period is reduced with the increase in the filling rate of the reservoir. The average time to fill the reservoir in this study was found to range from 20 to 231 months, depending on the filling rate. This is in

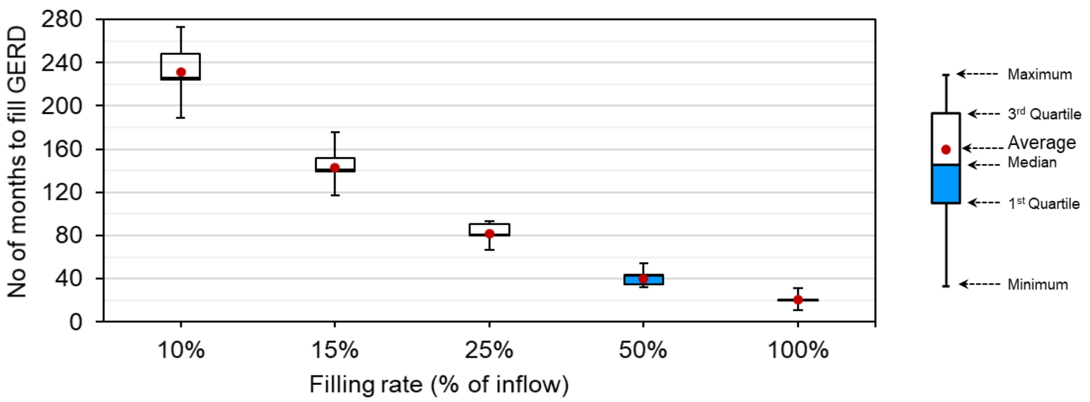


Figure 4.3 Box plots of the GERD filling time under filling rates 10-100%

accordance with the reported range of average GERD filling time reported in the literature, as shown in Table 4.1. After the reservoir reaches the FSL, the GERD is assumed to operate for hydropower generation only until the end of the simulation. Only one set of simulation results for the GERD operation is presented since the differences among the filling scenario results for all the operational phases are found to be negligible (less than 0.25%).

Table 4.1 Average GERD filling time

Fill policy	This study (months)	Previous studies (months)	Source
10%	231	140-285	(King and Block 2014; Zhang et al. 2016; Keith et al. 2017)
15%	143	94	(Keith et al. 2017)
25%	82	60-140	(Zhang et al. 2016; Keith et al. 2017)
50%	40	34	(Keith et al. 2017)
100%	20	21-36	(Wheeler et al. 2016; Keith et al. 2017)

4.4.2 Hydropower Generation

The annual hydropower generation across the basin for the case without the GERD is shown in Figure 4.4 for the main regions. The annual hydropower generation during the filling and operation of the GERD in Egypt, Ethiopia and Sudan is shown in Figure 4.5 as box plot graphs. In Egypt, the hydropower generation will be generally reduced during the GERD filling and operation compared to the case without the GERD, Figure 4.5.a and Table 4.2. The average hydropower reduction in the case of a 100% fill rate is less than the

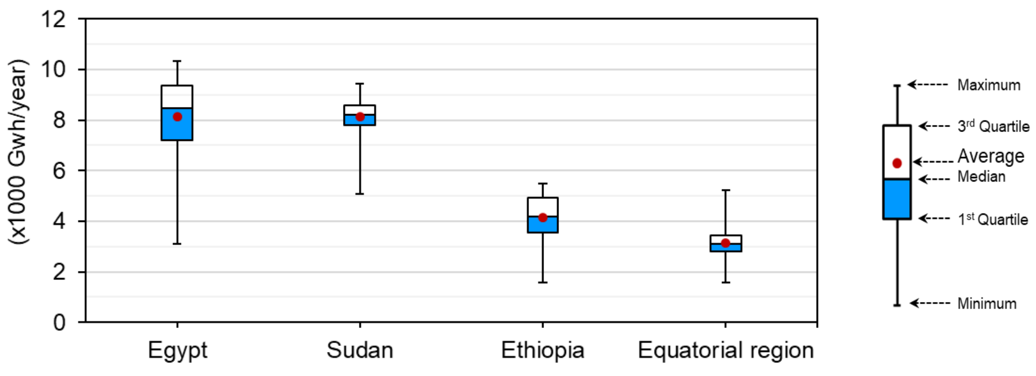


Figure 4.4 Hydropower generation in the basin for the case without the GERD

average hydropower reduction in other fill rates, i.e., 10-50%. This is due to (a) the relatively short filling period for the 100% fill rate compared to other fill rate policies, (b) the over year storage of HAD and (c) the expected water demands in Egypt during the 100% fill policy being less than the expected water demands

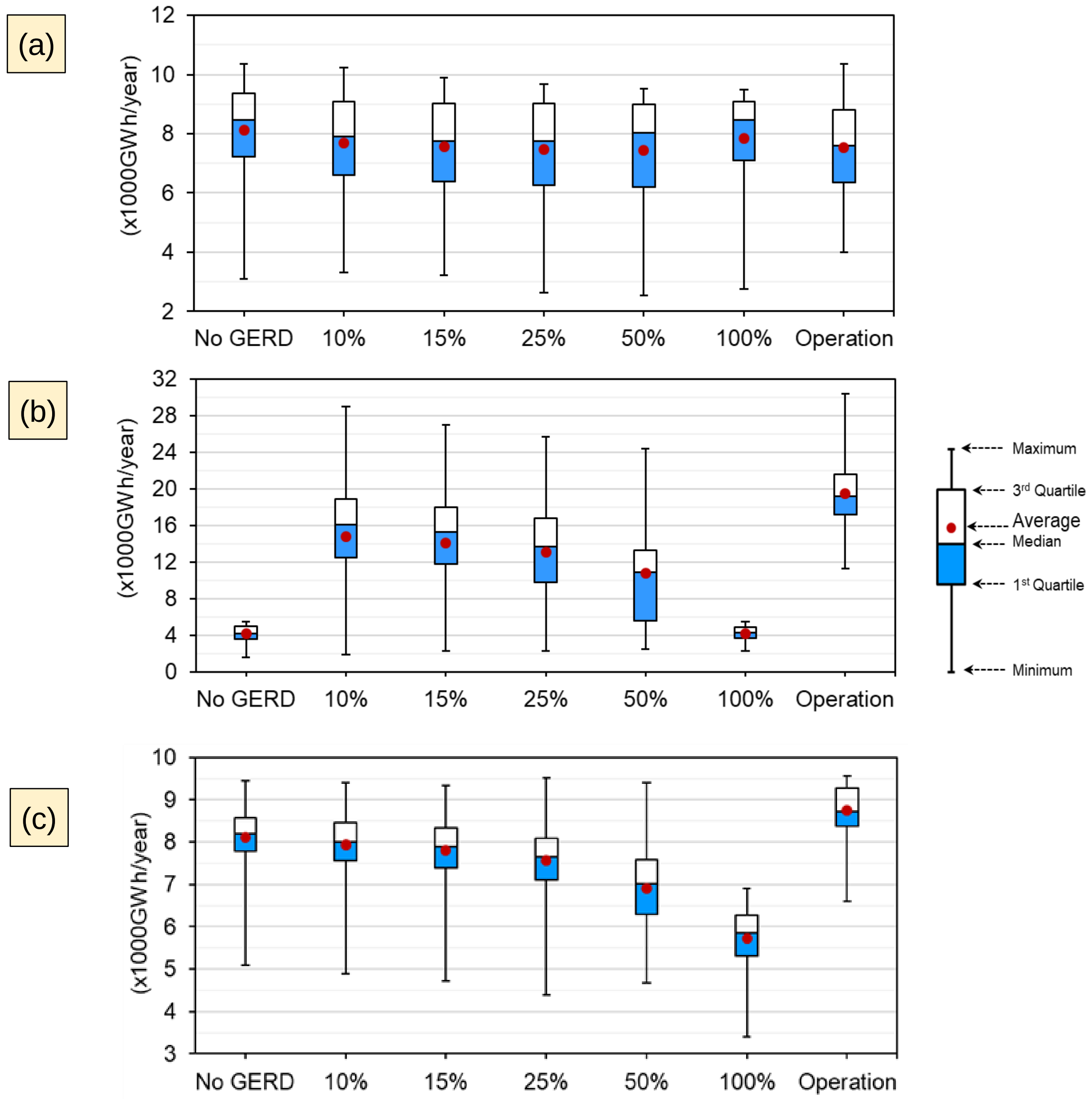


Figure 4.5 Annual hydropower generation during GERD filling for each fill scenario, subsequent operation and the case of no GERD in (a) Egypt, (b) Ethiopia and (c) Sudan

Note: Results are for different time spans: GERD filling results are based on time to fill for each filling scenario; GERD operation is over the subsequent period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length, i.e., 65 years

during the other fill rates (as the assumed demands in Egypt are projected to increase over time due to population growth and land development).

Table 4.2 Percent of change (%) in median (average) annual hydropower generation for GERD filling scenarios and operation with reference to the case of no GERD

Country	GERD filling[1]					GERD operation[2]
	10%	15%	25%	50%	100%	
Egypt	-7 (-5)	-9 (-7)	-8 (-8)	-5 (-9)	0 (-3)	-11 (-7)
Ethiopia	287 (258)	266 (241)	227 (216)	160 (161)	1 (1)	360 (371)
Sudan	-2 (-2)	-4 (-4)	-7 (-7)	-14 (-15)	-29 (-30)	6 (8)

Note: [1]calcuated over its own time to fill and [2]calculated over the rest of the simulation period (subsequent operation of each fill scenario had similar results) compared to the case of no GERD (full simulation length)

During the GERD operation, the median (and average figures given in brackets) HAD hydropower generation decreases by about 11% (7%) compared to the case without GERD as HAD will operate at lower levels (Guariso and Whittington 1987) due to the combined effect of river flow regulation and reduction caused by evaporation from the GERD reservoir, Figure 4.6 and increased water demands in Egypt. Analysis of the lower quartile and probability

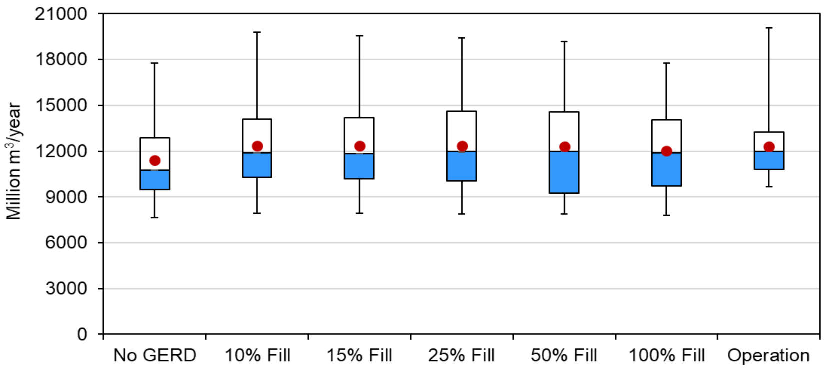


Figure 4.6 Box plot of the net evaporation from the system reservoirs during GERD filling and subsequent operation compared to the case of no GERD

Note: Results are for different time spans: GERD filling results are based on time to fill for each filling scenario, GERD operation is the subsequent filling period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length of non-exceedance (see appendix (D)) of HAD hydropower performance reveals the non-exceedance probability of generating hydropower below 7,000 GWh/year would increase, depending on the fill rate, during the GERD filling compared to the case without the GERD. It should be noted that probability of non-exceedance results was calculated over the time span of the concerned case, i.e., GERD filling, operation and the case of no GERD. Furthermore, the minimum hydropower generation would further reduce by about 15% for fill rates above 15% compared to the case without the GERD. This reflects the risks associated with HAD hydropower generation and the GERD filling during dry periods. It is should be noted that dry periods refer to dry years classified as such based on model outputs that fall below the average value and the wet periods (years) are classified for output values above the average value. On the other hand, the minimum HAD hydropower generation during the GERD operation would increase by about 30% compared to the case without the GERD, which reflects the role of GERD in providing improved low flows especially during dry periods.

In Ethiopia, the annual hydropower generation will be boosted by the GERD, Figure 4.5.b and Table 4.2, during the GERD filling and operation. During the filling phase, the annual hydropower generation is reduced with the increase in the filling rate due to the reduction in the amount of water released through the GERD turbines (i.e., the water is stored), Table 4.2. However, the median (average) of hydropower generation would be increased by up to 287% (258%), depending on the fill rate. Also, the hydropower generation would be greatly impacted and reach a minimum level if the GERD filling coincides with low flow periods, Figure 4.5.b. Once the filling process finishes, the GERD will be able to generate average hydropower of about 15,000 GWh/year which is similar to the values reported by (Elsayed et al. 2013; Digna et al. 2018b; Hamed 2018) and boost the hydropower generation in Ethiopia by about 360%, Table 4.2. Furthermore, there is a 20% chance Ethiopia would achieve hydropower generation above 22,000 GWh/year.

The Sudanese hydropower would be directly impacted by the GERD filling and operation in different ways. During the GERD filling, the hydropower generation would be reduced by about 2-30% compared to the case without the GERD depending on the fill rate, Figure 4.5.c and Table 4.2. Also, the reduction in hydropower generation is increased as the fill rate increases. In contrast, during GERD operation the hydropower generation would increase and the median (average) hydropower generation would rise by approximately 6% (8%), a value that is below the reported range 14-17% in the literature (e.g., Digna et al. 2018b, Wheeler et al. 2016). The improvement in Sudanese hydropower generation is due to the river flow regulation caused by the GERD operation (i.e., increase of low flows during the dry season and reduction of the high flows during the flooding season). The lower quartile of the hydropower generation would be further reduced by 4-32% during the GERD filling. However, during the GERD operation, the minimum hydropower generation would increase by about 30% compared to the case without the GERD, Figure 4.5.c.

4.4.3 River Flow Regime

The average monthly flows of the Main Nile at Dongola station (upstream of the Lake Nasser) and the Blue Nile at El Diem station (at the Ethiopian-Sudanese border) are shown in Figure 4.7. The impact of the GERD filling rates is reflected in the offset of the river flows during the filling phase, Figure 4.7. The Blue Nile and the Main Nile flows will be more regulated when the GERD comes online (i.e., the low flows during the dry season will be increased while the high flow during the flood season would be reduced) (Arjoon et al. 2014; Digna et al. 2018b). Furthermore, the peak of the Blue Nile flows will be delayed by one month due to the water attenuation in the reservoir, Figure 4.7.a. The median (average) annual Blue Nile flows at El Diem would be reduced by about 6% (3%) during the GERD operation. The median and average annual Main Nile flows at Dongola would be reduced by 6-40% during the GERD filling and the median (average) annual flows would be reduced by 4% (2%) during the GERD operation as a result of increased evaporation from the system reservoirs following the GERD operation, Figure 4.6.

The probability of non-exceedance of the annual Nile water quota for Egypt (65.5 km^3/year) according to 1959 agreement between Egypt and Sudan will be increased from (0.40 without the GERD) to (0.50 during the GERD operation), i.e., a 25% increase, Figure 4.8. The annual Main Nile flows at Dongola will be further impacted by the GERD operation, for example, the annual flows below 59 km^3 will slightly increase compared to the case without the GERD due to improved low flows. The flows above this value will be reduced due to increased evaporation from the GERD reservoir, Figure 4.6 and Figure 4.8.

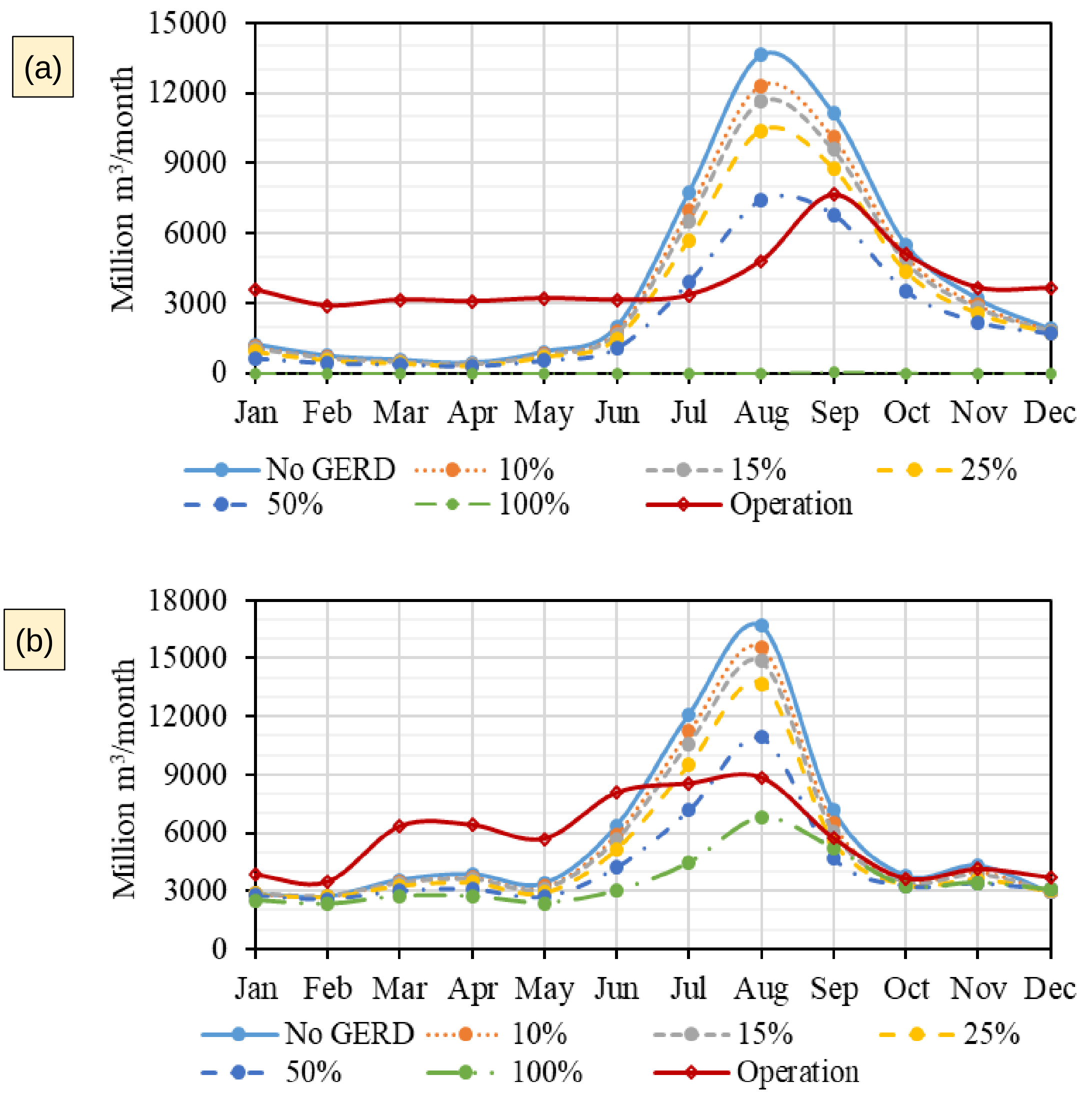


Figure 4.7 Average monthly flows during the filling and the operation of GERD at: (a) El Diem and (b) Dongola station compared to the case without GERD

Note: Results are for different time spans: GERD filling results are based on time to fill for each filling scenario; GERD operation is over the subsequent period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length, i.e., 65 years

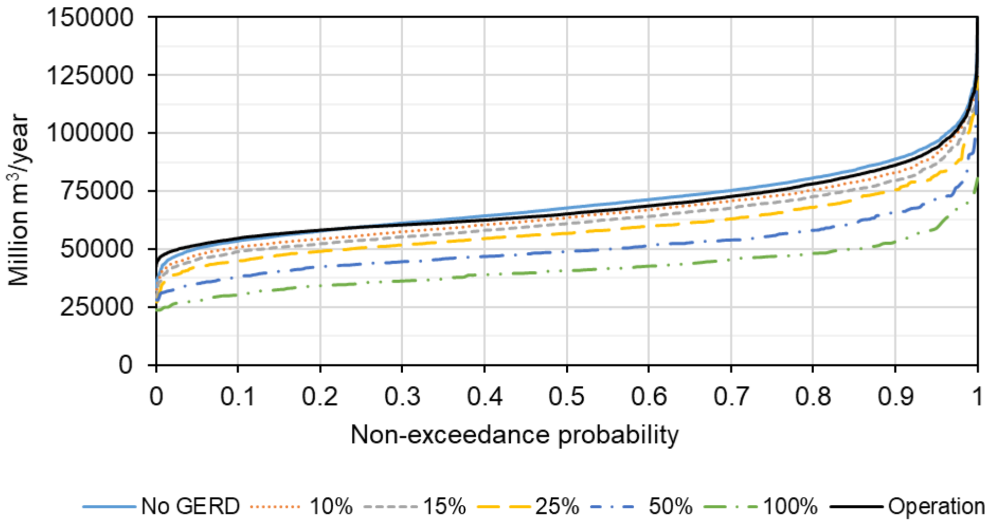


Figure 4.8 Probability of non-exceedance of annual Nile flow at Dongola with GERD (filling and operation) and without GERD

Note: Results are for different time spans: GERD filling results are based on time to fill for each filling scenario, GERD operation is the subsequent filling period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length

4.4.4 Irrigation Water Supply Reliability

The average monthly supply to demand ratio (i.e., irrigation supply reliability) will be impacted by the filling and operation of the GERD, Table 4.3. In Egypt, the ratio will be reduced by about 1% during the filling phase and a further reduction of about 3% is expected during the GERD operation. This reduction is due to the combined effect of increased water demands and reduced annual river flows caused mainly by retaining the water in the GERD reservoir. The average annual water shortage volume (sum of the monthly water shortage values) will increase by 3-14% for low fill rates (i.e., 10-15%) and decrease by about 4-28% for high fill rates (25-100%) compared to the case without the GERD. This happens because of the different periods (i.e., GERD fill time) over which the data was averaged and due to the increased water demands in Egypt over the fill time (the longer the fill time, higher the demand is expected due to increased population and land development, see Figure 4.9). During the GERD operation, the average volume of water shortages would increase by 21%, while the maximum shortage volume would decrease by about 19% due to improved low flows during dry periods, Figure 4.10. This reveals the importance of GERD during the low flow periods and future droughts (Arjoon et al. 2014). A potential coordinated policy among the system reservoirs could help alleviate the risks during low flows and dry periods.

Table 4.3 Average monthly supply to demand ratio percentage (irrigation supply reliability %) for GERD filling and operation and the case of no GERD

Country	No GERD[1]	GERD filling[2]					GERD operation[3]
		10%	15%	25%	50%	100%	
Egypt	90	89	89	90	90	92	87
Sudan	99	99	99	99	95	49	100

Note: [1]averaged over full simulation length, [2]averaged over own time to fill and [3]averaged over the rest of the simulation (subsequent operation of each fill scenario has similar results)

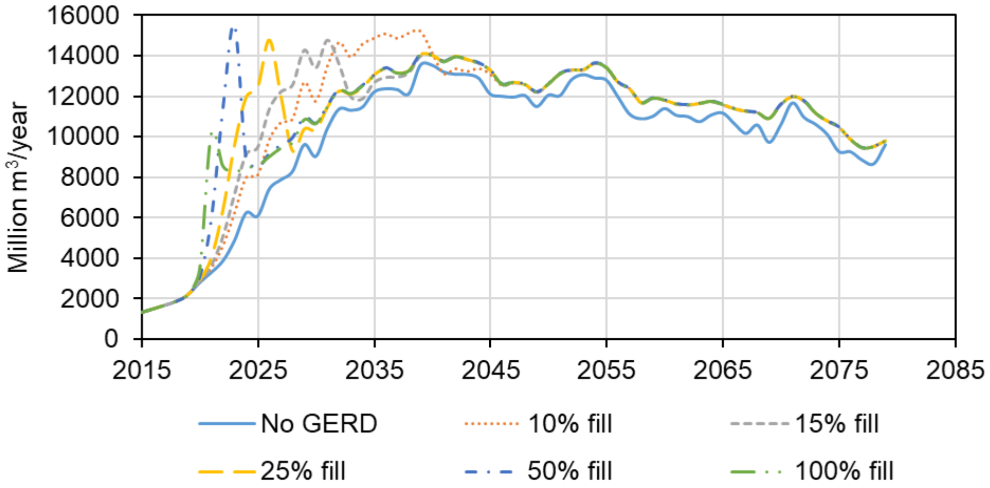


Figure 4.9 Average annual water shortage over time, during filling and subsequent filling of GERD compared to the case of no GERD in Egypt

In Sudan, the irrigation supply reliability will be affected by the higher fill rates (i.e., 50-100%) and the 100% fill rate could significantly reduce the irrigation supply reliability (to 49%), Table 4.3. However, the irrigation supply reliability would be improved during the GERD operation as a result of improved water supply caused by the river flow regulation by the GERD as discussed in MIT (2014). The annual water shortage volume will increase with the increase in fill rate and will be greatly impacted by the 100% fill rate compared to the other fill rates, Figure 4.10.b as a result of no downstream releases from the GERD. The average annual water shortage would be in the range of 40 to 6100 Million m^3 depending on the fill rate compared to just 30 Million m^3 in the case without the GERD.

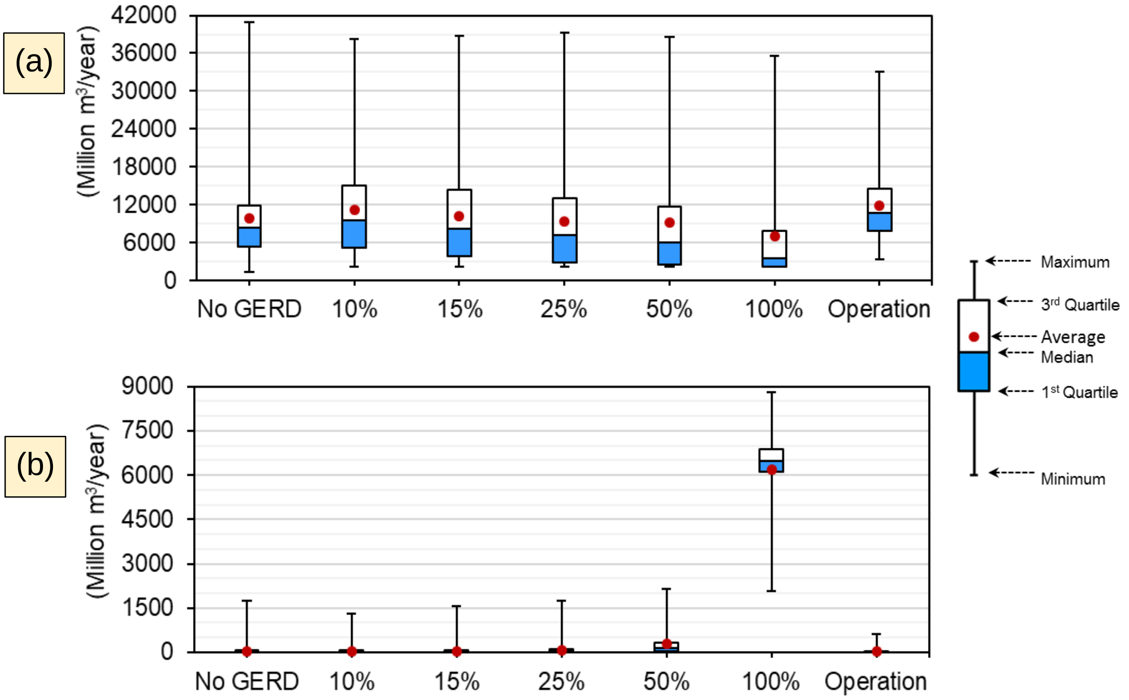


Figure 4.10 Box plots of the annual water shortage volume during GRED filling and operation compared to the case without GERD for (a) Egypt and (b) Sudan

Note: Shown results are for different time spans: GERD filling results are based on time to fill for each filling scenario; GERD operation is based on the post-filling period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length, i.e., 65 years

The non-exceedance probability of the monthly irrigation supply to demand ratio is shown in Figure 4.11 for Egypt and Sudan during the GERD filling and operation together with the case of no GERD. The non-exceedance probability of each case was calculated over its own time, i.e., the case of no GERD is calculated over a full simulation length (i.e., 65 years). With regards to the filling scenarios, it was calculated for each fill scenario depending on their own time to fill. The operation case was calculated over the subsequent filling phase of each fill scenario and found to be similar among the filling scenarios. The analysis of the non-exceedance probability plots for Egypt reveals that during the filling phase the non-exceedance probability of the low monthly supply to demand ratio will increase compared to the case without the GERD, Figure 4.11.a. This means that frequent water shortages are expected to increase in case the GERD filling occurs during dry periods. For example, the non-exceedance probability for the monthly supply to demand ratio at 70% will double (i.e., increased from 0.05 to 0.10). During the GERD operation, the non-exceedance probability of low supply to demand ratio (<62%) would be reduced due to improved low flows caused by the GERD. The latter reveals the importance of the GERD during the low flow periods and future droughts (Arjoon et al. 2014). A potential coordinated policy among the system reservoirs could help alleviate the risks during low flows and dry periods.

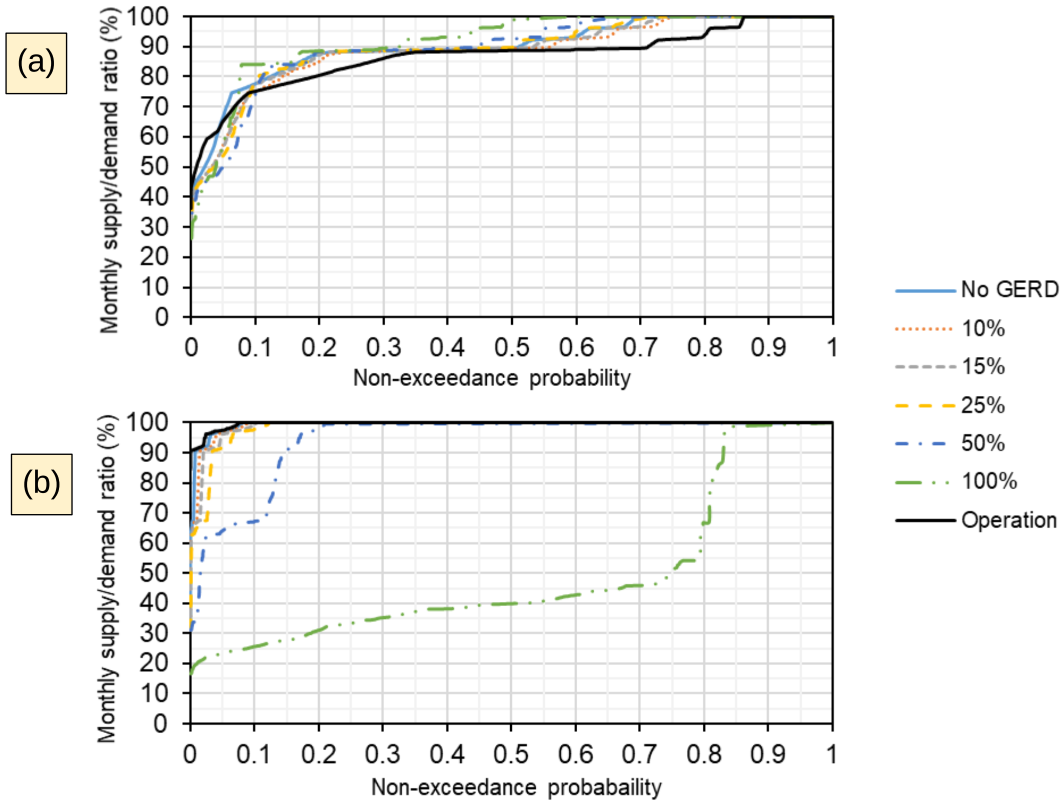


Figure 4.11 Non-exceedance probability of the monthly supply to demand ratio (%) during GRED filling and operation compared to the case without GERD for (a) Egypt and (b) Sudan

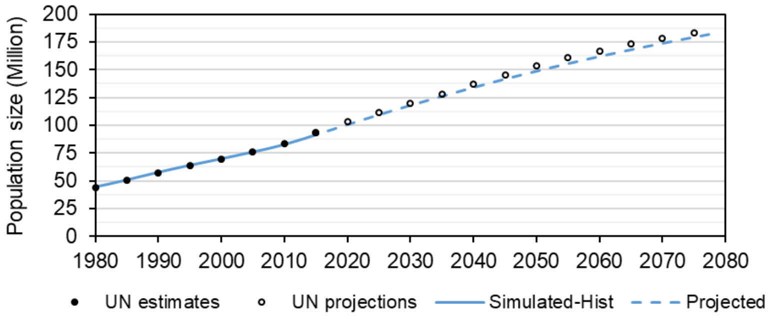
Note: Results are for different time spans: GERD filling results are based on time to fill for each filling scenario; GERD operation is over the subsequent period (was found to be similar after each fill scenario) and the case of no GERD is for a full simulation length, i.e., 65 years

In Sudan, the non-exceedance probability of the supply to demand ratio will increase with the fill rate increase compared to the case without the GERD, Figure 4.11.b. However, the ratio will have a 3% chance to fall below 90% for fill rates of 10-25%. The monthly supply to demand ratio will be greatly impacted by higher fill rates (50-100%). On the other hand, the supply to demand ratio will be improved during the GERD operation compared to the case without the GERD as discussed in MIT (2014). For example, the minimum ratio will reach 85% compared to 31% for the case without the GERD. It can be concluded that the Sudanese irrigation supply could be impacted in the short to medium-term (i.e., during case GERD filling, especially with higher fill rates), while it will be improved in the long term (i.e., during the case of GERD operation).

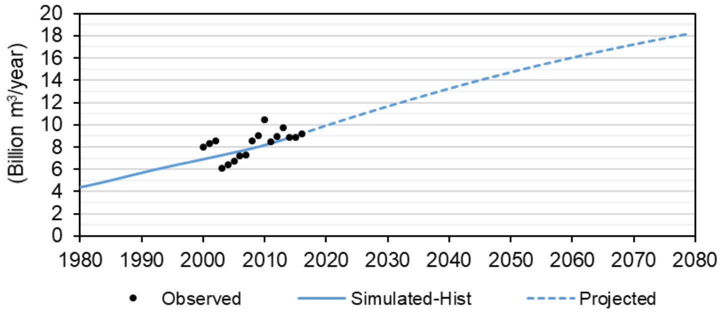
4.4.5 Egypt Results

The application of the WFE nexus framework in Egypt and the model simulation results are presented here considering the GERD filling and operation, which is then compared to the case without the GERD. The model population results agree with the population projection from the United Nations estimates, (United Nations 2017) as shown in Figure 4.12.a. The population is expected to reach about 180 Million by 2080. With regards to population growth and continuation of current per capita consumption rates, the domestic water demand is expected to double between 2020 and 2080, Figure 4.12.b. Domestic water demand is expected to reach the level of about 18 km^3/year by 2080. Likewise, energy demand in the domestic water sector is expected to grow. Accordingly, the demand could be doubled under current water and energy consumption rates, Figure 4.12.d. The agricultural land is expected to grow till the year 2036 as a result of the continuation of the planned land development. However, the area of agricultural land will start to decline as a result of the lack of available land suitable for irrigation and the continuation of land loss.

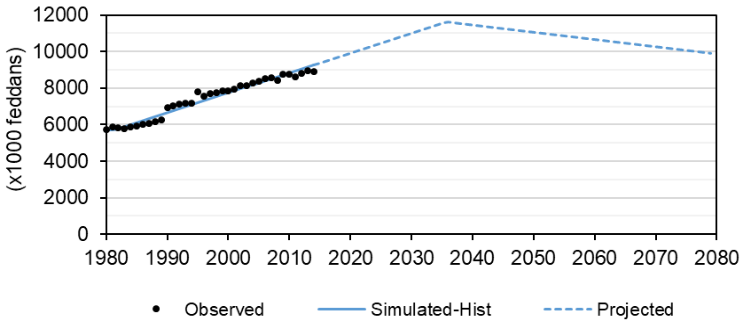
Food production and imports are impacted by several factors, including population growth, agricultural land expansion and available water resources. Food production in the case without the GERD is expected to grow at a slow rate and then to decline following the agricultural land pattern.



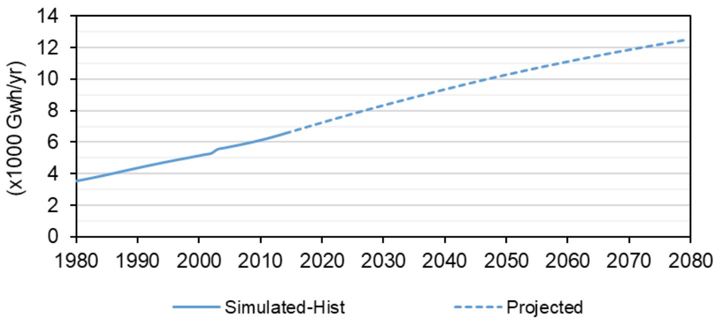
(a) Egypt’s population



(b) Domestic water demand, Egypt



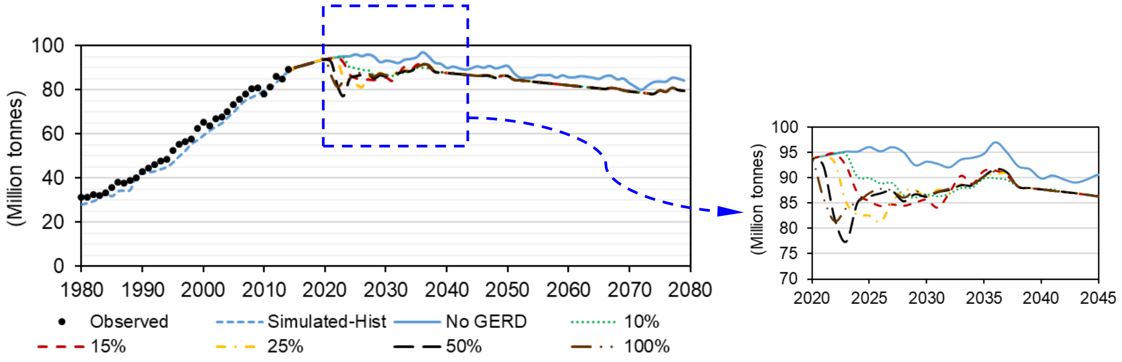
(c) Agricultural land, Egypt



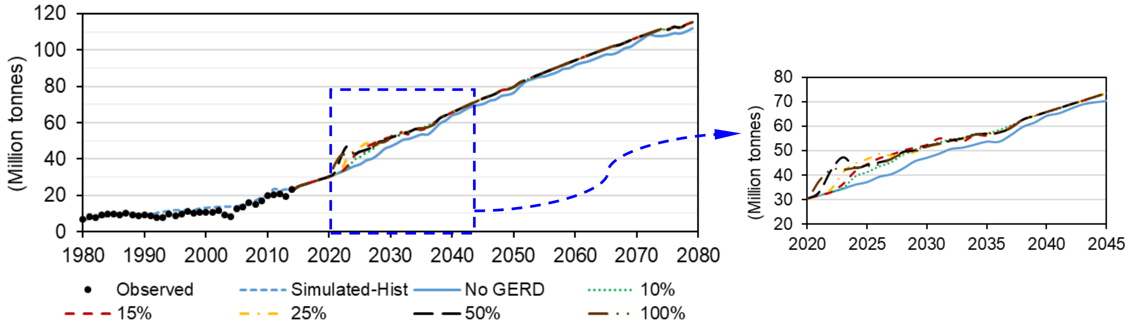
(d) Energy in domestic water, Egypt

Figure 4.12 WFE nexus results for Egypt, during the GERD filling and operation compared to the case without GERD

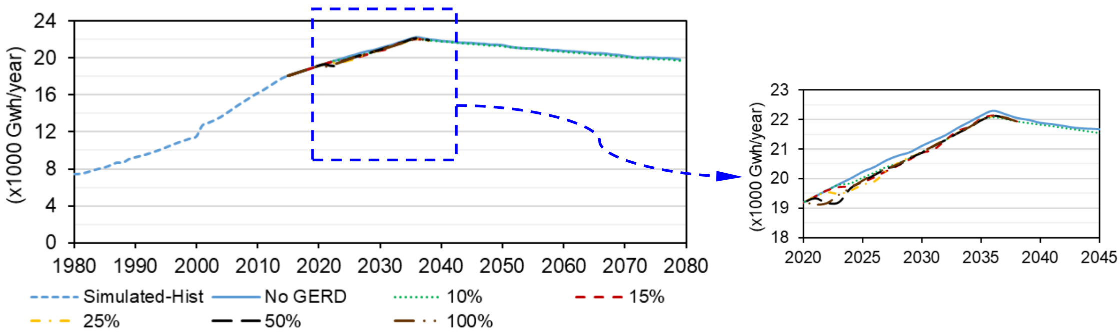
Note: * refers to median values



(e) Food production*, Egypt



(f) Food imports*, Egypt



(g) Energy in agricultural sector*, Egypt

Continued, Figure 4.12 WFE nexus results for Egypt, during the GERD filling and operation compared to the case without GERD

Note: * refers to median values

Furthermore, food production will be impacted as a result of the decline in the water available for irrigation due to increased domestic water demand (i.e., domestic water sector is given higher priority over the irrigation sector). Food production could be reduced by about 60% during dry periods due to significant reductions in the available water for irrigation, while it could be increased by 16% during wet periods due to improved irrigation water supplies (based on maximum, minimum values of food production values, not shown here). In contrast, food imports are expected to grow in the case without the GERD as a result of population growth and variations in domestic food production. The energy in the agricultural sector is expected to follow the agricultural land pattern as a result of land developments and it was assumed that the current management policies of the system (e.g., pumping rates and irrigation application methods) stay unchanged.

The model simulation results during the GERD filling and operation phases demonstrate the impact of the GERD on the WFE nexus in Egypt. The impact of the GERD on the Nile inflows, the volume of water shortages and hydropower generation in Egypt during the GERD filling and operation being discussed above, the extension of these impacts will be further analysed here. Food production will be reduced during the GERD filling and operation phases compared to the case without the GERD due to reduction in Nile inflows caused by the GERD (during filling and operation) as shown in Figure 4.12.e. The outcome will be affected by the filling rates of the GERD, with higher filling rates resulting in a greater reduction in gross food production within the range of about 9-19% for the median and 8-24% for the average, Table 4.4.

Higher filling rates cause higher reductions in food production but for a shorter time compared to lower filling rates. Also, food production in higher filling rates overtakes the lower fill rate cases (i.e., higher fill rates finishes the filling phase faster than slow fill rates), Figure 4.12.e. However, the reduction in the aggregate food production over the period from the beginning of the filling to reaching the equilibrium state increases from 5-7% as the fill rate increases, compared to the case without the GERD. After the filling phase is completed and the system reaches an equilibrium state, the food production levels for different fill rates overlap as the filling rate is no longer practised. During the GERD operation, the median (average) food production will be reduced by about 4% (3%) compared to the case without the GERD, Table 4.4.

The changes in food production during the GERD filling and operation compared to the case without the GERD are shown in Table 4.4. Food production will likely to be less affected if the GERD filling occurs during the average and above-average flow years. However, the filling process could cause significant losses to food production in Egypt if it occurred during dry periods, as discussed in MIT (2014). For example, changes to food production values below the median are 2-3 times higher than the changes to the median values during the GERD filling, Table 4.4. Another interesting result is that the minimum food production values during the GERD operation will be higher than in the case without the GERD, which reveals the role of the GERD during the dry periods for downstream users, as discussed above.

The food gap in Egypt will continue to grow as a result of population growth, increased competition between municipal water and the agricultural sector, variability in the Nile flows, and the agricultural land degradation. During the GERD impoundment, the food imports are expected to increase by about 14-37% for the median and 9-41% for the average compared to the case without the GERD. Moreover, the total food imports over the period from start GERD filling to the equilibrium state is increased due to the increase in filling rate, with a range of about 8-12% compared to the case without the GERD over the same period. However, food imports are expected to grow faster mainly due to population growth, Figure 4.12.f and the median (average) would increase by about 3%(2%) during the GERD operation compared to the case without the GERD. The energy demand for the agricultural sector will continue to increase correspondingly with the agricultural land trend. They will not be significantly affected during the filling and the operation of the GERD. The energy demand for agriculture is less sensitive to the reduction in surface water compared to other parameters (e.g., groundwater pumping and machinery use).

Table 4.4 Changes to food production (%) during GERD filling and operation compared to the case without GERD

Quartile	GERD filling[1]					GERD operation[2]
	10%	15%	25%	50%	100%	
Min	-24	-37	-62	-69	-66	+13
1st Quartile	-18	-24	-29	-42	-22	-6
Median	-9	-12	-14	-19	-9	-4
3rd Quartile	-6	-8	-9	-5	-2	-4
Maximum	0	0	0	0	0	0
Average	-8	-11	-17	-24	-15	-3

Note: [1]calcuated over their time to fill and [2]calcuated over the rest of the simulation (subsequent operation of each fill scenario had similar results) compared to the case of no GERD

4.5 Discussion

The results demonstrate the basin-wide impacts of the GERD during filling and operation from a WFE nexus perspective. Results show that the GERD filling during above-average years is likely to have a little impact on the downstream countries and it could accelerate the reservoir filling. In contrast, the reservoir filling during dry years is likely to cause significant impacts on the downstream countries, as in food production in Egypt as discussed above.

Once the GERD becomes operational, the dam will be able to generate enormous hydropower and could offer a cheap energy source for the riparian countries. However, downstream countries could be impacted by the GERD operation in different ways. Sudan would have improved water supplies for irrigation and hydropower generation as a result of river flow regulation caused by the GERD. Average hydropower generation and irrigation water supply in Egypt will be reduced during the filling and operation phases of the GERD. Conversely, the GERD will offer improved water supply during low flow years. The latter illustrates that a coordinated policy among the system reservoirs would be highly beneficial and can reduce the risks for downstream water supply. This also demonstrates the importance of cooperation among the riparian countries over their planned developments and the role of the nexus approach as an analytical tool for identifying synergies and trade-offs among nexus domains.

The purpose of the current study is to investigate the long-term impacts of the GERD development on the riparian countries rather than improving the management of the system based on actual predictions of the river flows. The novelty of this work is in considering a holistic framework such as the nexus approach which allows for carrying out integrated analysis across sectors, across regions and across scales for new infrastructure projects in river systems. This was performed using an integrated WFE nexus simulation model for the entire Nile basin together with comprehensive nexus component in Egypt following GERD development while considering the uncertainty in hydrologic river flow regime through stochastic analysis. Also, the inclusion of population into the nexus framework shows the impacts of internal and external drivers on the nexus in a certain country as considered for Egypt here.

This chapter assessed basin-wide impacts on the WFE nexus following GERD development. GERD filling strategies exemplifies here the encountered challenges in a transboundary river as a result of building a new dam. Such filling strategies may cause raise tensions among co-riparians in a shared river basin. For instance, higher fill rates are favoured by an upstream country, e.g., Ethiopia in this case, while low fill rates are favoured by downstream countries such as Egypt and Sudan here. The difference between individual scenarios presented here may seem small (such as irrigation supply reliability in Table 4.3) however, the impact on the nexus sectors in riparian countries is likely to be significant (i.e., water shortage, food production, etc.) especially during dry years as shown above. As an example of illustration, such reduction in food production in Egypt will lead to increase in food imports to compensate this loss and this will likely cost millions of US dollars (note: imports of crops and livestock products cost 12.91 billion US$ in 2017 according to FAO (2020)). Also, the increase in fill rate will speed up the filling process and boost the hydropower generation in Ethiopia by up to 260% during the filling process.

The above-presented results would help decision makers and stakeholders by implementing filling strategies that are likely to achieve their interests without causing significant impacts among others. For example, results suggest that low fill rates (≤15% and 25% in some cases) are likely to have less impacts on the nexus in general compared to the higher fill rates. At the same time they allow Ethiopia for anticipating early hydropower generation from GERD. On other hand, higher fill rates (>25%) could speed up the filling the process and are likely to have higher impacts on downstream users compared to low fill rates. However, higher fill rates could possibly cause significant impacts on downstream stakeholders if adopted during dry years or severe droughts. Based on these results, it is recommended to implement a dynamic filling approach that would reduce risks to downstream users and help upstream countries to achieve their goals and interests. This is a departure point for further analysis in the future. The developed model can be coupled with real-time streamflow forecasting tools that have been successfully developed for the region (e.g., Blum et al. 2019) and assist in implementing dynamic filling approaches.

CHAPTER FIVE: IMPACTS OF POLICY OPTIONS ON THE WFE NEXUS

5.1 Introduction

This chapter presents the analysis of multiple policy measures interventions in Egypt in the context of WFE nexus. The integrated simulation model were applied for this purpose.

5.2 Key Policy Tests

A set of key policy measures and plans are considered and tested to assess the overall impact of the application of an individual policy and/or a set of combined policies on the WFE nexus and its complex interdependencies. The integrated WFE nexus model that was developed for Egypt is employed here for this purpose. First, the baseline scenario is simulated over a 65-year period, (2015-2080), using basin-wide stochastically generated stream flows. It should be noted that the baseline scenario assumes that the current WFE nexus management in Egypt will continue over the simulation period without any changes. For population growth, the main projections from United Nations (2017) (i.e., medium-variant projection) are adopted for the baseline scenario. Also, the baseline scenario assumes that the current WFE nexus management policies in the upstream countries stay unchanged during the simulation period.

Based on the sensitivity analysis results and policy measures and targets considered in the national policies in Egypt (MALR 2009; MWRI 2011), a set of policy measures were chosen and tested to examine their outcomes in the context of the WFE nexus. The policy measures considered here can be categorised into five subgroups as follows: (a) water resources development, (b) water demand management, (c) food production, (d) population growth and (e) combinations from individual policies.

The Water Resources Development and Management Strategy up-to 2050 Horizon (WRDMS 2050), (MWRI 2011) aims at achieving water security at present and in the future through developing and applying a set of water policy measures. The water management policies aim at balancing supply and demand, as well as meeting the different water demands. The water policies can be divided into two main categories: (1) water supply policies and (2) water demand policies. The water balance of Egypt at the national level is shown in Figure 5.1.

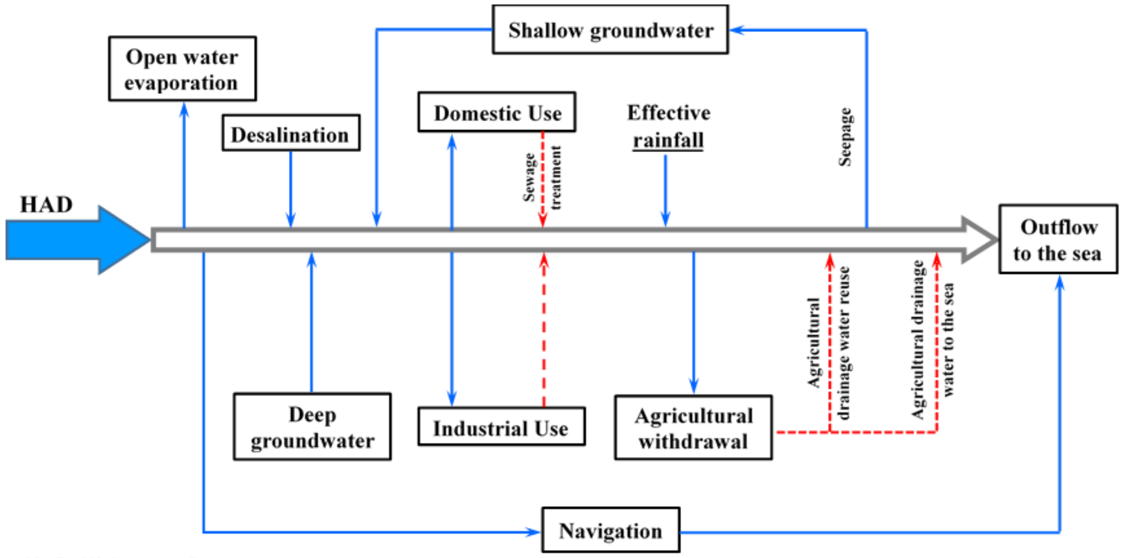


Figure 5.1 Egypt's water balance at the national level

The water supply policies include utilising the potential water from different water resources at their potential sustainable level. The additional water will be available from the expansion of the following resources: (a) shallow groundwater, (b) deep groundwater, (c) rainfall and flash flood harvesting, (d) agricultural drainage water reuse, (e) treated wastewater and (f) desalination. The potential expansion of these water resources is summarised in Table 5.1, according to WRDMS 2050, with reasonable assumptions made when data about the measure was not available. In contrast, the water demand policies aim at rationalising and improving the efficiency of water use of different water users. The water demand policy measures include: (a) reducing the consumption rates of domestic water, (b) improving the efficiency of the water distribution network, (c) improving the irrigation efficiency in the old lands and implement efficient irrigation techniques in the new lands and (d) changing cropping patterns.

The domestic water consumption rate is estimated for the urban population at 270 l/c/d and the rural population at 130 l/c/d. The overall consumption rate at the national level, considering the water distribution network efficiency (0.70), is estimated at 272 l/c/d (Calculated based population type, i.e., urban and rural, corresponding water demand rate and network efficiency. It can be calculated in a similar way as equation (3.12) but in daily format). It was assumed that the consumption rates would be reduced to 200 l/c/d for the urban population and 100 l/c/d for the rural population and the water distribution network efficiency would increase to (0.80) by the end of the simulation. Therefore, the domestic water consumption rate will be reduced from 270 l/c/d (in 2015) to 227 l/c/d (in 2050) and 190 l/c/d by the end of the simulation.

The agricultural water sector will rationalise its water use through improving the irrigation water efficiency in the old lands, implementing irrigation efficient methods in all the new lands and changing cropping pattern (MALR 2009; MWRI 2011). It was assumed that the irrigation efficiency in the old lands will increase from 0.61 (calibrated) to 0.75 (by 2050), similar to the assumption made by Abdelkader et al. (2018). Currently, half of the new lands apply efficient irrigation techniques (e.g., sprinkler and drip irrigation), (MWRI 2011). It was assumed that all of the new lands will apply efficient irrigation techniques by 2050. The cropping pattern changes include limiting the area of crops that use large amounts of water; namely rice and sugarcane (MALR 2009; MWRI 2011). Therefore, the rice area is limited to 1,300 thousand feddans, while sugarcane area is set not to increase beyond 350 thousand feddans.

The Sustainable Agricultural Development Strategy towards 2030 (SADS), (MALR 2009) aims at increasing the food security level and sustainable use of natural resources. In this regard, a set of policy measures were considered as follows: (a) improving land productivity, (b) agricultural land protection and (c) agricultural land development rate. According to SADS 2030, it is anticipated to increase crop productivity by 2030 via research and development programs and biotechnology utilisation. The trends of crop production are projected to the year 2030 and compared to the crop yield potential from SADS 2030 and found to be similar, (see appendix(C)). Accordingly, the crop yield potentials from SADS2030 are used and assumed to be achieved by 2030 in the considered scenario.

It is also assumed that achieving the crop yield potential would require increasing the machinery use. Therefore, it was assumed that the current trends in machinery use will continue in the future, appendix (C). The agricultural land is suffering from land degradation and leads to losing the valuable fertile lands. This was tested by assuming that land loss rate will be reduced from 40x1000 feddan/year, as calibrated, to 20x1000 feddans per year, which is a minimum value reported by El-Hefnawi (2005). One of the main pillars of SADS 2030 is the reclamation of additional new lands by 2030. However, WRDMS 2050 sets the land development target to the year 2050. It is worth mentioning here that both strategies set the land development targets based on water resources developments and water-saving policies discussed above. In the baseline scenario, it was assumed that the current land development rate (150x1,000 feddans per year) will continue in the future. Two further land development scenarios were tested including: (a) slow land development rate (120x1000 feddan) and (b) no land development scenario.

The uncertainty associated with population projections is further investigated by considering two traditional scenarios: (a) high-variant and (b) low-variant scenarios, Table 5.1. The high and low variants differ from the medium-variant only in the level of the total fertility rate, (United Nations 2017). Under the high-variant, the total fertility rate is projected to stay higher than the fertility level of medium-variant by 0.5 births. Conversely, the total fertility rate in the low-variant is projected to remain below the fertility level of the medium-variant by 0.5 births.

For the above-mentioned policy measures and variables, the model simulations were conducted assuming that only the considered policy is in force while the rest of the model variables are held unchanged at their baseline values during the simulation period (2015-2080). The above-described policy measures are summarised in Table 5.1 and Figure 5.2. It should be noted that individual measures such reducing agricultural land degradation and population growth will be controlled through concerned governmental institutions that are responsible for these sectors. This could include legislations and campaigns to raise the awareness of protecting the agricultural land for example. Also, different combinations from the above policies were set up and tested, Table 5.2. The application of individual policies allows for investigating the impact of a particular policy on the WFE nexus, while a combination of policy measures allows for investigating the broader impacts of a group of policies through complex linkages and feedback loops (Zhuang 2014). Also, these policy measures are coming from different sectors and institutions and could be implemented simultaneously to achieve national targets (e.g., food self-sufficiency). Therefore, testing possible combinations of policy measure are required to reflect their broader impact on the nexus. A number of plausible combinations were considered to assess their wide impacts on the nexus, however they are subjected to refinement.

The first combination (Comb1) considers the irrigation efficiency improvement, expansion in the agricultural drainage water reuse, and achieving crop yield potentials. The second combination (Comb2) is the expansion in groundwater (both shallow and deep) utilisation to their potentials and an increase in crop productivity. Alternatively, the third combination (Comb3) explores the development of all water resources potential. The fourth combination (Comb4) assumes high population growth along with agricultural land protection. In contrast, the fifth combination (Comb5) represents a preferred situation in which there is low population growth, a reduction in per capita water consumption, utilise potential water resources, irrigation efficiency improvement program is in action and crop yield potential achieved. The sixth combination (Comb6) investigates implementing the irrigation efficiency improvement, reduction in the domestic water consumption per capita, utilising all possible water resources, changing the cropping pattern and attaining the crop productivity potentials. Another combination named “All polices” considers policy measures (1-6), Table 5.1, that represent the application of policy measures and targets described in (MALR 2009; MWRI 2011).

For each simulation, it was assumed that the policy measure or the group of policy measures under investigation are only implemented, while the rest of other policies and model variables stay unchanged (i.e., at their baseline values). Each simulation runs over the period (2015-2080), same as the baseline scenario, and using basin-wide synthetic streamflow series. The impact of the certain policy measure(s) on model outputs at a particular point of time will be reported in the form of relative change to the baseline scenario as follow:

$$\Delta \mathrm{x}(\%) = \frac{(\mathrm{x}_{\mathrm{policy,time}} - \mathrm{x}_{\mathrm{base,time}})}{\mathrm{x}_{\mathrm{base,time}}} x100 \qquad (5.1)$$

Where $\Delta \mathrm{x}$ is the percentage of change in model output from the baseline, $\mathrm{x}_{\mathrm{policy,time}}$ model output under the considered policy, and $\mathrm{x}_{\mathrm{base,time}}$ model output under baseline at a specific point time or time interval.

Table 5.1 Policy measures for the WFE nexus in Egypt

Group	Policy measure		Description	Note
Water resources development	Groundwater resources (GW)	Deep groundwater	4.0 km^3 by 2050	WRDMS 2050[a]
		Shallow groundwater	8.0 km^3 by 2050	WRDMS 2050[a]
	Rainfall, water Reuse, and Desalination (RRD)	Rainfall	1.5 km^3 by 2050	WRDMS 2050[a]
		Reuse of agricultural drainage water	Increase to potential by 2050	WRDMS 2050[a]
		Reuse of treated wastewater	Current rate of increase will continue until the end of the simulation	Assumption
		Desalination	2.0 km^3 by 2050, rate of increase will continue until the end of the simulation	WRDMS 2050[a], assumption
Water demand management	Per capita domestic water consumption (PCWC)	Per capita domestic water consumption reduction	Urban water consumption decrease (from 270 to 220) l/c/d	Assumptions, Egyptian code of practice[b]
			Rural water consumption decrease (from 130 to 100) l/c/d	
		Improving water distribution network efficiency	Increase (from 0.70 to 0.80)	Assumption
	Improving irrigation efficiency (IE)		Old land efficiency increase (from 0.61 to 0.75)	WRDMS 2050[a], SADS 2030[c]
			All new lands apply efficient irrigation methods	
	Cropping pattern (CP)		Rice area (≯ 1300x1000 feddan)	WRDMS 2050[a], SADS 2030[c]
			Sugarcane area (≯ 350 x1000 feddan)	

Continued, Table 5.1 Policy measures for the WFE nexus in Egypt

Group	Policy measure		Description	Note
Food production	Land productivity (LP)	Crop yield	Achieving crop yield potentials by 2030	SADS 2030[c]
		Machinery use	Increase, current rate	Assumption
	Land development	Land loss reduction (LLR)	Reduce (from 40 to 20) x1000 feddans	Assumption
		Land development rate (LDR)	Reduce (from 150 to 120) x1000 feddans	Assumption
		No land development (NLD)	-	-
Population growth	Low population growth (LPG)	Low-variant	[2.30/1.86/1.48] [2030/2050/2080]	United Nations[d]
	High population growth (HPG)	High-variant	[3.30/2.86/2.48] [2030/2050/2080]	
	Medium population growth, (Baseline)	Medium-variant	[2.80/2.36/1.98] [2030/2050/2080]	

Note: [a](MWRI 2011); [b](MHUUC 2010); [c](MALR 2009); [d](United Nations 2017)

Table 5.2 Combinations of policy measures

Combinations	Description
Combination1 (Comb1)	Agricultural drainage reuse, IE,LP
Combination2 (Comb2)	GW, LP
Combination3 (Comb3)	Developing all potential water resources
Combination4 (Comb4)	HPG, LLR
Combination5 (Comb5)	LPG, PCWC, water resources, IE, LP
Combination6 (Comb6)	IE, PCWC, water resources, CP, LP
All policies	Policies (1-6), Table 5.1

5.2.1 Simulation Results

A set of model outputs that represent key components of each nexus domain (i.e., water, food and energy) are chosen and the impacts of the policy measure(s) will be reported here. Policy implications on the water sector will be explored through changes to; (a) domestic water consumption, (b) irrigation supply reliability, and (c) water shortage. The impacts on the food sector will be investigated through; (a) food production and (b) food imports. The energy demand in the domestic water and the agricultural sector and the hydropower generation from High Aswan Dam will be explored in the energy sector. The results of implementing different policy measures on the WFE nexus in Egypt over different time intervals are shown in Figures 5.3 and 5.4. A general observation from the simulation results is that the continuation of current water management would lead to increased water deficits, reduction in food production and increased food imports. In contrast, such policies such as developing water resources potential and/or demand management would improve the situation and this will be explained in detail below.

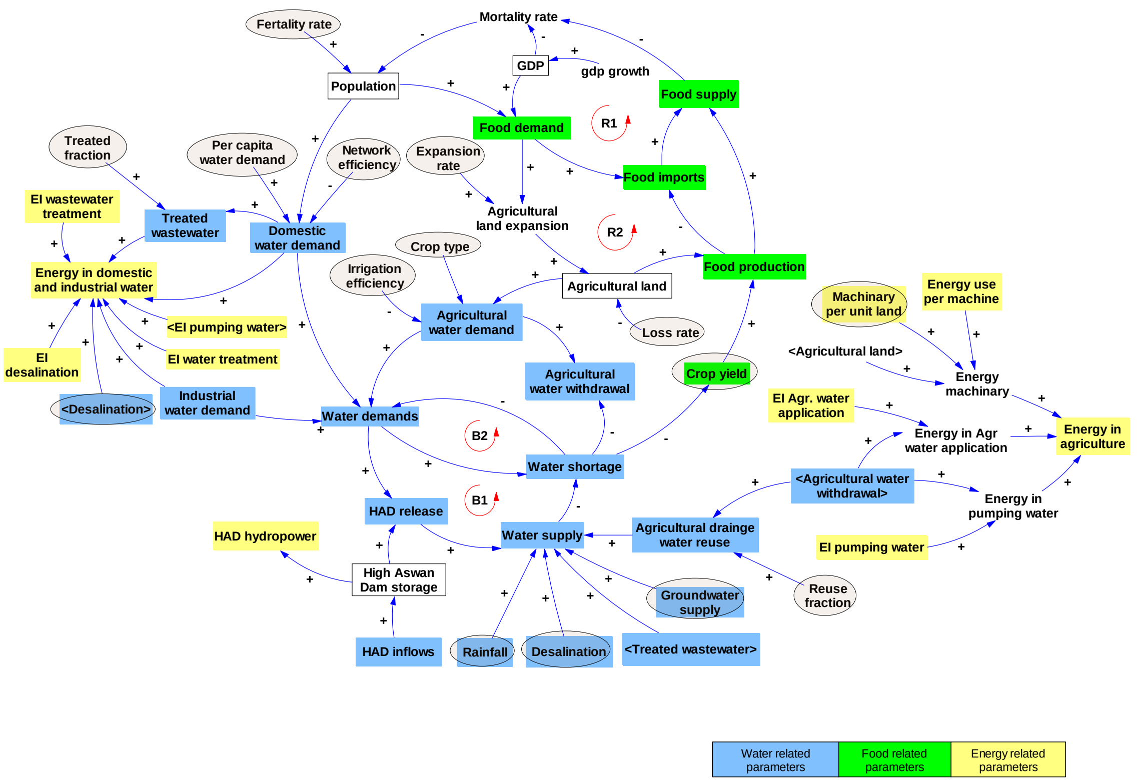


Figure 5.2 WFE policy measures tested (circled)

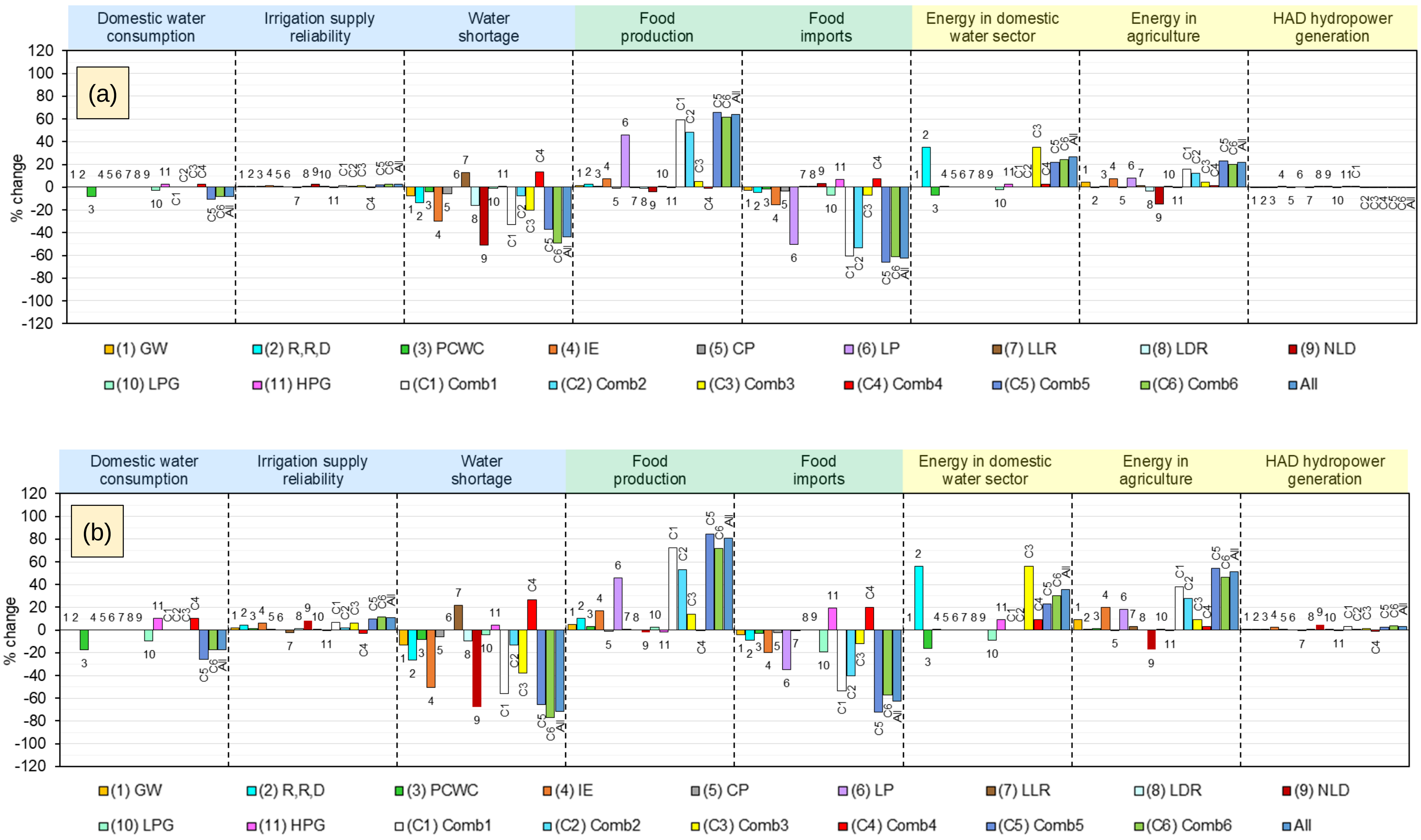


Figure 5.3 Impacts of policy measures on WFE nexus in Egypt by: (a) 2030 and (b) 2050

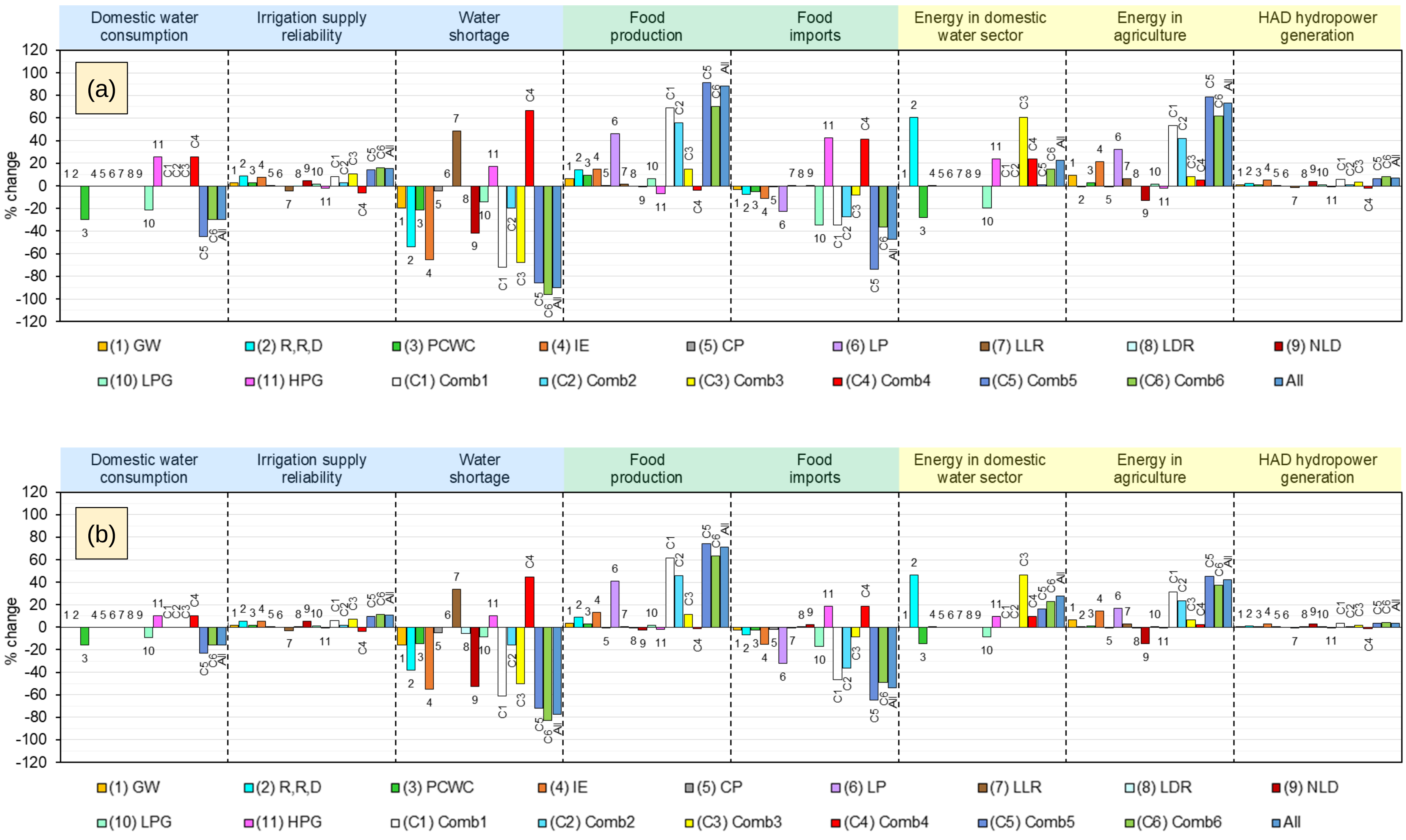


Figure 5.4 Impacts of policy measures on WFE nexus in Egypt: (a) at the end of simulation (2080) and (b) averaged over the simulation period (2015-2080)

5.2.1.1 Water Resources Management Experiments

Expansion in groundwater resources (both shallow and deep groundwater) to their potentials would slightly increase the irrigation supply reliability by 1.7%, while the average water shortage would be reduced by about 16.0% over the simulation course, Figure 5.3.b. Also, food production would increase by 3.3% while the food imports could be reduced by 2.8% compared to the baseline scenario. The energy demand in the agricultural sector would rise by 6.8% due to increased groundwater pumping. Relative changes in the key nexus components over the simulation course due to utilising the groundwater resources potentials can be observed through Figures 5.3.a, b and Figure 5.4.a. During the simulation, there is a gradual increase in the irrigation supply reliability, food production, and energy demand in the agricultural sector, while the average water shortage and food imports are gradually reduced.

The expansion in other water resources including the rainfall utilisation, treated wastewater, agricultural drainage water reuse and desalination have several impacts on the WFE nexus, Figure 5.3 and Figure 5.4. The irrigation water supply reliability will increase by approximately 5.5% on average during the simulation period, while the average water shortage will be reduced by about 38.0% as shown in Figure 5.4.b. Also, food production will be increased by 8.7%, while the food imports will be decreased by 6.6% compared to the baseline scenario, Figure 5.4.b. Looking into the energy demand in the domestic water sector, an obvious increase in the energy demand, as expected, by over 46.0% due to the expansion in desalination and wastewater treatment facilities that have high energy demands compared to other water activities. The impacts on the energy in the agricultural sector are negligible, as it is assumed that the energy demands in desalination and wastewater treatment activities will be attributed to the domestic water sector. The hydropower generation from HAD would be increased by approximately 1.2% due to the contribution of the considered water resources in reducing the water demands from HAD and hence increase in the HAD water levels. Also, the changes in the WFE nexus components along the simulation course can be traced through Figures 5.3.a, b, and Figure 5.4.a.

The reduction in the overall domestic water demand considered here through: (a) the reduction in the per capita water demand and (b) improving the water distribution network efficiency. The reduction in water demand per capita will have a considerable impact on the nexus domains. The overall domestic water consumption could be reduced by 16.0% and the average water shortage would be reduced by 15.0%. The irrigation supply reliability will be increased by 1.5%, close to the results obtained by utilising the groundwater potentials. Also, domestic food production could be slightly improved by over 3.0%, while food imports could fall by over 2.0%.

The energy in the domestic water sector could drop by more than 14.0%. In contrast, the energy in the agricultural sector will be increased by 1.0% due to the rise in agricultural water consumption (water saved from the domestic water sector being used by the agricultural water sector). The hydropower generation from HAD will slightly increase from rationalising the water use in the domestic water sector. Interesting results arise here from comparing the outcomes of rationalising the domestic water use and utilising the groundwater resources over the course of the simulation. Both measures have similar outcomes, on average, with respect to the irrigation supply reliability, water shortage and food sector, Figure 5.4.b. The overall energy demands (in the domestic water and the agricultural sectors) associated with rationalising domestic water use policies are lower than those associated with utilising the groundwater potentials, apparently due to increased water pumping. In other words, rationalising the domestic water use only offers promising outcomes towards improving the overall WFE nexus, compared to developing new groundwater resources.

The application of irrigation efficiency improvement, Table 5.1, reveals considerable impacts on the WFE nexus over the simulation course, as shown in Figure 5.3 and Figure 5.4. The irrigation supply reliability could be improved by over 5.0%, while the average water shortage could be significantly reduced, or by 55.0% on average compared to the baseline scenario, Figure 5.4.b. Interestingly, the water saved from the irrigation efficiency improvement programme will improve the water supply and contribute to reducing the water deficits, especially for the agricultural sector. The latter effect can be observed in the food sector as follows: the domestic food production would be improved by

13.0%, while the food imports would decline by 15.0% on average, Figure 5.4.b. The results highlight the importance of improving the irrigation efficiency and their significant implications to the water and the food sectors in general. Conversely, the energy use in the agricultural sector would rise by about 14.0% on average, due to implementing energy-demanding and efficient irrigation systems, e.g., sprinkler and drip irrigation. Also, the average hydropower generated from HAD would increase by 3.0% as a result of increased HAD water levels due to reduced water demands from HAD. Figure 5.3.a, b and Figure 5.4.a show the gradual progress of the WFE nexus impacts from implementing irrigation efficiency improvement policy. The rate of change of each key component of the nexus from the beginning of simulation until the year 2050, (target year to implement the policy), is greater than the rate of change over the rest of the simulation.

Changing in cropping pattern by restricting the areas of water-intensive crops will have modest to limited impacts on the nexus components, Figure 5.4.b. For example, the irrigation supply reliability would increase by 0.5%, while the water shortage could be reduced on average by 5.0%. Food production will be reduced by less than 1.0%, while the food imports could be reduced by 2.0% on average. The energy sector will be less impacted, for instance, energy in the agricultural sector and the hydropower generation from HAD will have negligible impacts. Also, the energy demands in the agricultural sector and HAD hydropower generation at different time intervals do not change significantly over the simulation course.

5.2.1.2 Food Production Experiments

Improving the land productivity by achieving the crop yield potentials will have direct impacts on the food sector and to some on extent the energy demand in the agricultural sector. Narrowing the yield gap would boost food production by approximately 41.0%, while food imports could drop on average by 32.0%, Figure 5.4.b. As mentioned above, attaining the potential crop yields will be accompanied by an increase in machinery use, and so the energy demand in the agricultural sector would grow on average by approximately 17.0%, Figure 5.4.b. It should be noted that direct energy use was only considered in estimating the energy demand in the agricultural sector. Indirect energy use such as the embodied energy in fertilisers was not accounted for here. Achieving the potential crop yields could require the extra applications of fertilisers and pesticides and in turn, increase the overall energy use in the agricultural sector. However, that was beyond the scope of current research. Tracing the changes to the food sector at different time intervals through Figure 5.3.a, b, and Figure 5.4.a reveals that food production would not change beyond the year 2030, (target year to achieve the potential crop yields) as the crop yields stay unchanged for the rest of the simulation. Food imports will be reduced at a lower rate (i.e., from 50.0% (2030) to 22.0% (2080), Figure 5.3.a, b, Figure 5.4a) due to population growth.

The agricultural land development was investigated in three scenarios as listed in Table 5.1, and shown in Figure 5.5. The three scenarios are as follows: (a) protecting the agricultural land by reducing the agricultural land loss, (b) rate of agricultural land development at a slow rate (c) assuming no land development would occur and the agricultural land stay unchanged, Table 5.1, Figure 5.5. Protecting the agricultural land results in an increase in agricultural land, therefore, agricultural water demand also increases. The irrigation supply reliability will be reduced on average by 2.8%, while the average water shortage will also increase by 34%, Figure 5.4.b. The food sector will not be considerably impacted and the average food production will increase by less than 1.0%, while the food imports will not be changed. Unsurprisingly the food sector will not be significantly impacted as the agricultural water demands and the currently available water resources are already exploited. Also, the energy in the agricultural sector will increase by 3.2%, while the hydropower generation from

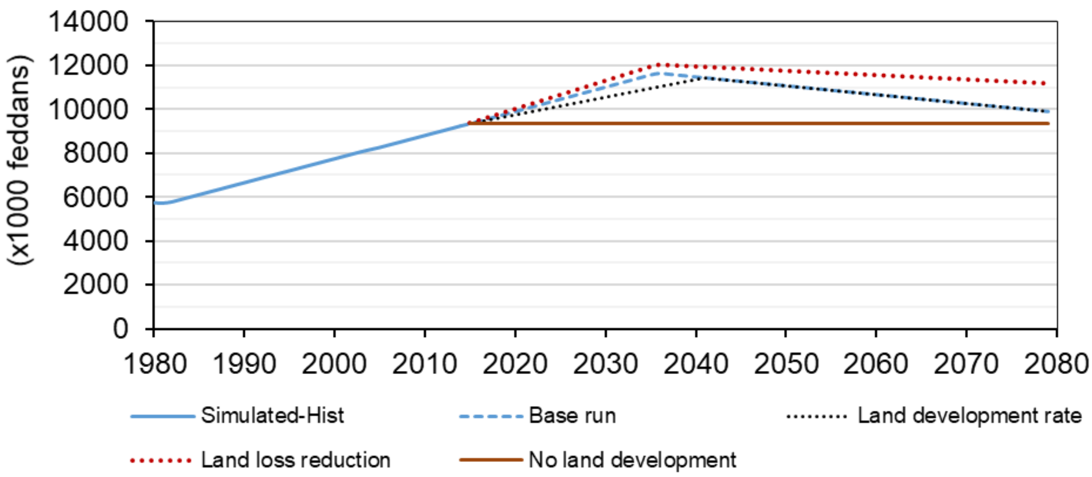


Figure 5.5 Agricultural land at different development scenarios

HAD will be reduced on average by 1.0%, Figure 5.4.b. The changes to the WFE nexus across the course of the simulation, Figure 5.3.a, b and Figure 5.4.a.

Developing the agricultural land at a slower rate than the baseline scenario showed little impact on the WFE nexus key components, Figure 5.4.b. The average water shortage would be reduced by about 6.0%, while the agricultural energy demand would be reduced by 1.0% on average. The changes over the course of the simulation can be traced through Figures 3.a, b and Figure 5.4.a. The nexus components will be affected until 2050 and after that, no changes are expected to occur as the agricultural land level will be similar to the baseline scenario. The irrigation supply reliability could be increased by 1.0% for the first part of the simulation (i.e., by 2050). Also, the average water shortage would be reduced by 10-16% during the same period.

The scenario of no land development reveals some interesting results to the WFE nexus domains. By looking into the average results over the course of the simulation, it is shown that the irrigation supply reliability would increase by about 5.0%, while the average water shortage could be substantially reduced by more than 50.0%, Figure 5.4.b. The latter indicates the significant impacts of expanding the agricultural land on the water sector. The food sector will be less impacted as shown in Figure 5.4.b. The food production would be reduced by 2.7%, whereas the food imports would rise by 2.0% on average, Figure 5.4.b. The energy demand in the agricultural sector would be reduced by 14.0% on average, as the agricultural land level is reduced from that in the baseline scenario. Interestingly, the hydropower generation from HAD would increase by 3.0%, due to the reduction in water demands, therefore, higher water levels at HAD.

The land development scenarios explored above reveal some interesting results. Agricultural land development has a direct impact on the water sector. For instance, the average water shortage would drop by more than 50.0% in the case of no land development. The average water shortage rose to 34.0% in the case of protecting the agricultural land (i.e., reducing the land loss). Food production was not greatly impacted by land development scenarios. Accordingly, the agricultural land expansion will not significantly increase food production due to lack of sufficient available water to meet the growing demands and increased competition with the domestic water sector. This suggests that developing water resources potentials and improving water-use efficiency are crucial to meet the growing demands, especially in the agricultural sector. These measures would also reduce the impacts of water shortage on food production, as discussed above in the water resources policy measures. Lastly, different combinations of water resources policy measures and their implications on the food sector will be further explained below.

5.2.1.3 Population Projections Experiments

As mentioned earlier, two different variants of population projections were considered: (a) high-variant and (b) low-variant, Figure 5.6 along with the medium-variant (i.e., baseline scenario). Population projection for each variant is shown in Figure 5.7. Under the medium variant, the population is likely to continue growing and a two-fold increase could be expected between 2015 and 2080. Also, the population could increase within a range between 144 and 231 Million by 2080. The simulation results for the variants of population projections, Figure 5.3.a, b and Figure 5.4.a, show that the change in key nexus components during the course of the simulation are broadly impacted by the change in population levels. At the beginning of the simulation, the changes to the nexus components are small or negligible as the population levels of the variants are similar. Afterwards, the range of changes expands as the range of population levels widens.

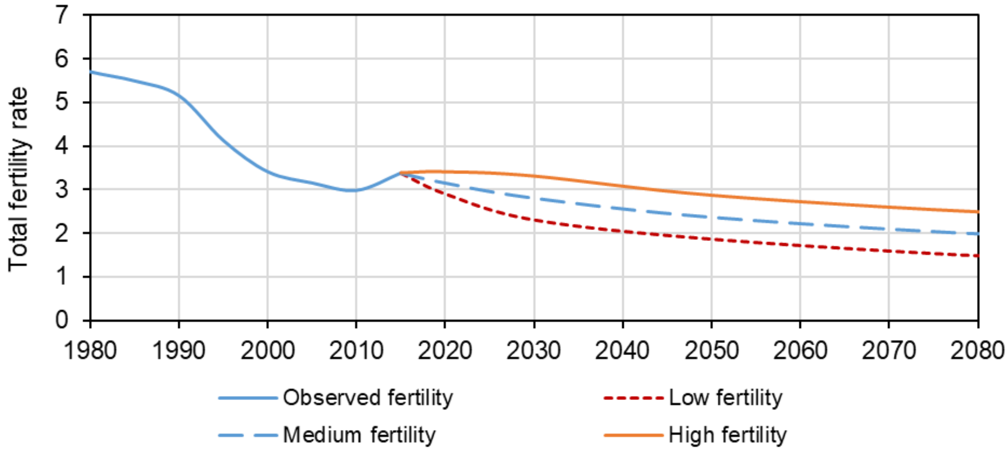


Figure 5.6 Total fertility rate associated population

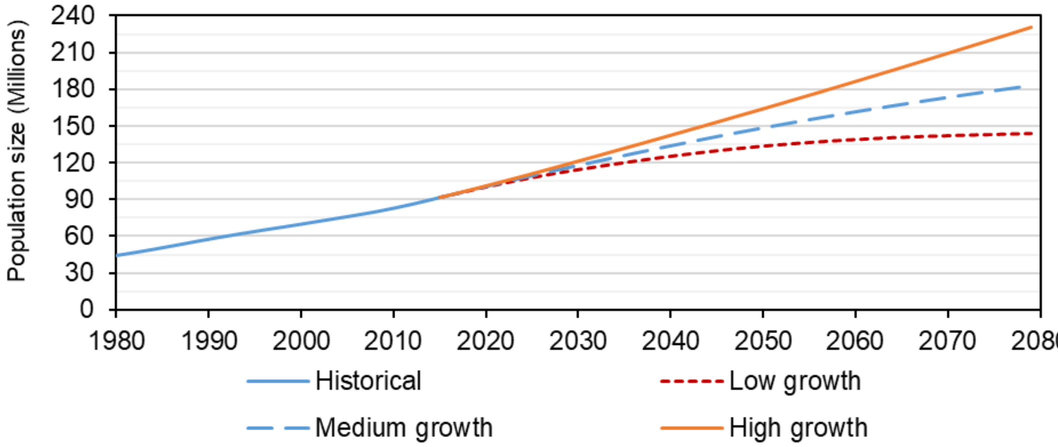


Figure 5.7 Population projections for different variants

The domestic water demand is directly impacted by the population and the demand increase would follow the population growth under the assumption that other variables that affect the demand stay unchanged (i.e., per capita demand and network efficiency), Figure 5.3. Figure 5.8 shows the changes to the domestic water demand for the two population variants compared to the baseline scenario during the course of the simulation. The domestic water demand could vary by more than 20% by 2080 under the two population variants. This reflects the significant impact of the population momentum on the overall domestic water demand.

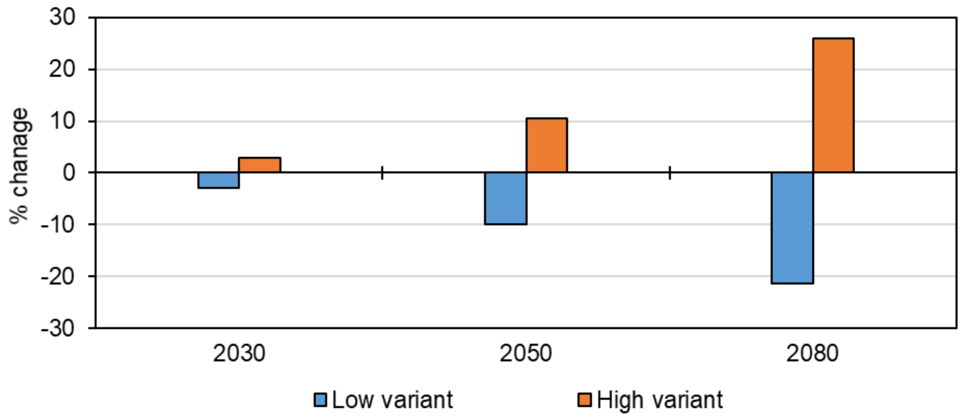


Figure 5.8 Changes to population for the low and high variants compared to the medium variant during the course of the simulation

The increase/decrease in water demands from population increase/decrease would subsequently affect the irrigation supply reliability and the average water shortage. The irrigation supply reliability will be less impacted under the two variants along the simulation course, Figure 5.3 and Figure 5.4. The irrigation supply reliability would on average increase/decrease by 1.0% for the low/high-variant projection compared to the baseline scenario, Figure 5.4.b. The average water shortage indicated a considerable change under the two population variants. For example, the average water shortage could be reduced by 9% for the low-variant scenario, while it could increase by 10% for the high-variant, Figure 5.4.b.

Similarly, the food sector is impacted by the variants of population projections. Food production could increase/decrease on average by 2.0% for low/high-variant, as a result of an increase/decrease in water availability associated with each variant. Contrarily, food imports would decrease/increase by 17.0% on average due to the combined effect of decrease/increase in population and increase/decrease in food production. Food imports are substantially impacted by the population variants compared to food production during the simulation, as shown in Figure 5.3.a, b and Figure 5.4.a. This is due to the impact of the population size on food imports in comparison with food production (i.e., in the event of no significant increase in food production levels, the more people, the more food imports and vice-versa).

The energy demand in domestic water sector follows the growth in the domestic water demand and the population projections for each variant, Figure 5.8. The energy demand decrease/increase gradually with low/high-variant of population projection compared to the baseline scenario, as shown in Figure 5.3.a, b and Figure 5.4.a. The change in energy demand in the domestic water sector is similar to the range of change in population projections. In contrast, the energy demand in the agricultural sector and the hydropower generation from HAD will be less impacted by the population projection variants, Figure 5.3 and Figure 5.4.

5.2.1.4 Policy Combinations Experiments

As mentioned earlier, different combinations of individual policies were developed, Table 5.2 and their broader impacts on the WFE nexus are discussed in detail below. The first combination (Comb1) investigates the expansion in the agricultural drainage use potentials, improving the irrigation efficiency and achieving the crop yield potentials simultaneously. Model simulation results indicate that irrigation supply reliability would increase by 6.0%, while the average water shortage would reduce by more than 60.0%, Figure 5.4.b. Due to such improvements in the agricultural water supply and the land productivity, domestic food production would be boosted by over 60% on average, while food imports will drop by 47.0%, Figure 5.4.b. Also, the energy in the agricultural sector will increase on average by more than 30% due to expansion in activities that acquire high energy input (e.g., efficient irrigation methods and machinery use). The average HAD hydropower generation will increase by about 3%, Figure 5.4.b due to reduced water demands from HAD.

The second combination (Comb2) explores the utilisation of groundwater resources potentials along with improving land productivity. The impacts on key water sector elements will be similar to the case of developing the groundwater resources only, Figure 5.3 and Figure 5.4. However, the food sector will be significantly impacted by the combined effects of implementing the two policies. Food production will increase on average by 45.0%, while food imports will drop by 36.0%, Figure 5.4.b. The energy use in the agricultural sector will increase by 24% due to increased water pumping and machinery use.

The combined impacts of developing all water resources potentials were investigated in Comb3. On average, the irrigation supply reliability would be increased by 7.0%, while the average water shortage would be halved. Interestingly, the reduction in the average water shortage for the case of implementing efficient irrigation methods will be higher than for the case of developing water resources potentials by 10%, Figure 5.4.b. This demonstrates the significance of implementing efficient irrigation methods over developing new water resources. The average food production would increase by 11.0%, while average food imports would reduce by 9.0%, Figure 5.4.b. The overall improvements in the food sector (i.e., food production and food imports) with implementing efficient irrigation methods, are higher than those of developing all water resources potentials, Figure 5.3 and Figure 5.4. The energy demands in the domestic water sector will increase by 46.0%, due to expansion in desalination and wastewater treatment facilities that have higher energy intensities. The energy demand in the agricultural sector would increase by 7.0%

on average, Figure 5.4.b, mainly due to the increase in groundwater pumping for irrigation. The hydropower generation from HAD would increase by 2.0% compared to the baseline scenario. Another interesting finding is that the overall energy demand in the case of developing water resources potentials would experience a higher than threefold increase compared to the case of implementing efficient irrigation methods. The results of these two policy scenarios, IE and Comb3, illustrate the overall impacts of implementing such measures in the water sector and their wide impacts on the WFE nexus.

The fourth combination (Comb4) represents the worst scenario, in which a high population growth rate and an increase in the agricultural land are projected. The domestic water demand would increase by 10.0% on average, while it increases by 25.0% at the end of the simulation, due to increased population. The irrigation supply reliability would decline by 4.0% on average, while the average water shortage could increase by 45%, Figure 5.4.b. Despite the increase in agricultural land, food production could be reduced on average by 1.4%. This reduction is due to increased water deficits in the agricultural sector resulting from increased competition between the domestic water and the agricultural sectors. Food imports would be increased on average by 19%, while at the end of simulation that increase would reach 41.0%, due to high population growth. The energy demand in domestic water sector would grow on average to 10.0% and to 24.0% by the end of the simulation, similar to the rate of increase in domestic water consumption, Figure 5.4. The energy in the agricultural sector would increase by 2.5%, while the average hydropower generation from HAD would drop by 1.3%.

The fifth combination (Comb5) can be considered as a preferred scenario in which low population growth is expected along with a reduction in per capita water demand, utilisation of water resources potentials, application of efficient irrigation techniques and improving land productivity. The domestic water consumption would drop on average by 23.0%, while by the end of the simulation it would be reduced by 45.0%, due to the combined impact of the reduction in per capita water demand and less population size. The irrigation supply reliability could be boosted by 10.0% due to increased water supplies that become available from saved water and additional water resources. Also, the average water shortage could be reduced by 72.0%, Figure 5.4.b. The enormous improvements in the water sector and land productivity is also reflected in the food sector. For instance, food production would increase on average by 74.0%, Figure 5.4.b. Conversely, food imports would drop by 65.0%, while at the end of the simulation would reach 74.0%, due to the combined effect of low food demands from the population and increased productivity of the agricultural land. The energy demands will be impacted by considerable changes in the water and food sectors. For example, energy demand in the water sector would increase on average by about 16.0%, Figure 5.4.b. The energy in the agricultural sector could increase by 45%, due to an increase in water consumption, efficient irrigation methods and machinery use. The average hydropower generation would increase by 3.5%, Figure 5.4.b.

The sixth combination examines utilising water resources potentials, reducing per capita domestic water demand, changing in cropping patterns, improving the irrigation efficiency and land productivity. Simulation results show that the domestic water demand would reduce on average by 16.0%, and the irrigation supply reliability would increase by 11.0%, (the highest among all simulations). Consequently, water deficits would reduce by 83.0% (the highest among all simulations). Food production would increase by 63.0%, while food imports would be halved in this scenario. The energy demand in the domestic water sector would increase on average by 23.0%, almost half of the value in Comb3 (i.e., developing water resources potentials with current consumption rates). This illustrates the significant impact of domestic consumption rates on energy demand in the domestic water sector. The energy demand in the agricultural sector would grow by 38.0% on average. The average hydropower generation from HAD would increase by 4.0% (the highest among all simulations).

The last combination called “All policies” investigates the implementation of proposed policies including developing new water resources, managing the demand side, and improving the agricultural land productivity at the same time. Also, this scenario differs from the previous scenario (i.e., Comb6) in the agricultural land where the land loss rate is reduced. Simulation results reveal that the domestic water consumption would be reduced by 16.0%, while at the end of the period would be reduced by 30.0%. The irrigation water supply reliability would be improved on average by 11.0% and by 15.0% at the end of the period. Also, water shortages are reduced on average by 77.0%, as a result of increased water supplies and additional water that became available from improving the efficiency of water use. Implementing policy measures in the water sector and achieving land productivity demonstrated significant impacts on the food sector. Food production could be increased by 71.0%, while food imports would drop on average by 54.0%, Figure 5.4.b. However, the energy demand in the domestic water sector and agricultural sector would rise due to expansion in desalination, water pumping, application of efficient irrigation methods, wastewater treatment facilities and agricultural machinery. The energy in the domestic water sector would increase on average by 28.0% and in the agricultural sector by 42.0%. The improvement in the water sector would lead to increased hydropower generation from HAD by 4.0%.

5.3 Discussion

The above-discussed policy measures and their combinations illustrate the impacts of implementing the policy measure(s) on the WFE nexus at the national level. Implementing the irrigation efficiency improvement through the application of efficient methods offers a promising step in improving the WFE nexus situation. For instance, simulation results indicate an average increase in food production by 13%, in irrigation supply reliability by 5%, and in energy demand in the agricultural sector by 14%. Also, food imports could reduce on average by 10% and water shortages by 54%.

Although reducing the domestic water consumption rates has a limited impact on the nexus, however, this measure demonstrates the impact of rationalising water consumption in the domestic sector since the current consumption rate is high. Model results suggest that reducing the current consumption rates could reduce on average the water and the energy consumption in the domestic water sector by approximately 15%, water shortage by 15% and food imports by about 2%.

The so-called unconventional water resources, e.g., desalination, reuse of treated wastewater, agricultural drainage water reuse and rainfall utilisation, can be considered as crucial resources. Although some resources have limited capacity, e.g., rainfall, and others have high energy demands such as desalination and wastewater treatment, jointly, they have considerable impacts on the nexus. Utilising these resources could on average increase food production by approximately 9%, irrigation supply reliability by 6%, while reduce on average food imports by 6% and water shortage by 38%. Also, the energy demand in the domestic water sector could increase on average by 46%. However, the progress in technologies, especially in desalination and wastewater treatment and through the use of renewable energy resources, will offer good opportunities in utilising these resources.

The expansion in groundwater resources would slightly improve the water, and food sector situation as they have limited potential, however, as a result the energy demand will increase. Regarding land development, development plans should be coordinated with adequate policies for both the water demand and supply sides. Continuation of land reclamation plans even with developing new water resources potentials showed varying impacts on the nexus domains, as shown in the Comb3 scenario. Simulation results showed an increase in average food production by 11%, in irrigation supply reliability by 7% and in energy demand in the domestic water sector by 46% and in the agricultural sector by 7%. Also, a reduction in food imports by 9% and in water shortage by 50%. In contrast, improving land productivity alone offers promising results regarding the food sector in particular. Achieving the potential crop yields would increase food production by 40% and energy demand in the agricultural sector by 17%, while reducing food imports by 32%. These results demonstrate that improving land productivity would exceed the impacts of other policy measures. An interesting result can be concluded here also, that improving land productivity can be prioritised over land expansions plans.

The combined impacts of improving land productivity and irrigation efficiency indicate and increase in food production by 61%, energy in the agricultural sector by 31%, the irrigation supply reliability by 6%. Food imports and water shortage would reduce by 47% and 61%, respectively. These results demonstrate possible policy measure(s) and their impacts on the WFE nexus at the national level. The results can assist in better understanding the WFE nexus and the impacts of different policy options on the nexus. Also, the model and the results can assist in screening the policy measures and in turn guiding in prioritising these measures.

This work explores the impacts of individual policy measures across nexus domains at the national level. While some of the measures managed to improve the food and water sectors, there was a simultaneous increase in the energy demand. This reflects the challenges associated with policies spanning over different sectors that could result in conflicts among different sectors and stakeholders. Therefore there is a need for cross-sector policies analysis that would lead to better policy designs and efficient policy implementation. This, however, this was beyond the scope of this thesis.

CHAPTER SIX: WFE NEXUS FOR TRANSBOUNDARY COOPERATION

6.1 Introduction

This chapter investigates means of cooperation among Egypt, Ethiopia and Sudan over GERD operation and their impacts on the WFE nexus in the Nile basin.

6.2 Cooperation Concept

In this section, the potential scenarios for cooperation over the GERD will be explored. As previously discussed, the river flows during low-flow and dry periods will be augmented as a result of the flow regulation caused by GERD when the dam comes online. Therefore, cooperation among the riparian countries over the GERD can be translated on the ground through additional releases from GERD to meet downstream water demands during droughts or when needed, Figure 6.1. This concept has been previously considered and explored in the literature, (e.g., Wheeler et al. 2016; Basheer et al. 2018; Digna et al. 2018b). However, these studies were limited to the assumptions that Egypt’s demands are fixed and did not consider the growing demands in Egypt. Furthermore, Basheer et al. (2018) work was limited to the Blue Nile basin only (i.e., between Ethiopia and Sudan).

Two extreme positions will be investigated, the full cooperation of the riparian countries and unilaterally motivated policies. The two positions are considered here together with different demand conditions in Egypt and with various options for the operation of the Sudanese reservoirs, Figure 6.2 and Table 6.1. Basin-wide impacts will be investigated for the unilateral and cooperation states for comparison with the case of no GERD. The unilateral state considers the hypothetical situation by which the riparian countries do not share information about the operation of their infrastructure or downstream releases. Accordingly, the current operation rules of the existing reservoirs in the basin are assumed to stay unchanged in the unilateral state and GERD is operated to maximise the hydropower generation regardless of potential downstream shortages. In the cooperation state, the riparian countries agree to cooperate, coordinate their reservoirs and share information about reservoirs conditions, e.g., releases, storage, etc. Therefore, downstream users can request additional releases from GERD in the case of experiencing a water shortage.

Figure 6.1 Cooperation concept over GERD, (map adapted from NBI (2012))

* Note additional GERD releases will be passed through Sudanese reservoirs

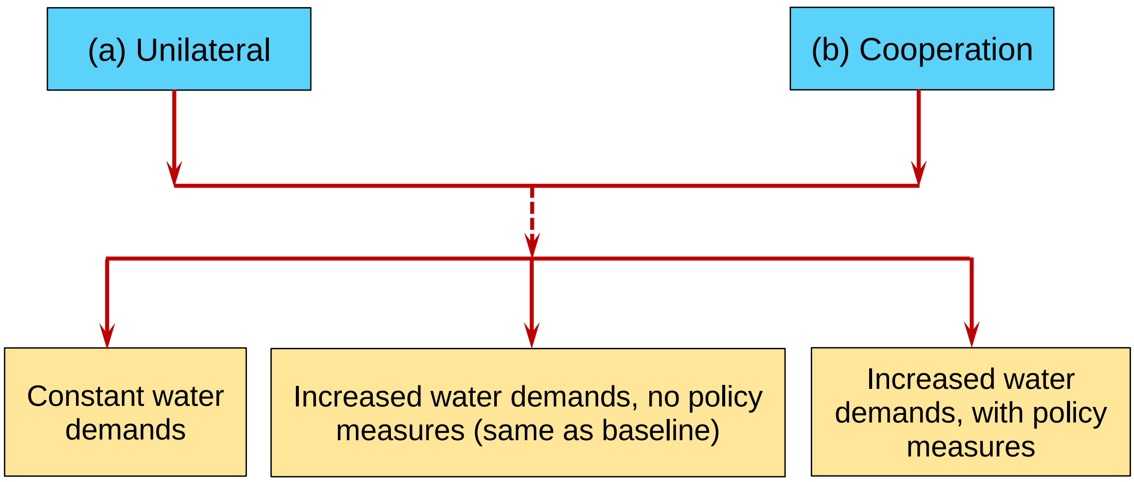


Figure 6.2 Egypt water demand conditions for: (a) unilateral state and (b) cooperation state for GERD

Table 6.1 Unilateral and cooperation positions explored in riparian countries

Country	Unilateral	Cooperation
Egypt	Constant water demands (Demands level before 2015)	Constant water demands (Demands level before 2015)
	Increased water demands with no additional water resources (same as baseline[1])	Increased water demands with no additional water resources (same as baseline[1])
	Increased water demands and developing water resources policy measures (1-5), Table 5.1	Increased water demands and developing water resources policy measures (1-5), Table 5.1
Ethiopia	Same as baseline conditions[1]	Additional releases from GERD to HAD when requested
Sudan	Same as baseline conditions[1]	Reservoirs on the Blue Nile are operated at their full supply level

[1]Baseline: Ethiopia maximises hydropower generation from GERD, no changes to the upstream demands and reservoirs' operation policies across the basin and water demands in Egypt continue to grow without additional water resources development

In Egypt, a number of varying demand conditions were considered as follows: (a) current water demand levels, (b) increased demands due to population growth and expansion in agricultural land but without developing additional water resources (baseline) and (c) similar to case (b) but assumes that Egypt succeeds in implementing policy measures (1-5), Table 5.1. The second demand scenario is an extreme case that examines the impacts of increased water demands in the downstream on the basin if cooperation is adopted. While the third demand examines the impacts of improved water management in Egypt if the countries agree to cooperate (i.e., preferred scenario). It should be also noted that the third scenario assumes that the adopted water management policies are expected to be successfully implemented. The three demand conditions were tested for the unilateral and cooperation actions, while the case of no GERD for each demand condition is used for comparison. A drought policy for HAD was applied in all the simulations. The policy applies a sliding fraction to the downstream demands based on the storage behind HAD, Table 6.2, (Donia 2013; Hamed 2018). The policy aims at reducing the chance of the reservoir being fully depleted. This is achieved by distributing the water shortage over longer periods and thus eliminating severe water deficits (Hamed 2018). In the unilateral state, no additional flows from GERD are released to HAD even in the case of drought and GERD is operated to maximise hydropower generation.

Table 6.2 Demand reduction factor for HAD

HAD storage (km^3)	HAD level (m)	Demand reduction factor (%)
55<S≤60	158.02<L≤159.44	5
50<S≤55	157.92<L≤158.02	10
S≤50	L≤157.92	15
Note: S: storage and L: level of water in the reservoir		

Joint operation of reservoir systems offers a significant opportunity for achieving cooperation and are likely to shape the way for reaching an agreement in shared river basins such as the Nile river basin. The cooperation state assumes that the riparian countries are sharing information regarding their dams including dam operation, reservoir levels, storage levels and discharges. Therefore downstream dams' operators and water managers will be aware of such excess releases from GERD. Furthermore, Sudanese reservoirs located downstream GERD are expected to pass the additional flows released from GERD to Egypt, Figure (6.1). In this state, it is assumed that HAD will request additional releases from GERD in case there is a water shortage in Egypt. Water shortage is expected to occur if the supply to demand (S/D) ratio falls below a certain level and this level is called the agreed ratio. Two agreed ratio levels are investigated here: 85% and 100% and can be considered as a proxy to the cooperation level. The first ratio is compatible with the maximum reduction factor to water demands from HAD during droughts, Table 6.2 and similar to the adequate supply reliability range (80-85%) that allows for applying deficit irrigation practises without causing detrimental impacts on crops yield, (Steduto et al. 2012). On the other hand, the 100% ratio investigates the willingness of riparian countries to jointly work on mitigating their individual risks as far as possible.

In this vein, the model calculates the monthly water demands from HAD and forecasts whether there is a water shortage or not. If the S/D ratio falls below the agreed ratio, the model estimates the additional water required to satisfy the ratio and is named Desired Additional Flows (DAF), Figure 6.3. After that, HAD requests DAF from GERD and the additional flows are then released from GERD based on the storage condition in the reservoir. Furthermore, maintaining the GERD reservoir level at the Minimum Operating Level (MOL) takes priority over downstream releases. It should be noted that GERD applies a reduction fraction to downstream releases (20%) if the water level in the reservoir falls below the level 638 m (a.m.s.l), (NBI 2016a). This rule is also applied to the DAF requests. The procedures of estimating and allocating HAD demands from GERD are summarised in Figure 6.3.

It is assumed that in Sudan, the Blue Nile reservoirs, (El-Roseires and Sennar) are operated with their current operation rules in the unilateral state. In that case the riparian countries do not share information regarding the management and operation of their infrastructure. Conversely, the cooperation state assumes that the riparian countries work together by exchanging information and jointly coordinate the operation of their infrastructure, e.g., downstream countries are informed of releases from an upstream reservoir. Accordingly, Sudan can operate El-Roseires and Sennar dams at their maximum feasible level without concerns over dam overtopping that might result from unanticipated releases from the GERD, (Wheeler et al. 2016; Basheer et al. 2018). Therefore, the Blue Nile reservoirs in Sudan - in the cooperation state - will be operated at their maximum feasible level, with releases aimed at meeting downstream demands, hydropower generation and flood control, while forgoing seasonal flushing for sediment (Wheeler et al. 2016). This point out to the essential role of the Sudanese reservoirs in reaching such a cooperation agreement among the riparian countries in the future.

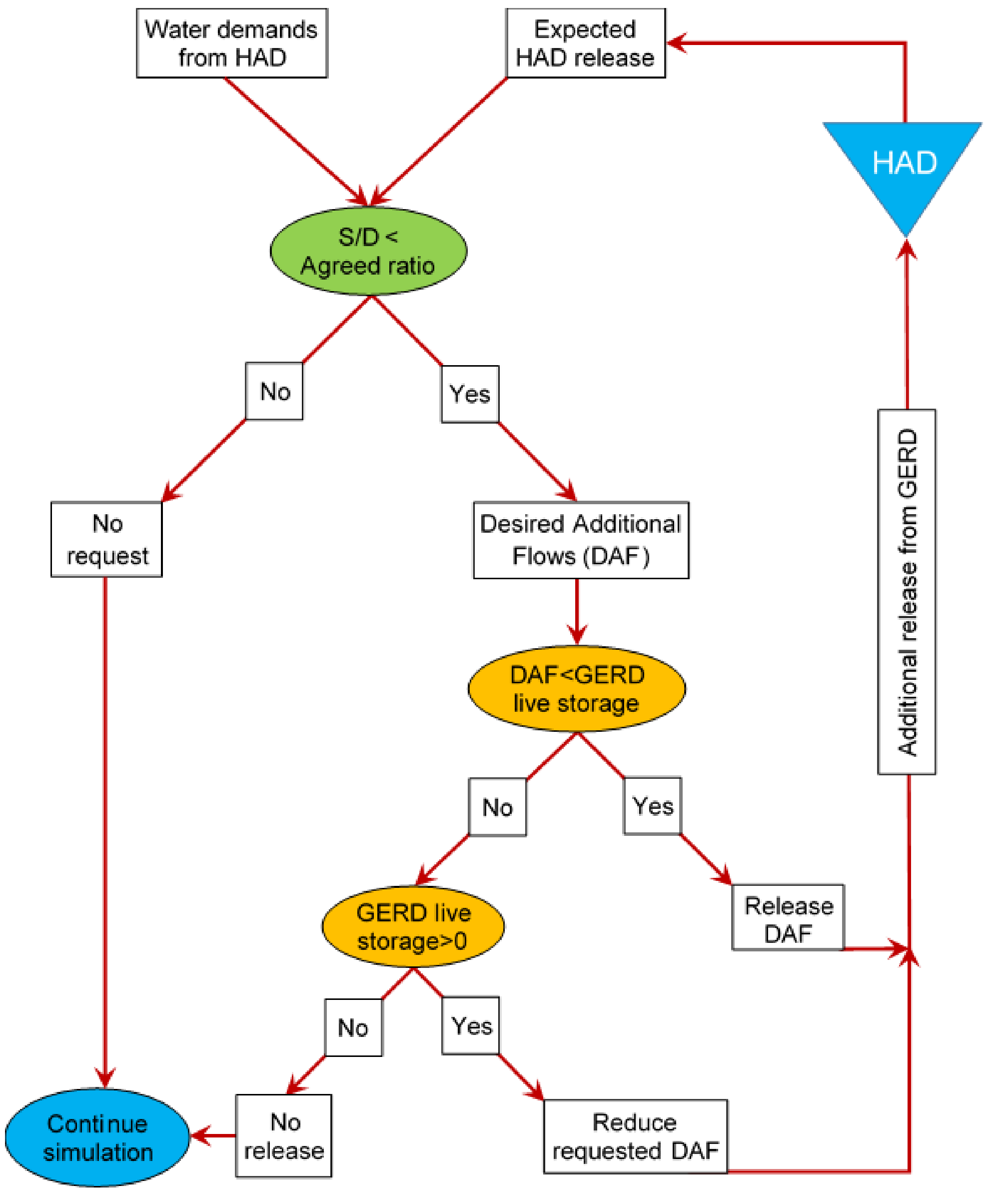


Figure 6.3 Allocation procedure of additional flows from GERD to HAD

* Note additional GERD releases will be passed through Sudanese

In Ethiopia, the GERD will be operated for hydropower generation only in both states. In the unilateral state, GERD will be operated to maximise hydropower generation with a target of 1,730 MW. The cooperation state assumes that GERD will be operated for hydropower generation at a target of 1,730 MW (first priority), in addition to releasing supplementary flows to HAD when requested, as explained above, Figure 6.3. In the event of GERD receiving a request from HAD, the model first checks the GERD storage level. The model determines by trial-and-error the additional releases to HAD without violating the MOL of GERD, Figure 6.3.

All simulations start in the year 2030, assuming that the first impoundment of GERD reservoir is complete and GERD is in the operation phase. At the beginning of the simulation, all reservoirs are considered full and HAD is at the elevation of 170 m (a.m.s.l). All simulations use the aforementioned one-hundred synthetic streamflow series with 65 years length. The current status of the system in terms of water management, water demands and withdrawals across the basin are assumed to stay unchanged. Varying demand conditions are considered for Egypt as explained above.

6.2.1 Simulation Results

Regional impacts for both unilateral and cooperation conditions are analysed considering the above-described demand conditions in Egypt. For each demand condition, the case of no GERD is also presented. Although the cooperation position is not limited to dry years, the focus here will be on the lower quartile of the water, food, and energy-related variables including minimum value, and x_{95} (value of the variable x that equalled or exceeded for 95% of the time) or the 5th percentile in the box and plot graphs. The median and average values will be also reported for significant changes in the outcomes. The two cooperation modes will be reported as $Coop_{85}$ and $Coop_{100}$ with agreed ratios of 85 and 100, respectively.

6.2.1.1 Food Production in Egypt

The impact of the different system configurations on food production (FP) in Egypt is shown as box plot graphs, Figure 6.4. The positive impact of GERD with and without cooperation is shown during the dry periods (i.e., 1st quartile of food production) as a result of improved low flows supplies from the GERD. For the case of constant demand patterns in Egypt, the minimum food production will be increased in both the unilateral and cooperation modes compared to the case of no GERD, Figure 6.4. The average increase in minimum food production over the simulation will increase by 2% for the unilateral state, 3% for $Coop_{85}$ and 5% for $Coop_{100}$ compared to the case of no GERD. By focusing on the $FP_{95\%}$ values, FP_{95} will reduce by 4% in unilateral state and by 5% in $Coop_{85}$ compared to the case of no GERD. In contrast, the case of $Coop_{100}$ showed no changes to the FP_{95}. While the impacts of cooperation might seem small but they have considerable implications. For instance, small improvements in food production will reduce food imports that could cost millions of dollars. Egypt's imports of crops and livestock products cost 12.91 billion US$ in 2017, according to the latest FAO statistics, FAO (2020). Interestingly, GERD operation modes did not have a significant effect (less than 1%) on the average food production in Egypt.

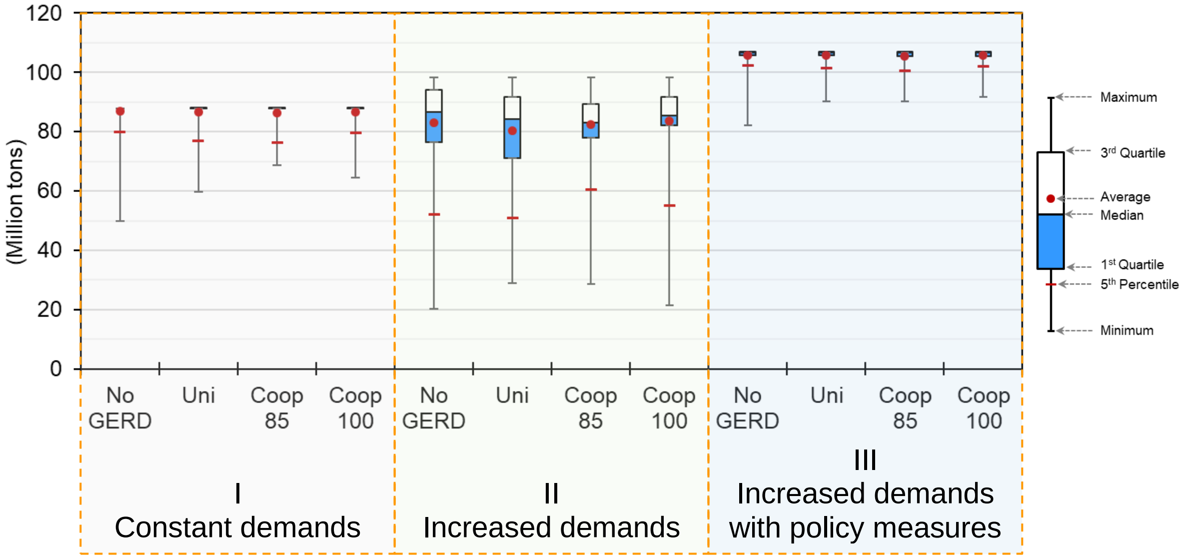


Figure 6.4 Food production in Egypt under the three demand conditions with and without cooperation and the case of no GERD

The second demand condition, i.e., increased demands with current water resources, demonstrates the impact of GERD operation modes on food production. The possible minimum values of food production are higher than in the case of no GERD. The minimum food production is increased throughout the simulation by 11% (the unilateral state), 19% ($Coop_{85}$), and 14% ($Coop_{100}$). However, FP_{95} in the unilateral state is decreased by 3%, while increased by 16% in the cooperation case $Coop_{85}$, and 5% in the cooperation case $Coop_{100}$.

Average food production will be reduced by approximately 3% in the unilateral case and by 1% in the cooperation case $Coop_{85}$. In the cooperation case $Coop_{100}$ the average food production is increased by 1%. The variability of food production around the average/median is reduced in the cooperation scenario as opposed to the unilateral state, Figure 6.4.

Food production under the cooperation condition is improved compared to the unilateral state. The latter indicates the role of cooperation in improving the downstream situation, while the associated upstream impacts will be discussed in detail below. The cooperation case $Coop_{100}$ illustrates the extended impacts of additional releases from GERD on the system. For example, the case of $Coop_{100}$ resulted unexpectedly in minimum values lower than the unilateral case, Figure 6.4. Regular high releases from GERD to HAD especially during dry years are likely to deplete the GERD reservoir, and in turn prolong the drought period compared to the unilateral state and even the case of no GERD.

The third scenario is similar to the previous one but Egypt is expected to successfully implement policy measures to meet the growing demands. The impact of GERD operation modes and water policy measures on food production is shown in Figure 6.4. The minimum food production averaged throughout the simulation, is increased by 1% in the unilateral case and the cooperation case $Coop_{100}$ compared to the case of no GERD. The cooperation case $Coop_{85}$ showed no changes to the minimum food production. Also, the FP_{95} is reduced by less than 1% in the unilateral state, and 2% in the cooperation case $Coop_{85}$ when compared to the case of no GERD, unlike in the cooperation case $Coop_{100}$ that showed no changes.

The operation modes of GERD have negligible effects on average food production in comparison with the case of no GERD. This is in agreement with previous work on the GERD impacts during operation phase (see Kahsay et al. 2015, Arjoon et al. 2014). The comparison between food production under the second scenario (extreme scenario) and third scenario (preferred scenario) shows the water-food nexus interdependency. Increasing the pressure on the water resources could significantly impact food production (the second scenario), while sucessfull implementation of water policy measures could greatly improve food production (the third scenario). For instance, average food production in the third scenario is higher than average food production in the second scenario by 20%, Figure 6.4. Although the second demand scenario might not seem the preferred scenario, it emphasises the significance of improving water use efficiency in the basin and the cooperation among the riparian countries. Furthermore, the difference between the second and the third scenario results show the range of potential benefits that can be achieved through cooperation and improved water management policies. It is also noteworthy that average food production under the first and third demand conditions did not significantly change under different GERD operation modes as compared to the case of no GERD. This means that for an average year, there is no conflict between GERD operation mode and food production in Egypt (i.e., assuming that the current Egypt demand pattern from HAD stays unchanged). This is in agreement with previous work on the GERD impacts during operation phase (see Kahsay et al. 2015, Arjoon et al. 2014).

6.2.1.2 Hydropower Generation

The impact of hypothetical cooperation and unilateral scenarios on hydropower generation (HP) in Egypt, Ethiopia and Sudan under different demand patterns in Egypt are shown in Figure 6.5. The hydropower generation in Egypt and Sudan will be reported with reference to the case of no GERD, while in Ethiopia it will be reported for the operation modes of GERD as compared to the unilateral state (i.e., preferred scenario).

For the constant demand pattern, the minimum hydropower generation in Egypt would increase under both the unilateral and cooperation conditions by more than 15%, Figure 6.5.a. However, HP_{95} is reduced by 5% in the unilateral state and 6% in the cooperation case $Coop_{85}$, while it did not change in the cooperation case for $Coop_{100}$ when compared to the case of no GERD. Also, the average HAD hydropower generation in the unilateral and the two cooperation states is reduced by about 2%. The hydropower generation in Ethiopia is found to be only affected in the cooperation state $Coop_{100}$, while the cooperation state $Coop_{85}$ showed no changes compared to the unilateral action, Figure 6.5.b. The minimum hydropower generation, in $Coop_{100}$, is reduced by 19%, but the hydropower generation below 14,500 GWh/year has less than 2% of a chance of falling below the level of the unilateral state. Alternatively, HP_{95} increases by 2%, as a result of releasing additional flows from the GERD turbines. Also, the average hydropower generation could be slightly reduced, i.e., by less than 1%.

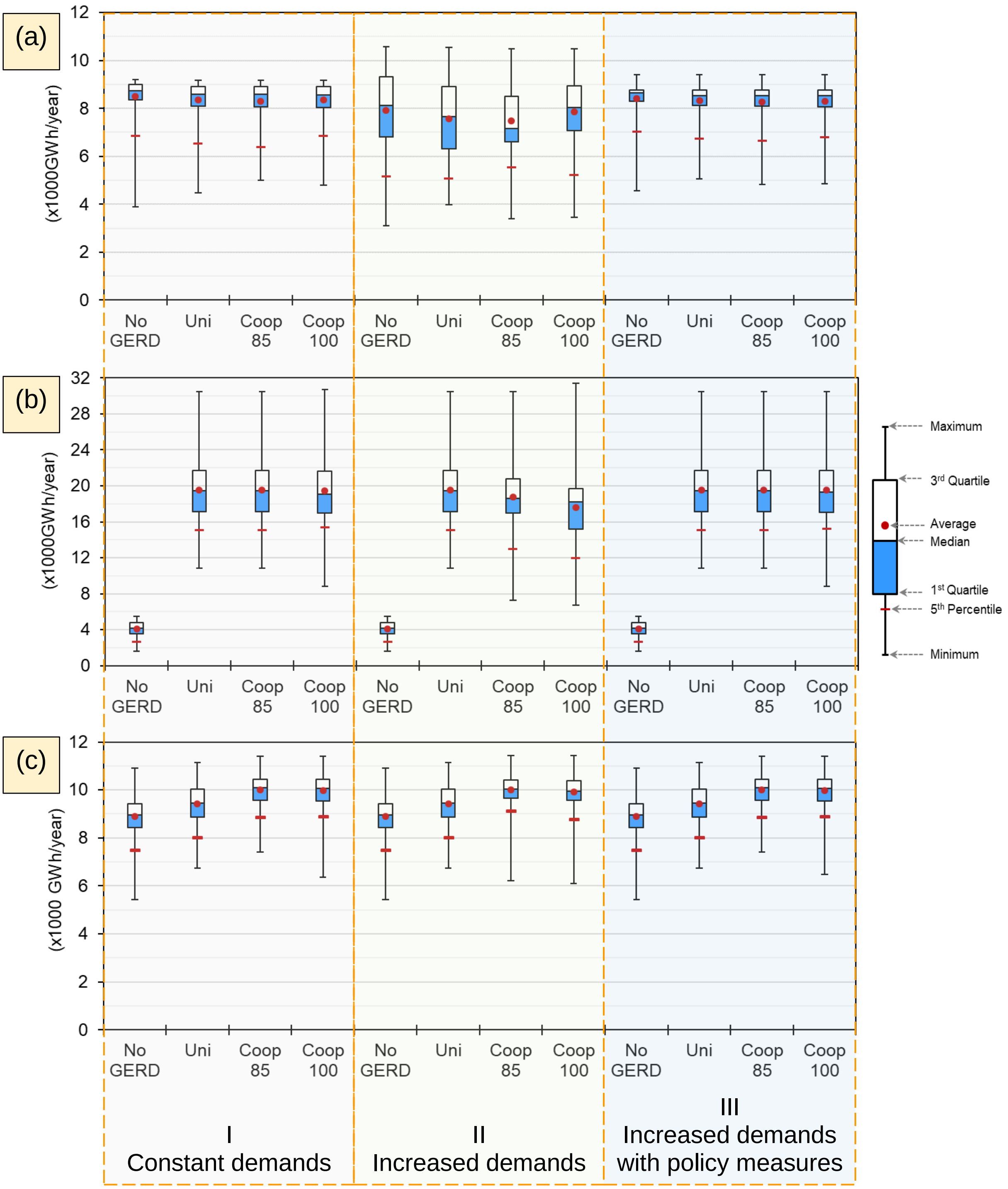


Figure 6.5 Hydropower generation in (a) Egypt, (b) Ethiopia and (c) Sudan for with and without cooperation under the three demand patterns in Egypt

In Sudan, the hydropower generation will improve in both cooperation and unilateral states when compared to the case of no GERD, Figure 6.5.c. That happens as a result of the river flow regulation caused by GERD operation. For instance, the minimum hydropower generation is increased by 24% in the unilateral state, 36% in $Coop_{85}$ case and 17% in $Coop_{100}$ case compared to the case of no GERD. Furthermore, HP_{95} is increased by 7% in the unilateral state and by more than 18% in the two cooperation states, Figure 6.5.c. Average hydropower generation is increased by 6% in the unilateral state and 12% in the cooperation state. Interestingly, GERD regulation and operating the Blue Nile dams at their full supply level could solely increase the average hydropower generation in Sudan by about 6%. The minimum hydropower generation in Ethiopia and Sudan for $Coop_{100}$ case is lower than $Coop_{85}$ case, due to operating the reservoirs, particularly GERD and Sudanese dams, at lower levels in the $Coop_{100}$ during droughts. However, the latter case has only a minimal chance to occur as shown above.

The second demand pattern in Egypt shows the basin-wide impacts on hydropower generation under GERD operation modes. In Egypt, the minimum hydropower generation is increased by approximately 28% in the unilateral state, 9% in $Coop_{85}$ and 11% in $Coop_{100}$. Unlike expected, the unilateral state gives higher values compared to the cooperation states, due to increased probability of reaching the MOL of HAD under the cooperation state with increased downstream demands. Increased regular releases from GERD particularly during droughts could prolong the drought period. In contrast, HP_{95} is reduced by 2% in the unilateral case, while increased by 7% in $Coop_{85}$ and 1% in $Coop_{100}$. Average hydropower generation in $Coop_{100}$ case is higher than the unilateral and $Coop_{85}$ case.

Regular releases from GERD to HAD are likely to have significant effects on hydropower generation in Ethiopia and GERD hydropower in particular, as shown in Figure 6.5.b. For instance, the minimum hydropower generation in Ethiopia in $Coop_{85}$ and $Coop_{100}$ is substantially reduced by more than 33%. Moreover, HP_{95} could be reduced by more than 14% for the two cooperation conditions, due to the increase in the frequency of operating GERD at low levels. Average hydropower generation is reduced by 10% in the $Coop_{100}$ case and 4% in the

$Coop_{85}$ case. Also, the probability of non-exceedance of attaining average hydropower generation, in the unilateral state, increases by 24% in $Coop_{85}$ and 43% in $Coop_{100}$.

In Sudan, the hydropower generation is less impacted by this scenario. For instance, average hydropower generation will be increased by 13% in $Coop_{85}$ and 11% in $Coop_{100}$. HP_{95} is increased by 22% in $Coop_{85}$ and 17% in $Coop_{100}$. The minimum hydropower generation in the two cooperation conditions is increased by 12% that is less than those of the first demand scenario. This scenario shows the limitation to cooperation among the riparian countries as increased demands from downstream users could not lead to desirable results in the basin.

The third scenario is similar to the previous but assumes that Egypt develops water policy measures either in cooperation or unilateral state. The average HAD hydropower generation is slightly decreased by 1% in the unilateral state and about 2% in the cooperation state compared to the case of no GERD. Also, HP_{95} is reduced by 4% in the unilateral state, by 6% in $Coop_{85}$, and 3% in $Coop_{100}$. However, the minimum hydropower generation is increased by 11% in the unilateral action and 6% in both cooperation conditions. In Ethiopia, the average hydropower generation is not affected by cooperation conditions. However, the minimum hydropower generation could be reduced by 19%, but with a 1% chance to fall below the hydropower generation in the unilateral state. The impacts of GERD operation modes on the hydropower generation in Sudan are found to be similar to those of the first scenario.

The comparison between the second and third scenarios demonstrates interesting results. The second scenario (extreme) indicates the willingness of the upstream countries to cooperate solely, while the third scenario (preferred) shows a high level of cooperation between both upstream and downstream countries. In the third scenario, Egypt (a downstream country) is expected to successfully implement policy measures, while Ethiopia (an upstream country) release additional flows to Egypt when required. In contrast, Ethiopia in the second scenario releases additional flows to Egypt, while no policy measures are implemented in Egypt.

The hydropower generation in the riparian countries is less likely to be significantly impacted by the cooperation conditions in the first and third scenarios, contrary to the second scenario. Proper water management policies in the downstream and high coordination among the riparian countries could substantially alleviate the risks associated with droughts. However, increased claims from downstream users are likely to considerably impact the overall hydropower generation in the basin in case the countries agreed to cooperate. Interestingly, the first and third scenarios have similar results, especially in cooperation states. This indicates that coordination between the riparian countries could reduce the risks associated with dry years with little changes to the hydropower generation in the basin, in case of demand pattern from HAD stays unchanged. However, substantial efforts from the riparian countries and a high level of coordination are required.

6.2.1.3 Water Shortage

The water shortage in Egypt is only discussed here, as Sudan is found not to be impacted by any operation mode of GERD and the demand considered conditions in Egypt. Also, water shortages have occurred in the Atbara basin due to inadequate water supplies and siltation problems (Awulachew 2012). The impact of GERD operation modes on water shortage (W) in Egypt for the three demand conditions is shown in Figure 6.6. The maximum water shortage will be reduced with the GERD either in unilateral or cooperation conditions, due to improved low flow supplies caused by GERD regulation.

The case of current demand patterns in Egypt indicates that the average water shortage is increased by 16% in the unilateral case, 23% in the $Coop_{85}$, and 8% in the $Coop_{100}$ compared to the case of no GERD. Moreover, the W_{95} increased by 25% in the unilateral state, and 35% in the $Coop_{85}$ case, but the case $Coop_{100}$ showed no changes compared to the case of no GERD. The case of $Coop_{85}$ significantly reduces the maximum water shortage however, the duration of high water shortage increased compared to the other cases, Figure 6.7.a. The increase in average water shortage and W_{95} for the case of $Coop_{85}$ can be explained as HAD requests from GERD are limited to dry periods (i.e., S/D<85%). Additional releases from GERD during droughts are likely to deplete

GERD reservoir (i.e., reaching the MOL), and consequently, prolong the drought period. Unlike the $Coop_{100}$ case, in which additional flows are released from GERD once there is a water shortage in Egypt. Such releases from GERD during below-average flow years (i.e., before droughts) are likely to greatly alleviate the impact of significant droughts compared to the other cases, Figure 6.7.a. In some cases, additional releases from GERD are not enough to raise the HAD storage stage to reduce the demand reduction factor, Table 6.2 however the additional releases are stored instead and can be used later especially in severe drought periods. The latter case indicates the HAD capability of storing additional releases from GERD and in turn reducing the overall water shortage in Egypt. Moreover, the risks of such a water shortage particularly during drought periods can be substantially reduced with proper coordination among the riparian countries.

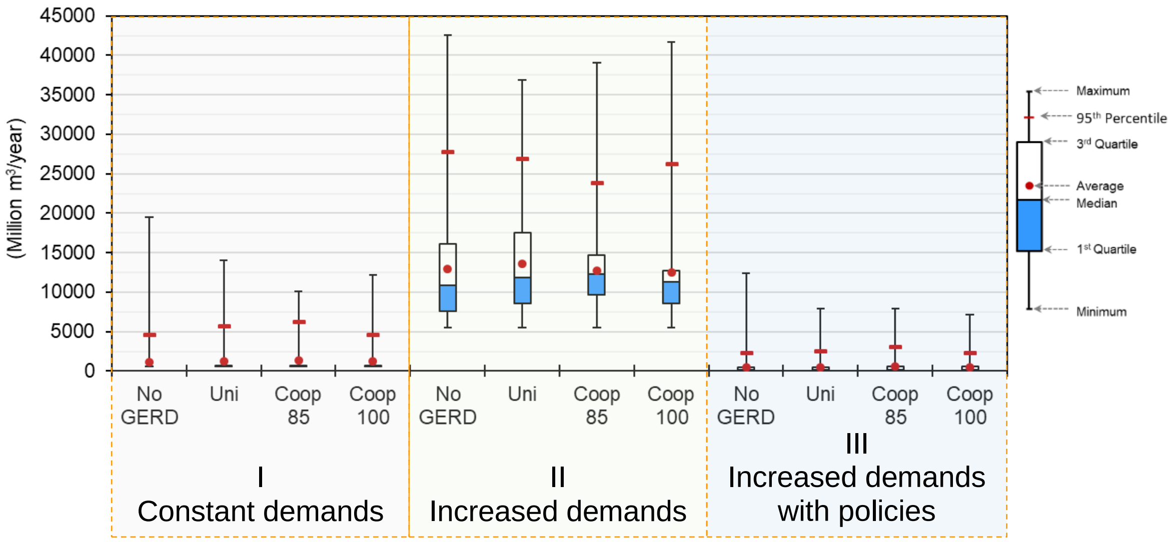


Figure 6.6 Water shortage in Egypt under the three demand conditions with and without cooperation and the case of no GERD for each demand condition

The second case demonstrates the impact of increased demands and cooperation levels on water shortage in Egypt. The average water shortage increased by 5% in the unilateral state, while decreased by 1% in the $Coop_{85}$ case, and 3% in the $Coop_{100}$ case compared to the case of no GERD. Also, the W_{95} and the maximum water shortage are decreased either in unilateral, or cooperation conditions. The maximum water shortage in the cooperation states are higher than the unilateral state, but with a probability of less than 1%, Figure 6.7.b. Despite the significant impacts of this scenario on the overall system in the cooperation state, the average water shortage is reduced and the non-exceedance probability of the above-average water shortage is increased, in the cooperation state, compared to the unilateral and the case of no GERD, Figure 6.7.b.

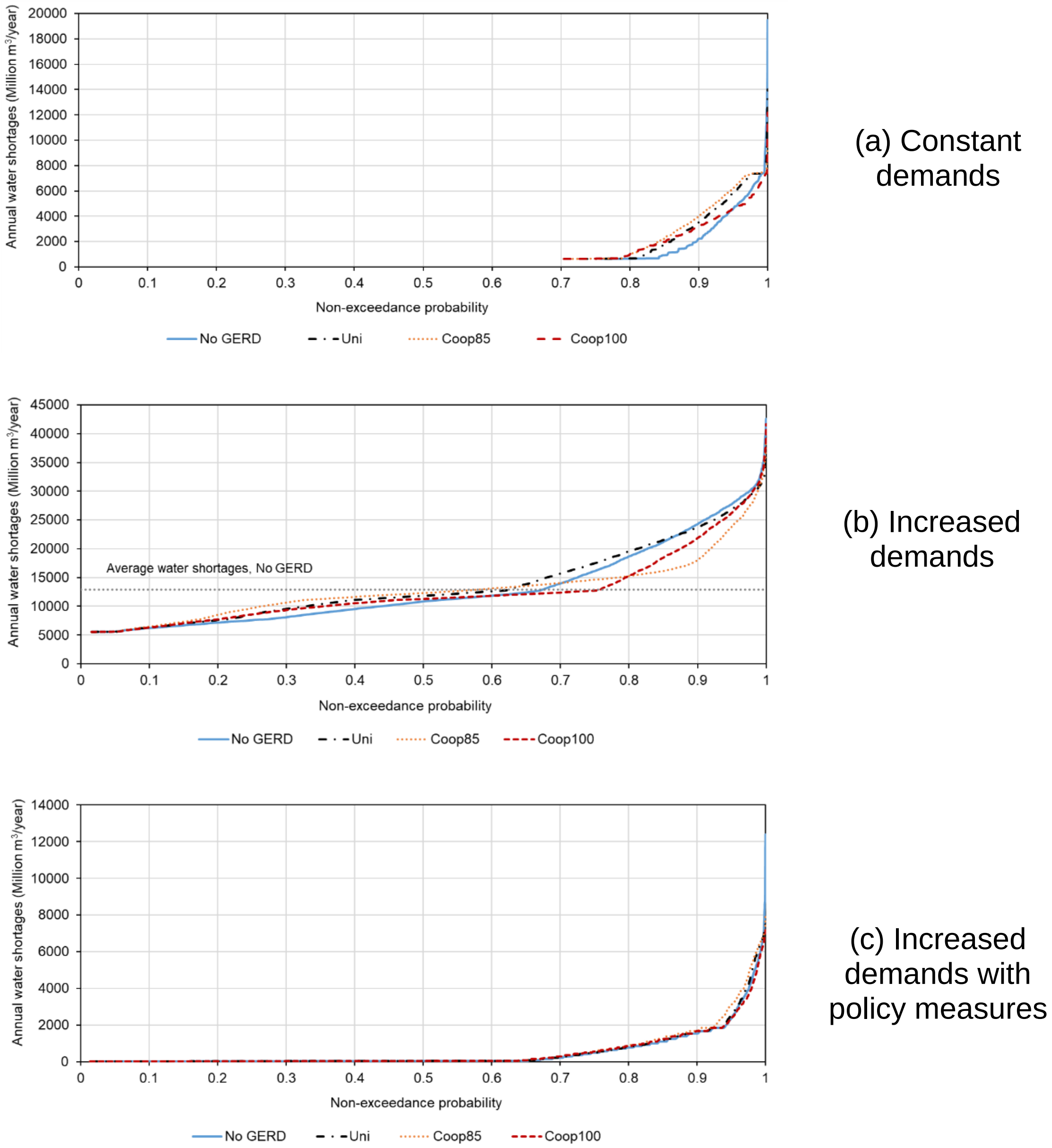


Figure 6.7 Non-exceedance probability of annual water shortage under three demand conditions in Egypt with and without GERD

The third scenario reveals the significance of implementing water policy measures and cooperation over GERD in reducing the water shortage in the face of increased demands, Figure 6.6. Average water shortage increased by 4% in the unilateral state, 13% in the $Coop_{85}$ case and 1% in the $Coop_{100}$ case compared to the case of no GERD. The W_{95} increased by 7% in the unilateral sate and 30% in the $Coop_{85}$ case, while the $Coop_{100}$ case showed no changes compared to the case of no GERD. Maximum water shortages reduced by over 36% with and without cooperation in comparison with the case of no GERD. The non-exceedance probability of the above-average water shortage in the $Coop_{100}$ case is found to be similar or higher than the other cases, Figure 6.7.c. Unlike the $Coop_{85}$ case, the frequency of annual water shortages (>2000 MCM/year) increased compared to other cases, Figure 6.7.c.

The implementation of water policy measures including demand and supply sides in the cooperation state $Coop_{100}$ showed that the water shortage could be substantially reduced, as shown in Figure 6.6 and Figure 6.7.c. This suggests that the willingness of riparian countries to cooperate – Ethiopia to provide additional releases and Egypt to implement policy measures for better water management – have the potential to considerably reduce the drought risks. Also, the comparison between the second and the third scenarios indicates the substantial effort in facing the growing demands in Egypt and the role of cooperation and coordination among the riparian countries to mitigate the risks associated with droughts.

6.2.1.4 Net Evaporation from Reservoirs

The net evaporation from reservoirs in the basin is shown in Figure 6.8, for the three demand conditions in Egypt with and without GERD. The average net evaporation increases when the GERD comes online. The average net evaporation with GERD increased by 8% in the first demand scenario, 8-11% in the second demand scenario and 9% in the third demand scenario compared to the case of no GERD. The increase in the net evaporation is mainly from the GERD reservoir, while operating the Sudanese reservoirs at their full supply level has a negligible effect as shown in Figure 6.8.I, III. Also, the GERD operation mode did not significantly affect the net evaporation from the reservoirs.

Meanwhile, the evaporation from HAD is the largest in the basin when compared to the evaporation from other reservoirs as it is clearly shown by the difference between the second demand scenario and the two other demand scenarios. In the second demand scenario, the evaporation from HAD is substantially reduced as a result of operating HAD at low levels, unlike the first and the third scenarios, where HAD is operated at high levels.

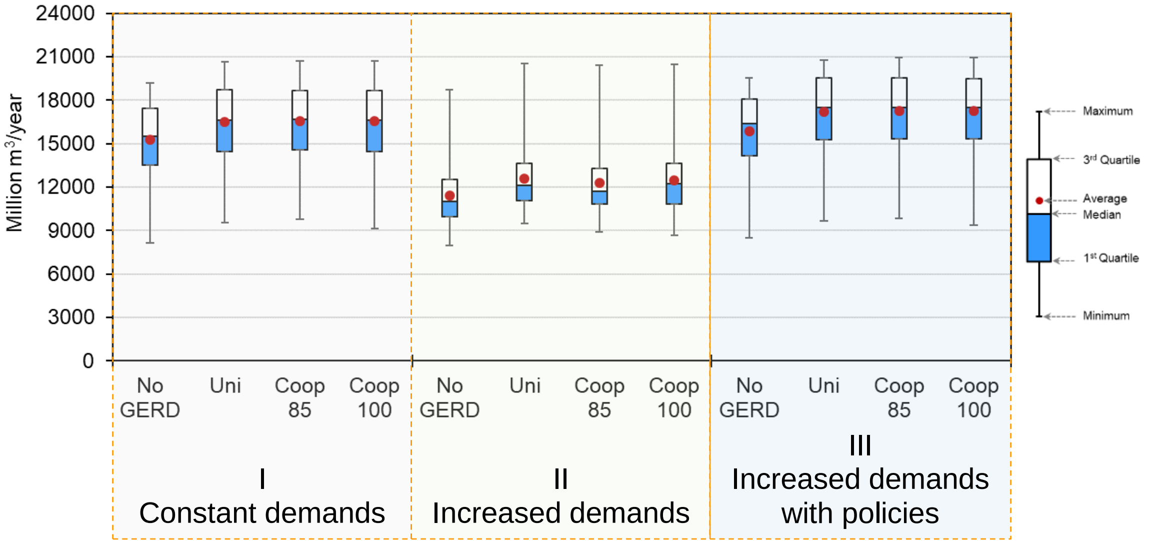


Figure 6.8 Net evaporation from the reservoirs across the basin under the three demand conditions in Egypt

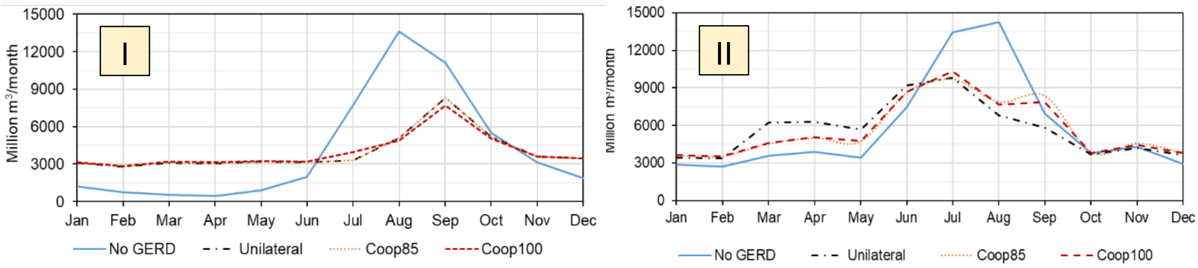
6.2.1.5 River Flow Regime

A Monthly Flows

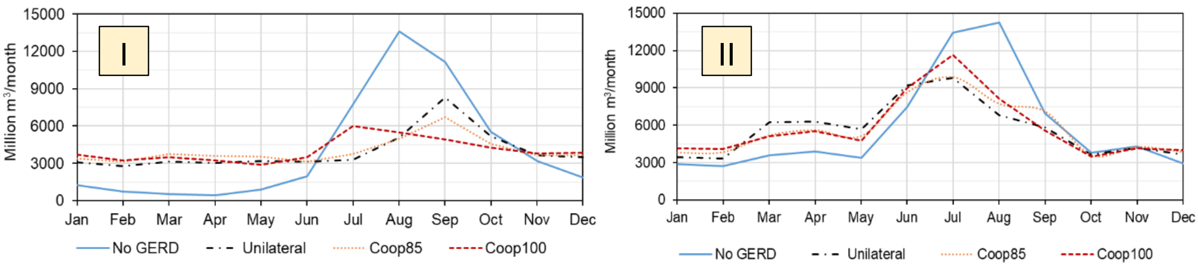
The changes to the average monthly river flow with and without cooperation over GERD under different demand conditions in Egypt are shown in Figure 6.9. It shows the changes to: (I) the Blue Nile flow at Diem gauge (on the left), and (II) the Main Nile flow at Dongola gauge (on the right). The case of no GERD is also added for comparison purposes.

In the current demand pattern scenario, the average monthly Blue Nile flows in the Coop$_{85}$ case are found to be similar to the unilateral case. In the Coop$_{100}$ case, the Blue Nile flows are slightly changed during the high demand season in Egypt (i.e., July-October) when compared to the unilateral state, Figure 6.9.a.I. The latter shift in the Blue Nile flows reflects the impact of the high demand season in Egypt on GERD releases in the cooperation condition. Conversely, the Main Nile flows in the cooperation state are altered from the unilateral state. The monthly flows are reduced before the flood season, but they are increased during the flood season, Figure 6.9.a.II. This shift resulted from the combined effect of operating the Blue Nile reservoirs in Sudan at their full supply level and releasing additional flows from GERD to HAD. The river flows during the cooperation state illustrates the significance of coordination among riparian countries and timely releases from GERD to downstream users, particularly during low flow and drought periods. A coordinated operation policy for the system reservoirs can be further investigated in more detail in future research.

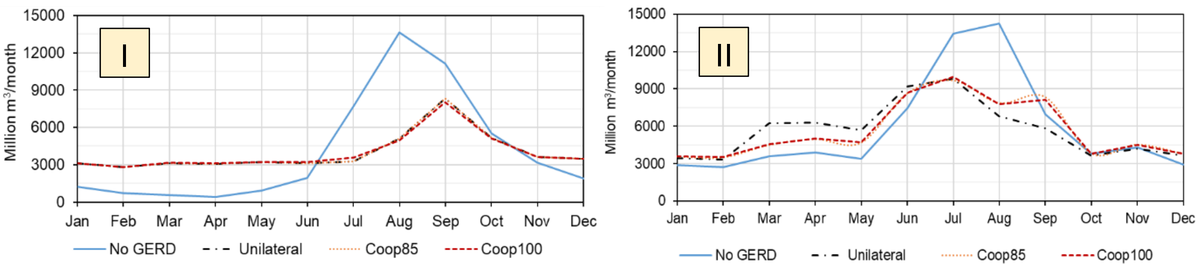
The second case of increased demands in Egypt shows the significant impact of additional releases from GERD on the Blue Nile flows especially in the $Coop_{100}$ case, Figure 6.9.b.I. The Blue Nile flows in the case of $Coop_{85}$ have a similar pattern to the flows in the unilateral state with considerable alternations during the high demand season in Egypt. Unlike the $Coop_{100}$ case, the Blue Nile flows become more regulated around the year and peaks in July, as a result of



(a) Constant demands



(b) Increased demands



(c) Increased demands with policy measures

Figure 6.9 Average monthly flows of: (I) Blue Nile at Diem gauge and (II) Main Nile at Dongola gauge under demand conditions in Egypt with and without GERD continuous GERD releases to HAD. Also, the river flows are substantially reduced during the flood season, as the GERD reservoir fills up. This indicates the impact of increased additional releases from GERD on the Blue Nile flows and the flood season in particular.

The alternation in the Blue Nile flows is also reflected in the Main Nile flows. The Main Nile flows in the two cooperation states showed a similar pattern to the unilateral state. However, the river flows in the $Coop_{100}$ case is higher than the two cases during the high demand season; but becomes close to the unilateral state by the end of high demand season, unlike the $Coop_{85}$ case. The third scenario shows that the monthly Blue Nile flows in the cooperation state have a similar pattern to the river flows in the unilateral state, unlike the previous scenario. The monthly flows of the Main Nile in the two cooperation states are found to be similar. The comparison between the second and third scenarios for the changes in the Blue Nile and the Main Nile flows, in the cooperation and unilateral states, illustrates the impact of collective cooperation among the riparian countries on the river flow regime.

B Annual River Flow

The average annual river runoff (R) in the unilateral state is reduced by 2% due to additional evaporation caused by the GERD reservoir, Figure 6.10. However, the minimum river flow is increased by 29% and the R_{95} increased by 1% due to improved low flow supplies resulting from GERD regulation. The cooperation states did not significantly affect the average annual river flows in the first and third demand scenarios as shown in Figure 6.10. The average annual river flows in the second demand scenario are reduced by 1% in the $Coop_{85}$ case, while the $Coop_{100}$ case showed no changes compared to the case of no GERD. On the other hand, the minimum river flows increased by 24% in the $Coop_{85}$ case and 7% in the $Coop_{100}$ case in the first and third demand scenarios.

The second demand scenario shows the impact of increased HAD requests from GERD on the annual river runoff. The minimum river flows in the cooperation states increased by 11% however, the minimum flows are less than those in the unilateral state. Also, the R_{95} in the $Coop_{85}$ case increased by 1% in the first and third demand scenarios and 6% in the second demand scenario. The R_{95} in the $coop_{100}$ case increased by approximately 4% in the three demand conditions.

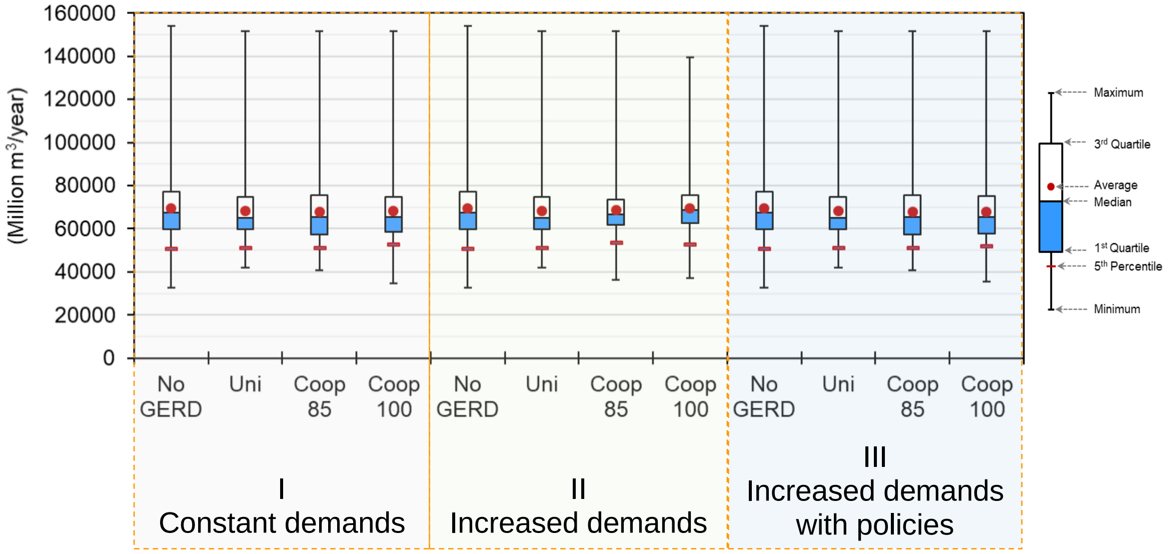


Figure 6.10 Annual River flows at HAD with and without GERD under three demand conditions in Egypt

6.3 Discussion

The above-investigated scenarios demonstrate the potential of achieving mutual benefits from such new developments in a transboundary river as well as reducing the risks that might face downstream countries from a new upstream development. Also, the idea of using an agreed supply to demand ratio illustrates the range of risks and benefits associated with the cooperation among the co-riparian countries and the impact of downstream claims from an upstream reservoir on the entire basin. Furthermore, it can be used as a proxy to the cooperation level among the riparian countries. These were examined in the Nile basin considering the GERD development in Ethiopia as a case study. Varying demand levels in Egypt were considered: (a) current water demand levels, (b) increased water but without developing additional water resources and (c) similar to (b) but water policy measures are in force.

The results suggest that the cooperation among the riparian countries over GERD has the potential to reduce risks to downstream countries, especially during dry and drought periods. The first and third demand scenarios outcomes suggest that for an average year, GERD has a little to negligible impacts on the WFE nexus in Egypt either in the cooperation or unilateral states. Sudan will have more benefits in the cooperation scenario than in the unilateral state (increased in hydropower generation and improved water supplies). The average hydropower generation in Ethiopia – in particular GERD hydropower – will not be largely affected by the cooperation conditions (less than 1%). Furthermore, the two scenarios suggesting that cooperation and coordination among riparian states are likely to reduce risks to downstream users without significantly affecting upstream users especially in drought periods.

On the other hand, risks to Egypt in dry years (e.g., water shortages and food production loss) can be substantially reduced if the riparian countries agree to cooperate and sacrifice for some loss, e.g., loss in hydropower generation, especially during severe droughts. For instance, results showed that cooperation states are likely to increase the possible minimum food production by 3-5% in the first demand condition and by 1% in the third demand condition when compared to the case of no GERD, Figure 6.4. Also, FP_{95} values under the first and third demand condition are found to be similar to the case of no GERD. Possible minimum hydropower generation will increase by 23-28% in the first demand condition and by 6-7% in the third demand condition, Figure 6.5. Furthermore, the possible maximum water shortage, Figure 6.6 in Egypt compared to the unilateral position. Furthermore, the GERD can release additional water to Egypt in dry years without significantly impacting its hydropower generation either on average or below average years (i.e., dry years), see Figure 6.5. However, hydropower generation in Ethiopia may experience a further drop during severe droughts in $Coop_{100}$, but with a 1% chance. The Sudanese water supplies will not be impacted by the different operation modes of GERD. However, hydropower generation during severe dry periods may endure further drop, in cooperation conditions, but with less than a 1% chance.

The second demand scenario shows the limitation of cooperation among the riparian countries. Regular releases from GERD to balance the increased demand could substantially impact the WFE nexus in the basin and prolong the drought period. However, the comparison between the second and the third scenarios indicates that the cooperation among riparian countries depends on the commitment and the success of implementing policies in Egypt to balance the growing demands and the willingness of Ethiopia to cooperate and release additional flows to Egypt when needed. On the other hand, the difference between the second and third scenario results show the range of benefits that can be gained from coordination and collaboration among riparian states. A high level of coordination, commitment and trust among the riparian countries are urgently required to achieve the cooperation benefits. Last but not least, the results call for further investigation of coordinated operation policy for the system reservoirs.

CHAPTER SEVEN: FUTURE OF THE WFE NEXUS IN THE NILE BASIN UNDER CLIMATE CHANGE

7.1 Introduction

In the previous chapters, the impact of the GERD project during the filling and subsequent operation phases is explored. In this chapter, different development scenarios including hydropower and irrigation expansion projects in the riparian countries are considered. Furthermore, the impacts of climate change on the planned developments are investigated.

The Nile basin countries have devised ambitious master plans to utilise the potential resources in the basin (e.g., irrigation expansion and hydropower projects) to meet the growing water, food and energy demands of their populations and sustain their economies. Recent developments in the basin include the Upper Atbara and Setit Dam Complex (UASDC) in Sudan, commissioned in 2016, and the Isimba hydropower plant in Uganda, commissioned in 2019. The largest development project in the basin is the GERD in Ethiopia, Figure 7.1, with initial operation expected to commence by the end of 2020 (Maasho 2019). Karuma hydropower plant has been under construction since 2013 (UEGCL 2020) on Victoria Nile in Uganda, Figure 7.1 and once finished will be the largest in Uganda.

A number of planned hydropower projects included in the master plans of the riparian countries have been nominated for feasibility studies. Accordingly, only hydropower projects with completed feasibility studies are considered in this work; however other long-term planned projects can be incorporated in a similar way. According to the national water master plan 2030 in Kenya (MEWNR 2013) two multipurpose dams are planned in Lake Victoria basin: Nandi Forest Dam and Magwagwa Dam, Figure 7.1. In South Sudan, four main hydropower dams are planned on Bahr Eljebel: Fula Dam, Shukoli Dam, Lakki Dam, and Bedden Dam, Figure 7.1 (MEDIWR 2020). In Ethiopia, a number of hydropower projects are planned in Sobat River basin including Geba hydropower plant, Baro hydropower plant and Genji hydropower plant, Figure 7.1 (Derbew 2013). Recent and planned hydropower projects with completed feasibility studies in the Nile basin are shown in Table 7.1.

Figure 7.1 Existing, ongoing and planned hydropower developments with completed feasibility studies in the Nile basin adapted from NBI (2012)

Table 7.1 Ongoing and planned hydropower projects in the basin with completed feasibility studies

Country	Dam	Status	Installed capacity (MW)
Kenya	Nandi Forest Dam	Planned	50
	Magwagwa Dam	Planned	115
Uganda	Ismba hydropower plant	Commissioned 2019	188
	Karuma hydropower plant	Under construction	600
South Sudan	Fula Dam	Planned	890
	Shukoli Dam	Planned	235
	Lakki Dam	Planned	410
	Bedden Dam	Planned	570
Ethiopia	Grand Ethiopian Renaissance Dam	Under construction	6000
	Geba hydropower plant	Planned	481
	Baro I & II hydropower plant	Planned	680
	Genji hydropower plant	Planned	214
Sudan	Upper Atbara and Setit Dam Complex	Commissioned 2016	320

Irrigated agriculture across the basin is currently predominant in Egypt and Sudan, while other Nile countries have small irrigation areas in the basin as shown in Table 7.2. All the Nile countries have proposals for irrigation expansion projects in the basin to meet the growing food demands of their populations and strengthen their expanding economies. Increased rainfall variability, droughts and crop failures in upstream countries together with population growth have forced riparian countries to invest in irrigated agriculture even at a high cost (Awulachew 2012).

In this study, planned irrigated agriculture projects in the riparian countries with completed feasibility studies are considered following national targets of the Nile countries and NBI reports, Figure 7.2. As with the hydropower projects, other long-term irrigation projects can be incorporated in the model in a similar way but this is beyond the scope of the current study. Riparian countries of the Equatorial

Lakes Region (ELR) have plans to develop their potential irrigated areas in the ELR (WWAP 2006; MEWNR 2013; MWI 2018). Therefore, the potential irrigation expansion schemes in the ELR are considered in this work. Potential irrigation expansion schemes in South Sudan are also considered, according to the national water master plan (MEDIWR 2015).

Table 7.2 Current Irrigated areas in the Nile basin countries

Country/region	Existing irrigation area (1000 ha)
Equatorial Lakes Region[1]	101.57[2]
Egypt	3823.53[3]
Ethiopia	91.00[2]
South Sudan	0.50[2]
Sudan	1764.63[2]

Note:

[1] Includes Burundi, Kenya, Rwanda, Tanzania, and Uganda

[2]NBI (2016b)

[3]CAPMAS (Various years-c)

Irrigation expansion schemes in Sudan with completed feasibility studies include Great Kenana irrigation scheme, El Rahad phase II irrigation scheme, and the Upper Atbara irrigation scheme (ENTRO 2009). The irrigation development programme in Ethiopia included several irrigation expansion projects in the Nile basin (Awulachew et al. 2007). Irrigation projects with completed feasibility studies in Ethiopia include irrigation expansion schemes in Lake Tana basin, Upper Beles irrigation scheme, Neshe irrigation expansion project, Anger and Didessa irrigation expansion projects in the Blue Nile Basin, Humera and Angreeb irrigation projects in the Atbara River basin (Cherre 2006; Awulachew et al. 2007; ENTRO 2009). Planned irrigation projects in the basin that are included in this work are presented in Figure 7.2 and Table 7.3.

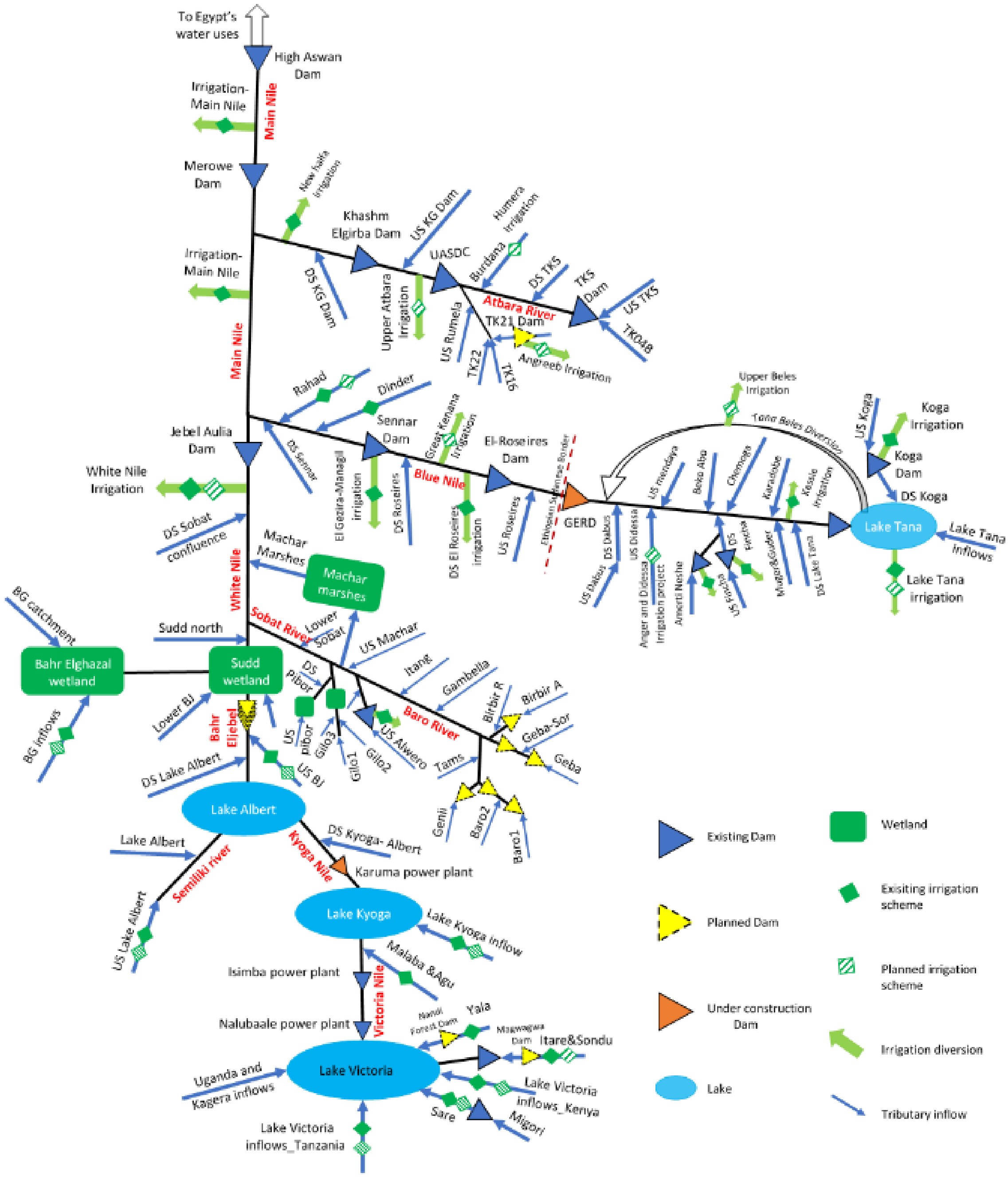


Figure 7.2 Schematic diagram of existing, ongoing and planned hydropower and irrigation projects with completed feasibility studies in the Nile basin

Table 7.3 Irrigation expansion schemes in riparian countries

Country/region	Assumptions		Irrigated area (ha)
Egypt	Continue land development programme		Indigenous variable
Equatorial Lakes Region	Develop their potential irrigation projects		267039[1]
Ethiopia	Blue Nile River basin	Lake Tana irrigation expansion	36209[1]
		Gilgel Abay Irrigation project	135562[2]
		Tis Abay irrigation expansion	22575[1]
		Upper Beles irrigation project	53000[2]
		Anger irrigation project	14450[2]
		Didessa irrigation project	37095[2]
		Neshe Irrigation expansion project	4670[2]
	Atbara River basin	Humera irrigation project	34647[3]
		Angreeb irrigation project	16535[2,3]
South Sudan	White Nile Basin	Develop potential irrigation projects	4330[1,3]
Sudan	Blue Nile River basin	Great Kenana irrigation project	420000[2]
		El Rahad II irrigation project	21000[2]
	Atbara River basin	Upper Atbara irrigation project	117600[2]
Note: [1]Estimated from NB DSS data [2]ENTRO (2009) [3]Cervigni et al. (2015)			

7.2 Food Production from Irrigated Agriculture in the Nile Basin

Food production from irrigated agriculture in the Nile countries can be estimated following previous work for Egypt presented in earlier chapters. A simple form of food production is considered here at the country level. Food production can be estimated by multiplying the irrigated area (A) by the average land yield (Y_a). To account for the reduction in food production due to reduction in water supplies, a simple form of the crop yield decrease due to the relative reduction in crop evapotranspiration is considered using an approach similar to that of FAO (K_y) (Steduto et al. 2012). The food production (FP) (ton) can be estimated as follows:

$$FP = A\,Y_a \tag{7.1}$$

$$Y_a = Y_m \times \left(1\text{-}K_y \times (1\text{-}(ET_a/ET_c))\right) \tag{7.2}$$

Where, A denotes the cropped area (ha), and Y_{ai} the actual crop yield (ton/ha), Y_m is the maximum possible yield of the crop under full water supply, K_y is the yield response factor, and ET_a/ET_c denotes the ratio of actual evapotranspiration of crop to the maximum evapotranspiration of crop represented by the actual crop water consumption to the crop irrigation water demand.

Irrigated areas in riparian countries outside Egypt, for the considered development scenarios, are shown in Table 7.4. Average crop yields at the national level for existing and planned irrigation schemes in riparian countries were available from Siderius et al. (2016). The yield response factor (K_y) is assumed to be the yield response factor for dominant crops in the cropping system for each riparian country.

Table 7.4 Food production parameters in riparian countries for the considered development scenarios

Country/Region		Irrigated area (1000 ha)		Land yield (ton/ha)		Yield response factor (K_y)
		Existing irrigated area	Total irrigated area with planned schemes	Existing yield[1]	Potential yield[1]	
Sudan		1752.0	2499.6	9.7	19.5	1.20
Ethiopia		91.0	312.5	1.5	19.5	1.20
South Sudan		0.5	4.4	9.7	19.5	1.15
ELR	Uganda	12.0	20.0	2.9	4.0	1.15
	Kenya	63.4	218.5	2.4	4.0	1.15
	Tanzania	33.0	137.0	1.7	4.0	1.15

[1]Siderius et al. (2016)

7.3 Climate Change and Future Development Scenarios in the Nile Basin

The Nile River basin is unique because of its varied topographies and climates. The river has distinct sub-basins with different hydrologic regimes and the Nile flows are inherently highly sensitive to small changes in rainfall. The Nile river basin is vulnerable to climate change, which will add further uncertainties to the hydrologic variability of the river. This uncertainty will have potentially significant impacts on the local and regional economies, the livelihoods in the basin, the Nile river system itself and the sustainability of the planned developments across the basin (Beyene et al. 2010; NBI 2012). The literature indicates a warming climate trend across the basin by the end of the 21st century, with significant consistency among previous studies (Barnes 2017). Unlike temperature, the rainfall and streamflows showed considerable variability and inconsistency among the previous climate change studies (Conway 2005; Barnes 2017; Siam and Eltahir 2017). Changes to the streamflows as a result of climate change may further strain the Nile basin system and lead to significant impacts on livelihoods and socio-economic conditions in the basin (NBI 2012; Siam and Eltahir 2017).

The combined impacts of climate change and the future developments in the Nile basin on the WFE nexus in the basin are the focus here. To account for the variability and the uncertainty of the river flow regime under climate change, basin-wide stochastically generated streamflows based on future river flows under climate change are considered. This can be done in a similar way to previous work as follows: (a) Obtain basin-wide streamflows for each climate model of the RCP 4.5 and RCP 8.5 from the NB DSS database, (b) Generate synthetic streamflow series for each climate model using the stochastic generator developed in Tsoukalas et al. (2017) and Tsoukalas et al. (2018a), (c) Basin-wide stochastically generated streamflows for each climate model of the RCP 4.5 and RCP 8.5 are used to drive the whole system to assess the future of the WFE nexus under the planned developments and climate change. A comparison between simulated (i.e., stochastically generated) and future modelled statistical characteristics (mean, standard deviation, skewness, lag-1 month to month correlation) of the 72 streamflows of river tributaries of each climate model is provided in Appendix (D).

The impacts of the planned projects on the WFE nexus are explored through plausible scenarios with and without climate change, Figure 7.3. The case of no developments (Baseline) assumes the status-quo of the basin before the year 2015. This scenario is considered for comparative purposes and to explore the current risks and benefits to the riparian countries. Alternatively, the ongoing developments scenario (SC0) considers that the projects currently under construction in the basin are completed and operational. The hydropower development scenario (SC1) assumes that the ongoing and planned hydropower projects in the basin are completed and operational, and explores the impact of hydropower developments on the WFE nexus in the basin. The hydropower and irrigation development scenario (SC2) is similar to the hydropower developments scenario but considers implementing irrigation expansion projects in the riparian countries under existing management policies. The last scenario (SC3) resembles SC2 but assumes that the riparian countries will implement policy measures to improve water-use efficiency and food production as well. A description of infrastructure and projects for each scenario is provided in Table 7.5.

Regarding climate change, two Representative Concentration Pathways (RCP$_s$): RCP 8.5 and RCP 4.5 by the Intergovernmental Panel on Climate Change (IPCC) of its Fifth Assessment Report (AR5) are investigated here. For each RCP$_s$, basin-wide streamflows from two General Circulation Models (GCM$_s$) were available from the NB DSS database (NBI 2016a). The provided GCM$_s$ per each RCP$_s$ represent the wettest and driest (i.e., extreme) climate conditions in the basin by the year 2050 (NBI 2016c), Table 7.6. The selected two climate models of each climate scenario were ranked (i.e., dry or wet) based on Climate Moisture Index (NBI 2016c). Thus, the basin's hydrological conditions in each climate model are not associated to the historical hydrological conditions in the basin (i.e., wet scenario does not necessarily be wetter than the historical condition or vice versa). Taking into account the reported inconsistency among climate models in the literature, the selected GCM$_s$ cover extreme hydrologic conditions and provide a wide range of possible changes in future river flows under climate change. This facilitates an exploration of the wide impacts of uncertainty in future river flows on the WFE nexus in the basin under climate change using synthetic streamflow series.

Table 7.5 Description of development scenarios and their assumptions

Scenario	Description	Projects considered	
No developments scenario (Baseline)	No planned developments outside Egypt	-	
Ongoing developments scenario (SC0)	Currently under-construction projects are completed and operational	GERD	Ethiopia
		Isimba	Uganda
		UASDC	Sudan
Hydropower development scenario (SC1)	Planned hydropower projects- with completed feasibility studies- are operational	Nandi Forest Dam	Kenya
		Magwagwa Dam	
		Ismba hydropower plant	Uganda
		Karuma hydropower plant	
		Fula Dam	South Sudan
		Shukoli Dam	
		Lakki Dam	
		Bedden Dam	
		GERD	Ethiopia
		Geba hydropower plant	
		Baro hydropower plant	
		Genji hydropower plant	
		UASDC	Sudan
Hydropower and irrigation development scenario (SC2)	Planned hydropower and irrigation projects - with finished feasibility studies - are operational Planned irrigation schemes are operated under current management policies (i.e., crop yield and irrigation efficiency are similar to those of existing schemes)	Develop potential irrigation expansion projects	Kenya
			Tanzania
			Uganda
			South Sudan
		Great Kenana irrigation project	Sudan
		El Rahad II irrigation project	
		Upper Atbara irrigation project	
		Lake Tana irrigation expansion project	Ethiopia
		Tis Abay irrigation project	
		Lower Beles irrigation scheme	

		Anger and Didessa irrigation projects	
		Humera irrigation project	
		Angreeb irrigation project	
Hydropower and irrigation development scenario with policy measures (SC3)	Same as the previous scenario (SC2), but (a) Riparian countries improve irrigation efficiency, (b) Riparian countries achieve potential crop yield, and (c) Egypt to utilise potential water resources at sustainable levels.		

Table 7.6 Description of selected climate models from the NB DSS database

Climate model		Climate Centre
RCPs 4.5 (Dry)	Beijing Climate Center Climate System Model (BCC_CSM1.1)	Beijing Climate Center
RCPs 4.5 (Wet)	Australian Community Climate and Earth-System Simulator (ACCESS1.3)	Collaboration between Commonwealth Scientific and Industrial Research Organisation (CSIRO) , Australia and Bureau of Meteorology (BOM), Australia
RCPs 8.5 (Dry)	GISS-E2-H model	NASA Goddard Institute for Space Studies (NASA GISS)
RCPs 8.5 (Wet)	Model for Interdisciplinary Research On Climate (MIROC5)	The University of Tokyo Center for Climate System Research, National Institute for Environmental Studies, Japan, Japan Agency for Marine-Earth Science and Technology Frontier Research Center for Global Change

7.4 Common Assumptions

In this work, the considered development projects are assumed to be in the operational stage (e.g., the first filling of GERD is complete and it is in the operational phase). Sudanese reservoirs will operate under the existing operating rules in the baseline scenario, while for the remaining scenarios they will operate at their maximum feasible supply level following GERD development. One hundred synthetic streamflows with a length of 65 years for each climate model of the RCP 4.5 and RCP 8.5 together with the case of no climate change are generated and employed for each development scenario (i.e., each development scenario runs for five synthetic streamflow series). Each simulation starts from the year 2030 under the stochastically generated streamflows of the considered climate model. Therefore, a total of 25 scenarios were considered including 20 scenarios under climate change (2 $RCP_s \times 2 \, GCM_s \times 5$ development scenarios), and 5 scenarios without climate change, Figure 7.3.

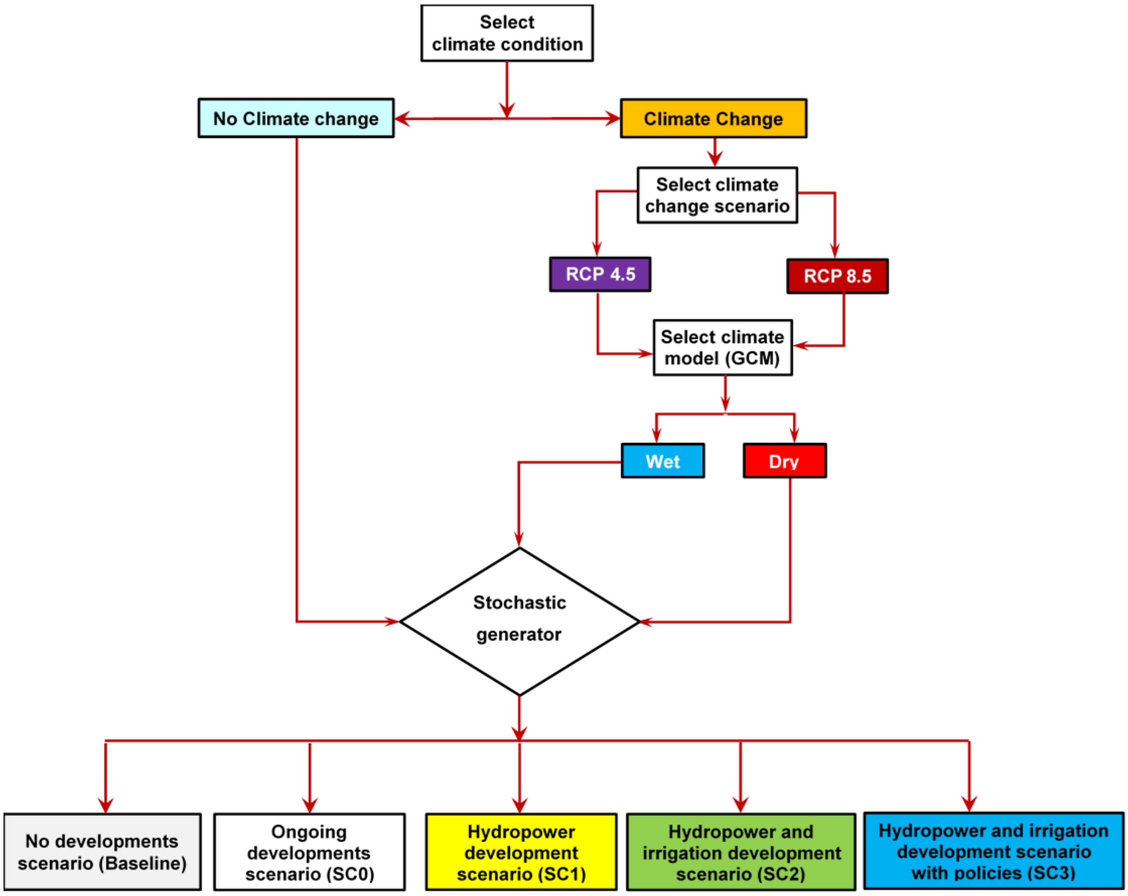


Figure 7.3 Flow chart of the considered development scenarios with and without climate change

7.5 Simulation Results

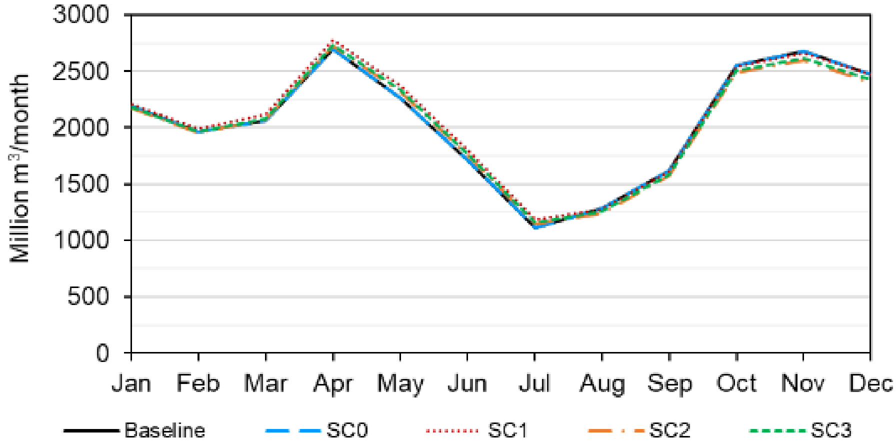
7.5.1 River Flow Regime

7.5.1.1 Impacts of the Planned Developments on River Flows

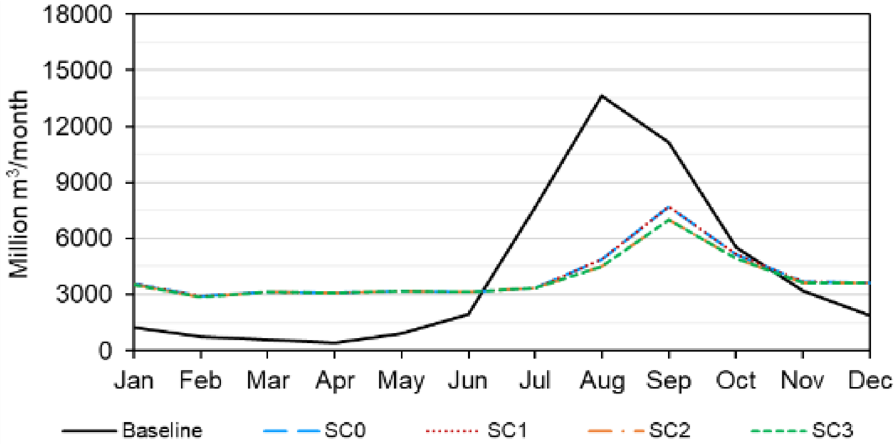
The impact of the planned developments on the river flow regime is explained for the case of no climate change, Figure 7.4. The river flows are assessed at three key gauge locations: (a) The White Nile at Mogren gauge station, (b) the Blue Nile at El Diem gauge station, and (c) the Main Nile at Dongola gauge station. The changes in the river flow under the development scenarios are reported here with reference to the case of no development (baseline).

The monthly White Nile flows will be slightly altered under the planned hydropower projects (SC1) and irrigated agriculture expansions in the White Nile basin (SC2 and SC3) as shown in Figure 7.4.a. Average annual White Nile flows will increase by approximately 2% under planned hydropower projects (SC1), while being reduced by just 1% under irrigation expansions in the White Nile basin (i.e., SC2), Table 7.7. Also, improving irrigation efficiency (i.e., SC3) indicates that planned developments in the White Nile basin will have negligible impacts on the annual White Nile flows, Table 7.7. The small changes in the annual White Nile flows can be explained by the effects of the wetlands on the White Nile flows. The net evaporation from the wetlands in the White Nile basin is reduced by 1% in SC1, 3% in SC2 and 2% in SC3, Table 7.8. The regulation caused by hydropower developments in the White Nile basin will reduce net evaporation from wetlands (1% in SC1) and thus slightly increase the annual White Nile flows. Therefore, increased irrigation abstractions in the ELR (i.e., SC2 and SC3) will be balanced by the reductions in net evaporation from the wetlands and lead to negligible changes in the White Nile flows.

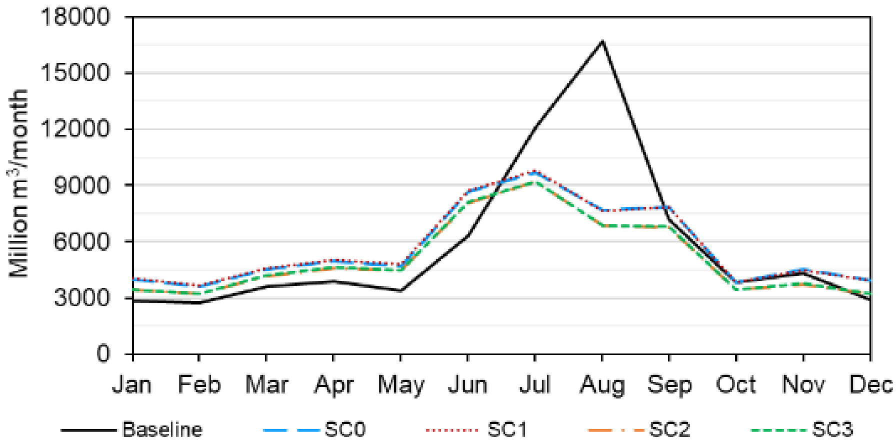
The Blue Nile and Main Nile flow will be regulated as a result of GERD operation, Figure 7.4.b, c, as discussed in previous chapters. Average annual Blue Nile flows will be reduced by 3% for the ongoing and planned hydropower development scenarios (i.e., SC0 and SC1 respectively), Table 7.7, as a result of increased evaporation from new reservoirs (mainly from the GERD). Planned irrigation abstraction in the Blue Nile in Ethiopia (i.e., SC2 and SC3) will reduce the average annual Blue Nile flows by 6%, Table 7.7. The Main Nile flows will be impacted by the upstream developments, depending on the level of development. Average annual Main Nile flows will be reduced by 3% in the ongoing development scenario (SC0) and by 2% in the hydropower development scenario (SC2), as a result of increased evaporation from new reservoirs (mainly GERD in Ethiopia and UASDC in Sudan), Figure 7.5. Average annual Main Nile flow is reduced by 12% with planned upstream irrigation expansions (i.e., SC2 and SC3) in the basin, particularly in Ethiopia and Sudan, Table 7.7.



(a) The White Nile at Mogren



(b) The Blue Nile at El Diem



(c) The Main Nile at Dongola

Figure 7.4 River flow regime for the: (a) The White Nile at Mogren, (b) The Blue Nile at El Diem and (c) The Main Nile at Dongola under the different development scenarios without climate change

Table 7.7 Percent of change (%) in annual river flow under different development scenarios compared to the case of no development and no climate change

Scenario	SC0	SC1	SC2	SC3
White Nile	0	+2	-1	0
Blue Nile	-3	-3	-6	-6
Main Nile	-3	-2	-12	-12

Table 7.8 Changes in net evaporation from wetlands in the White Nile basin compared to the case of no developments and no climate change

Scenario	SC0	SC1	SC2	SC3
Average reduction in net evaporation from wetlands in the White Nile basin (MCM/year)	0	349	1536	1117
Percent of reduction (%) in net evaporation from wetlands in the White Nile basin	0	-1	-3	-2

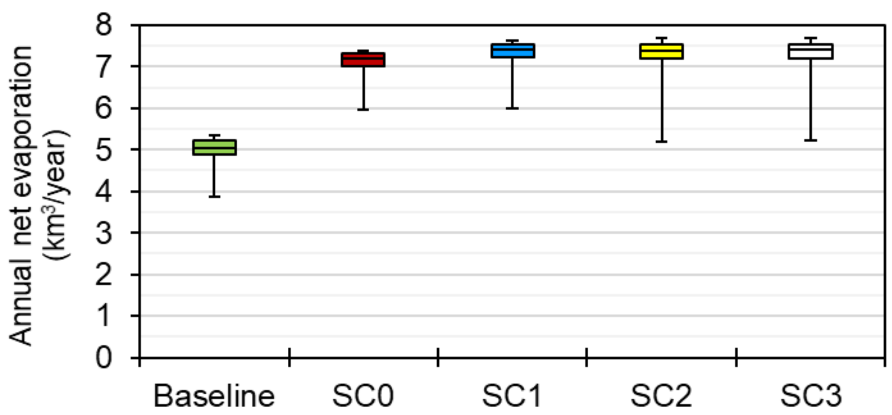


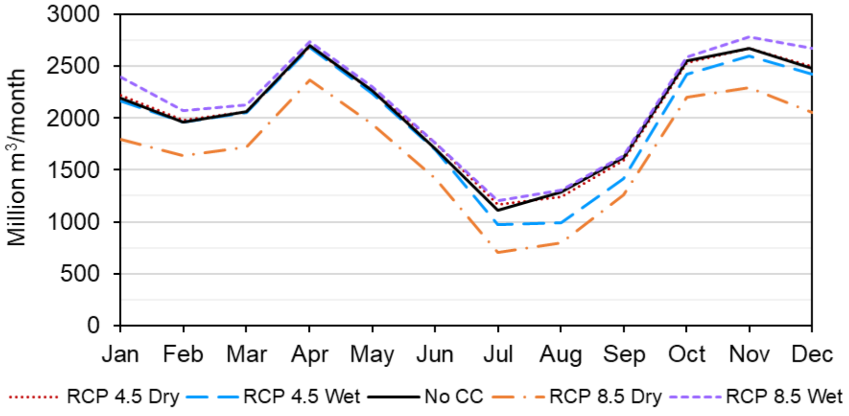
Figure 7.5 Annual net evaporation from reservoirs upstream HAD for the different development scenarios and no climate change

7.5.1.2 Impacts of Climate Change on River Flows

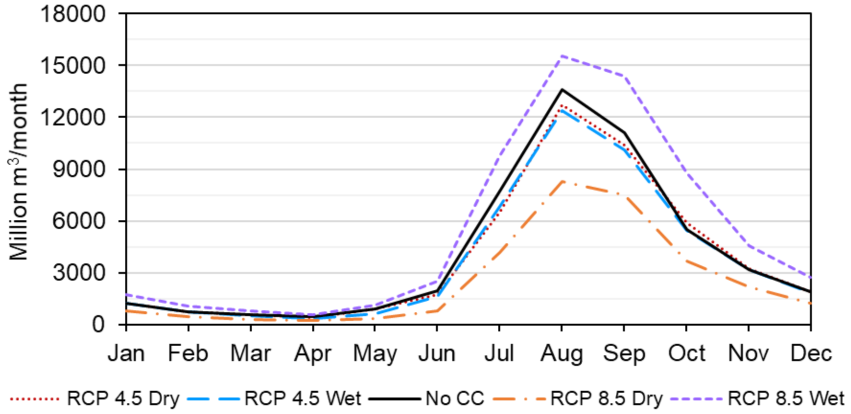
Due to the large uncertainty and inter-annual variability associated with river flows, river flows are further assessed here under climate change to assess their response under climate change and the wide impact on food and energy as will be discussed below. The case of no developments (Baseline) is used here to illustrate the impacts of climate change on the river flows regime. The river flows are assessed at three key gauge locations: (a) The White Nile at Mogren gauge station, (b) the Blue Nile at El Diem gauge station, and (c) the Main Nile at Dongola gauge station. The monthly and annual average river flows show a wider range of change under the RCP 8.5 than the RCP 4.5, Figure 7.6 and Table 7.9.

The White Nile flows are decreased under the wettest model of the RCP 4.5 compared to the driest model, Figure 7.6.a. The wettest model showed 5-23% decrease in the White Nile flows from July to October. Furthermore, average annual White Nile flows are decreased by 4.0% for the wettest model, while the driest model showed negligible changes, Table 7.9. The driest model of the RCP 8.5 showed significant reductions in average White Nile flows with a range of 12-38% in the monthly flows and 18% in average annual flows. In contrast, the wettest model showed a modest range of increase in the river flows: 1-9% for the monthly flows and 4% for the average annual flows, Table 7.9.

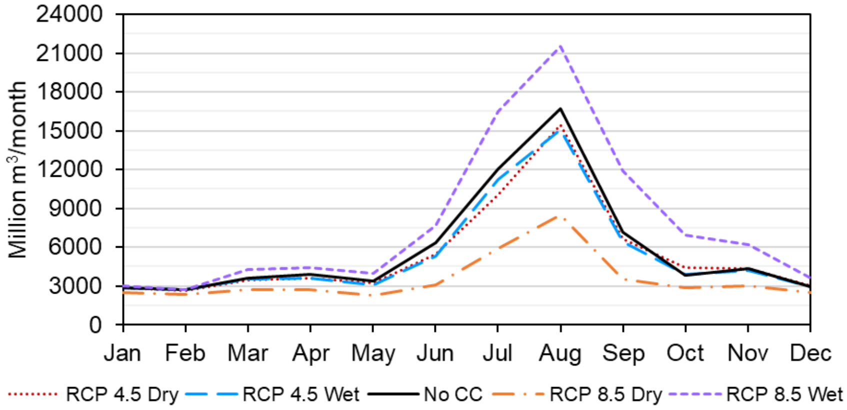
Simulation results show that the average Blue Nile flows are generally decreased under the two climate models of the RCP 4.5, Figure 7.6.b. Average monthly Blue Nile flows during June-September are decreased by 9-19% for the wettest model and 6-16% for the driest model. Furthermore, average annual Blue Nile flows are reduced by 8% for the wettest model and 6% for the driest model, Table 7.9. On the other hand, the climate models of the RCP 8.5 showed a wider range of change in the Blue Nile flows with a clear signal of change (i.e., river flows are reduced in the dry model simulations, while increased in the wet model simulations). Average monthly Blue Nile flows are significantly decreased during June-October - by 34-60% - in the driest model, while increased by 14-59% in the wettest model. The annual flows of the Blue Nile also demonstrate a wide range of change. Average annual Blue Nile flows are decreased by 39% in the dry model, while increased by 30% in the wet model of the RCP 8.5, Table 7.9.



(a) The White Nile at Mogren



(b) The Blue Nile at El Diem



(c) The Main Nile at Dongola

Figure 7.6 River flow regime for the: (a) The White Nile at Mogren, (b) The Blue Nile at El Diem and (c) The Main Nile at Dongola with and without climate change for the case of no development (Baseline)

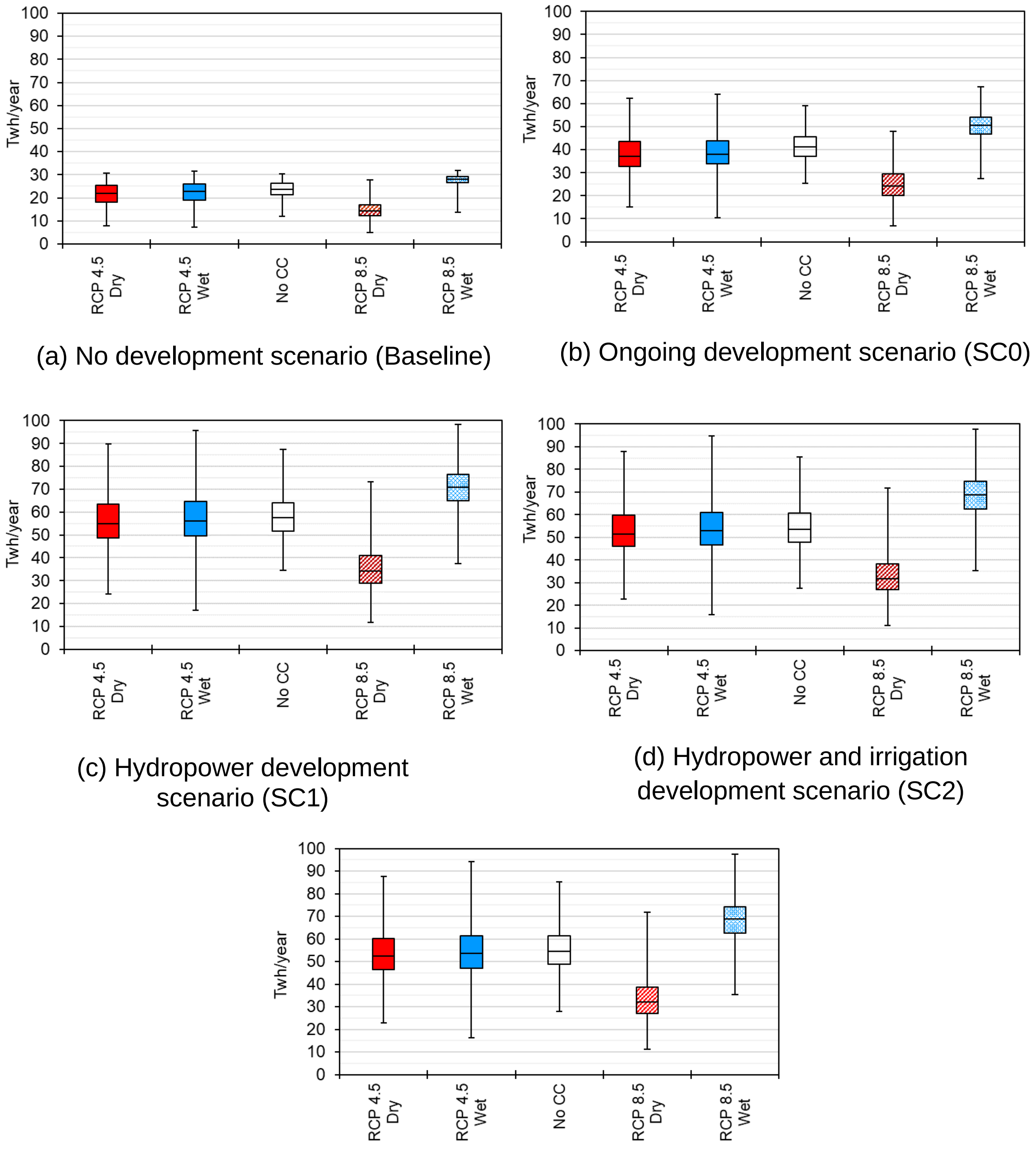
The combined impact of changes in the Blue Nile and the White Nile flows are reflected in the Main Nile flows, Figure 7.6.c. The influence of the Blue Nile flows on the Main Nile flows is obvious; for instance, the changes in the average annual Main Nile flows are similar to those of the Blue Nile, Table 7.9. Also, the monthly Main Nile flows show a wider range of change under the RCP 8.5 compared to the RCP 4.5, especially during the high-flow season. For the RCP 4.5, the monthly average Main Nile flows from June to September are reduced by 7-13% in the dry model, and 7-16% in the wet model. The Main Nile flows under the RCP 8.5 show significant changes compared to those of the Blue Nile and the White Nile. The Main Nile flows from June to October are reduced by 25-51% in the dry model, while the wet model simulations show an increase by 21-82%.

Table 7.9 Percent of change (%) in average annual river flows under climate models for the RCP 4.5 and RCP 8.5 compared to the case of no climate change for the case of no developments scenario (Baseline)

The White Nile @ Mogren					The Blue Nile @ Diem					The Main Nile @ Dongola			
RCP 4.5		RCP 8.5			RCP 4.5		RCP 8.5			RCP 4.5		RCP 8.5	
Dry	Wet	Dry	Wet		Dry	Wet	Dry	Wet		Dry	Wet	Dry	Wet
0	-4	-18	4		-6	-8	-39	30		-7	-7	-40	33

7.5.2 Hydropower Generation

Hydropower generation at the basin level under different development scenarios is shown in Figure 7.7 with and without climate change. The ongoing developments across the basin, once completed and operational, will contribute up to 18 TWh/year on average, mainly from the GERD in the case of no climate change, Figure 7.7.b. Other planned hydropower developments once finished (i.e., SC1) will add an average of 34 TWh/year compared to the baseline scenario and approximately 16 TWh/year compared to the ongoing development scenario. Planned irrigation projects (i.e., SC2) will impact hydropower generation in the basin, reducing it by up to 3.4 TWh/year on average (approximately a 6% reduction). Improving irrigation efficiency in the basin showed insignificant impact on hydropower generation; for instance, hydropower generation in SC3 exceeds hydropower generation in SC2 by just 1%.



(a) No development scenario (Baseline)

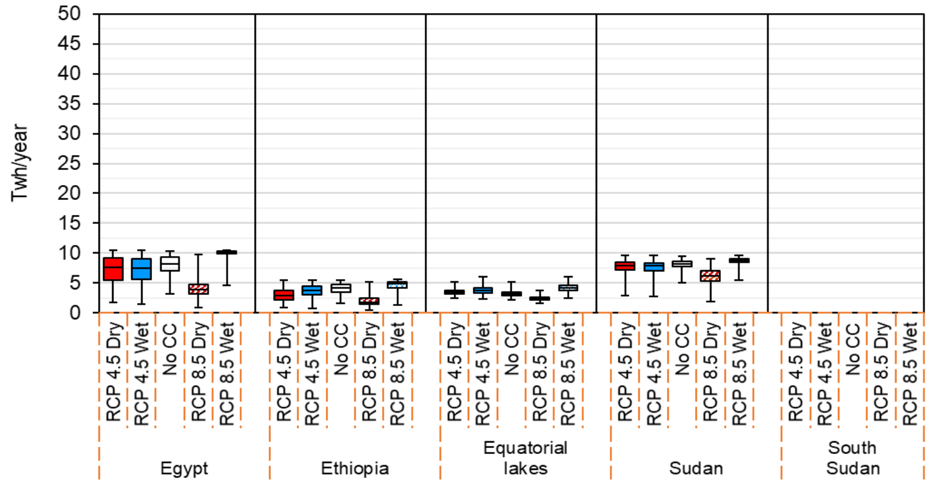
(b) Ongoing development scenario (SC0)

(c) Hydropower development scenario (SC1)

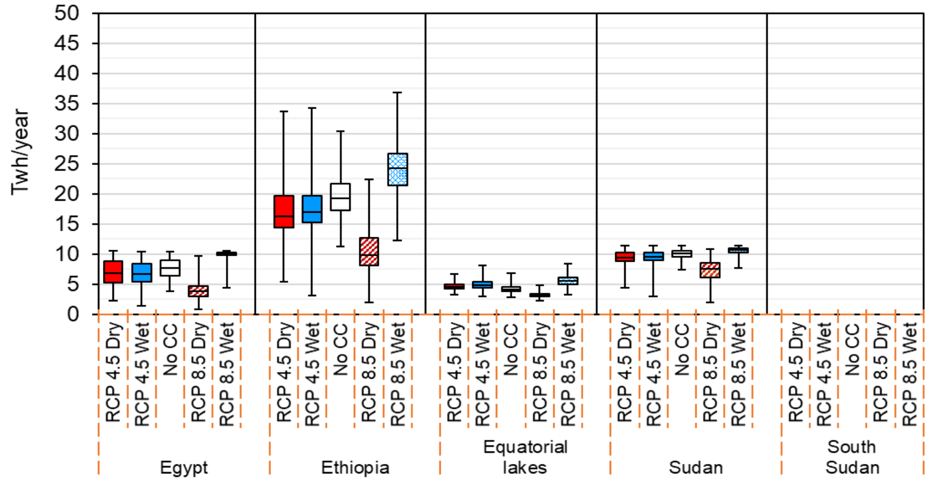
(d) Hydropower and irrigation development scenario (SC2)

(e) Hydropower and irrigation development scenario with policies (SC3)

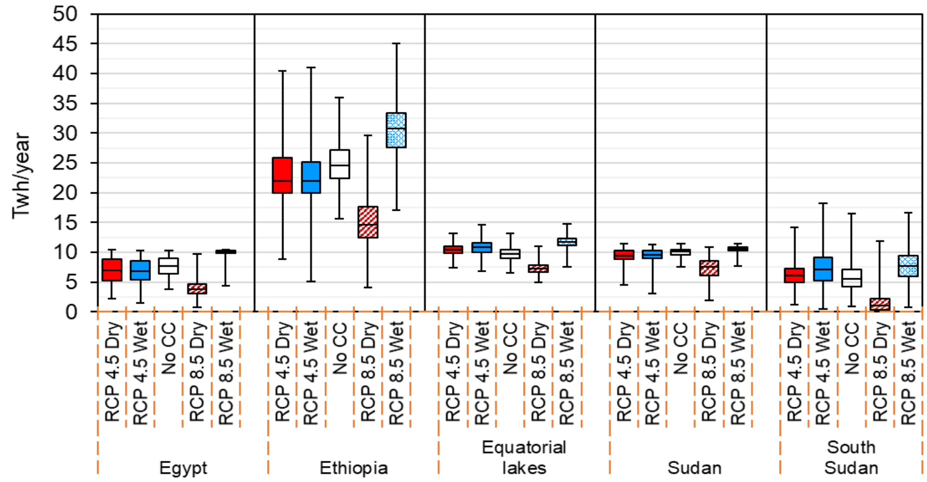
Figure 7.7 Basin-wide hydropower generation with and without climate change scenarios for the considered development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1), (d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies



(a) No development scenario (Baseline)

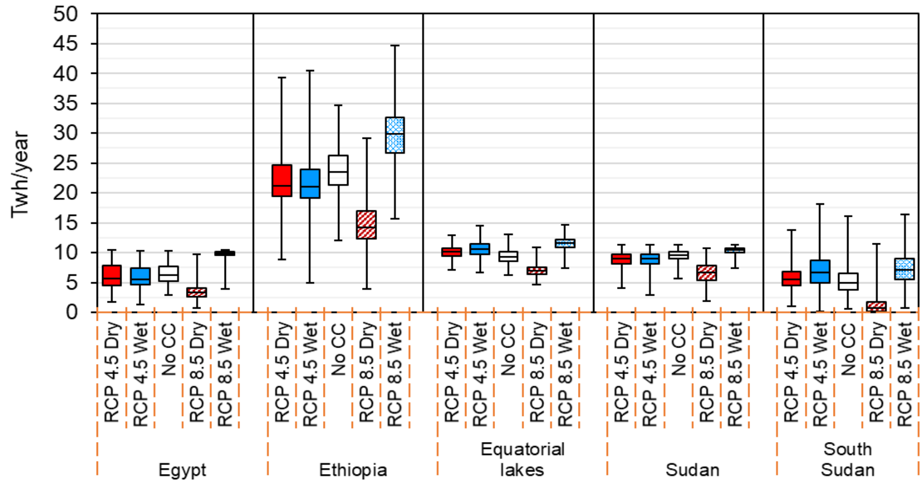


(b) Ongoing development scenario (SC0)

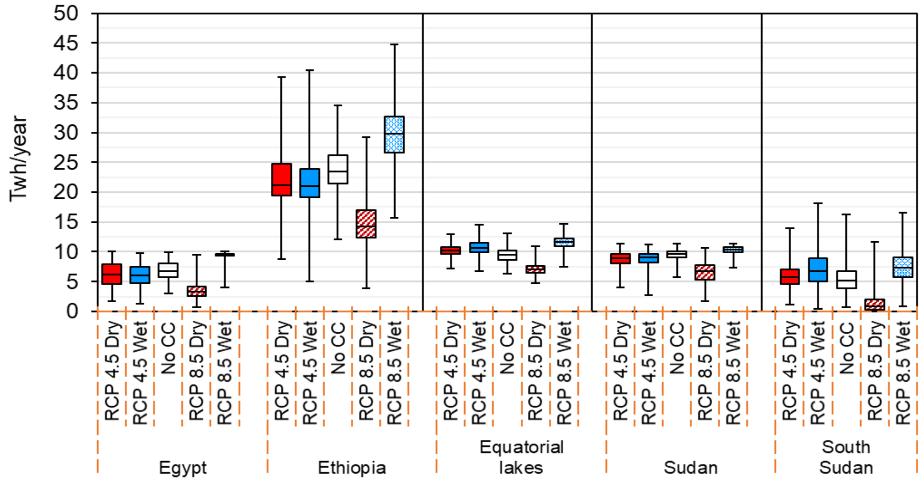


(c) Hydropower development scenario (SC1)

Figure 7.8 Hydropower generation in riparian countries for development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1), (d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies (SC3) with and without climate change



(d) Hydropower and irrigation development scenario (SC2)



(e) Hydropower and irrigation development scenario with policies (SC3)

Continue Figure 7.8 Hydropower generation in riparian countries for development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1), (d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies (SC3) with and without climate change

Climate change will impact hydropower generation and planned hydropower projects in the basin in different ways, depending on the RCP, the level of development and the sub-basin of interest (represented here by riparian countries). It is worth mentioning that reported changes in the outputs under climate change are estimated with reference to the case of no climate change per development scenario. For the RCP 4.5, simulation results show that the average basin-wide hydropower generation is reduced by 4-8% in the baseline and 6-8%

in the ongoing development scenario compared to 1-3% for the rest of the development scenarios (SC1, SC2 and SC3), Table 7.10. The reduction in hydropower generation in the ongoing development scenario (SC0) is mainly due to reductions in Ethiopian hydropower generation and, to some extent, other riparian countries.

Conversely, the small reduction in the average basin-wide hydropower generation for the development scenarios SC1, SC2 and SC3) is attributed to the overall change in hydropower generation in the basin (i.e., the reduction in hydropower generation in some countries is counterbalanced by an increase in hydropower generation in other riparian countries). Results from the dry climate model showed a greater reduction in hydropower generation compared to the wet model at the basin level, Figure 7.7, however, this was not the case for the riparian countries, Figure 7.8. Under the two climate models of the RCP 4.5 hydropower generation is generally reduced; in Egypt by 6-10%, Ethiopia by 7-12%, and Sudan by 5-7%. Conversely, the ELR and South Sudan demonstrated an overall increase in hydropower generation by 8-18% and 7-30%, respectively, Figure 7.8. The direction of change in hydropower generation under climate change in riparian countries relates to the distinct hydrologic regimes of the river sub-basins that govern their response under climate change (NBI 2012).

Hydropower generation in the basin is significantly impacted in the RCP 8.5 scenario, with a change in output ranging from -41% to +24%, Figure 7.7 and Table 7.10. For the driest model, average basin-wide hydropower generation is substantially reduced by 37% in the baseline scenario and up to 40% for the rest of the development scenarios, Table 7.10. In contrast, under the wettest model of the RCP 8.5 hydropower generation is increased by 18% in the baseline and up to 24% in the other development scenarios. Hydropower generation at the basin level and country-level has the same direction of change i.e., hydropower generation is decreased under the driest model and increased under the wettest model in the basin, Figure 7.7 and Figure 7.8. The level of change in average hydropower generation is varied among the riparian countries with little difference from one development scenario to another in each country.

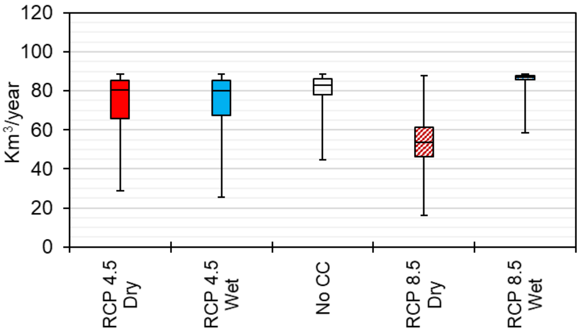
For instance, average hydropower generation showed a wide range of change in Egypt (-47% to +48%) and South Sudan (-77% to +37%), while Ethiopian hydropower generation varied between -46% and +24%. The ELR showed symmetric change in hydropower generation ± 24%, while in Sudan it varied between -31% and +8%. Interestingly, the reduction in hydropower generation in Ethiopia for the ongoing and future development scenarios contributes to more than 40% of the overall reduction in hydropower generation in the basin. This illustrates the significant impacts of climate change on the Blue Nile flows and the hydropower generation in particular. Moreover, results from the climate models of the RCP 8.5 indicate the large uncertainty associated with future river flows under climate change and its impact on hydropower generation in the basin.

Table 7.10 Percent of change (%) in basin-wide hydropower generation under the climate models for the RCP 4.5 and RCP 8.5 with reference to the case of no climate change for each development scenario

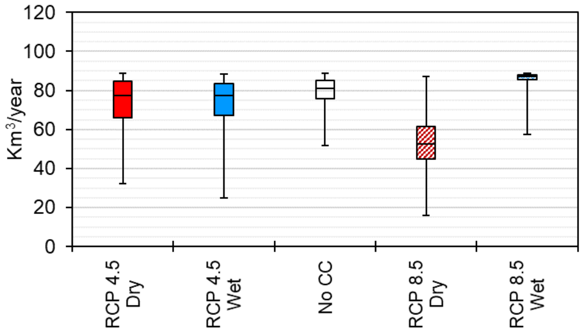
Scenario	RCP 4.5 Dry	RCP 4.5 Wet	RCP 8.5 Dry	RCP 8.5 Wet
Baseline	-8	-4	-37	18
SC0	-8	-6	-40	21
SC1	-3	-1	-39	22
SC2	-3	-1	-40	24
SC3	-3	-1	-40	24

7.5.3 Irrigation Water Withdrawals

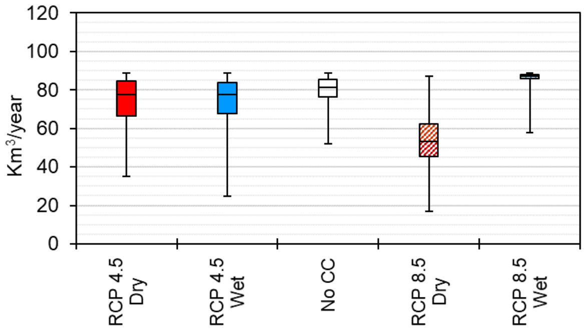
Irrigation water withdrawals in the basin under the different development scenarios, with and without climate change, are shown in Figure 7.9. Irrigation water withdrawals in the basin are predominant in Egypt and Sudan and to a lesser extent in other riparian countries, as shown in Figure 7.10. Basin-wide irrigation water withdrawal is slightly reduced by 1% for both the case of no climate change and with planned hydropower projects in the basin (i.e., SC0 and SC1). Planned irrigation expansions in the basin will increase basin-wide irrigation withdrawals by about 3% (i.e., SC2) for the case of no climate change. Improving irrigation efficiency (i.e., SC3) will reduce the irrigation withdrawals by about 2%. It should be noted that HAD releases are used here instead of irrigation water withdrawals in Egypt since that irrigation is the largest water user in Egypt, and to reflect the impacts of upstream developments on Egypt's water supplies



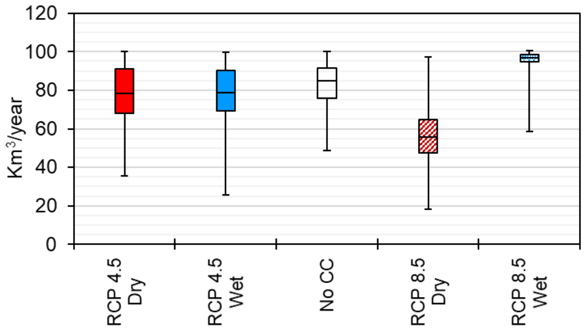
(a) No development scenario (Baseline)



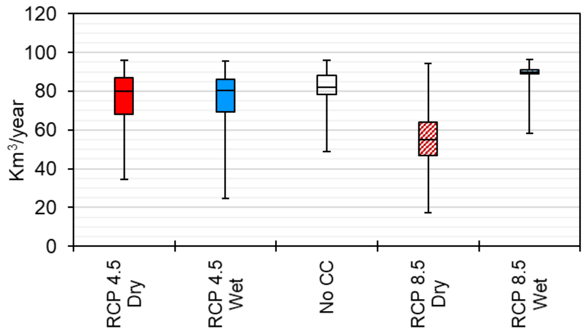
(b) Ongoing development scenario (SC0)



(c) Hydropower development scenario (SC1)

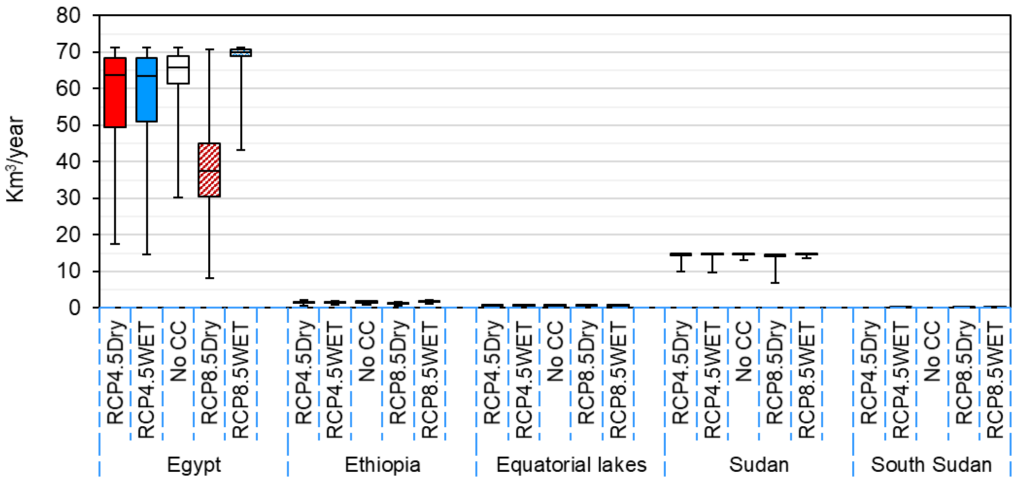


(d) Hydropower and irrigation development scenario (SC2)

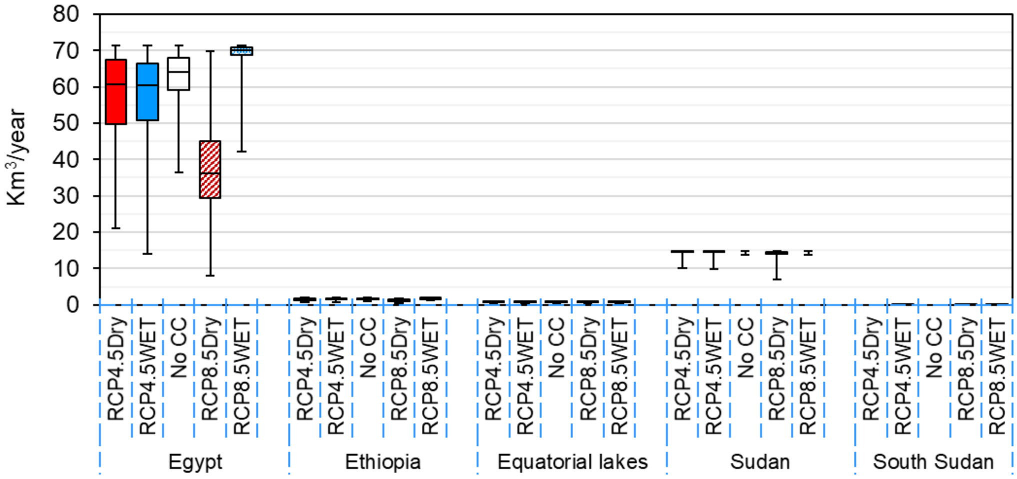


(e) Hydropower and irrigation development scenario with policies (SC3)

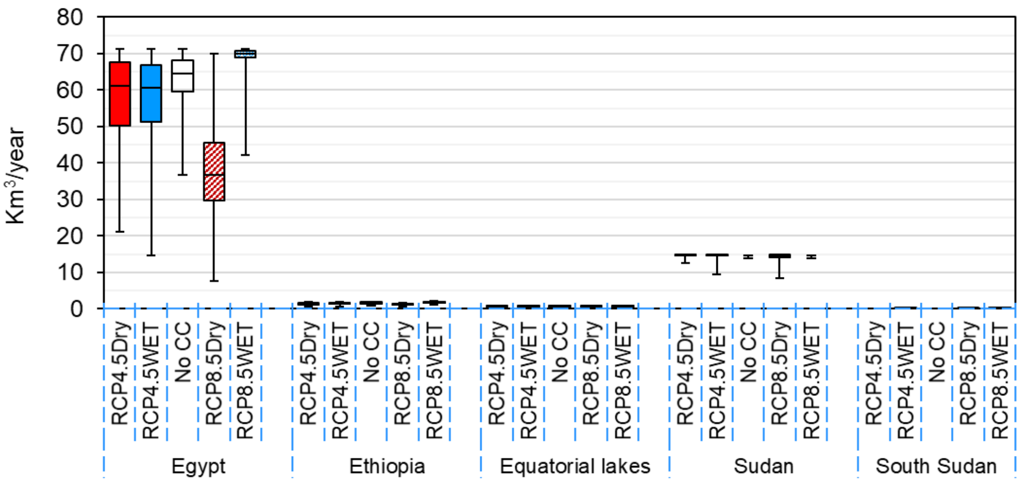
Figure 7.9 Basin-wide irrigation withdrawals with and without climate change for different development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1), (d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies (SC3)



(a) No development scenario (Baseline)

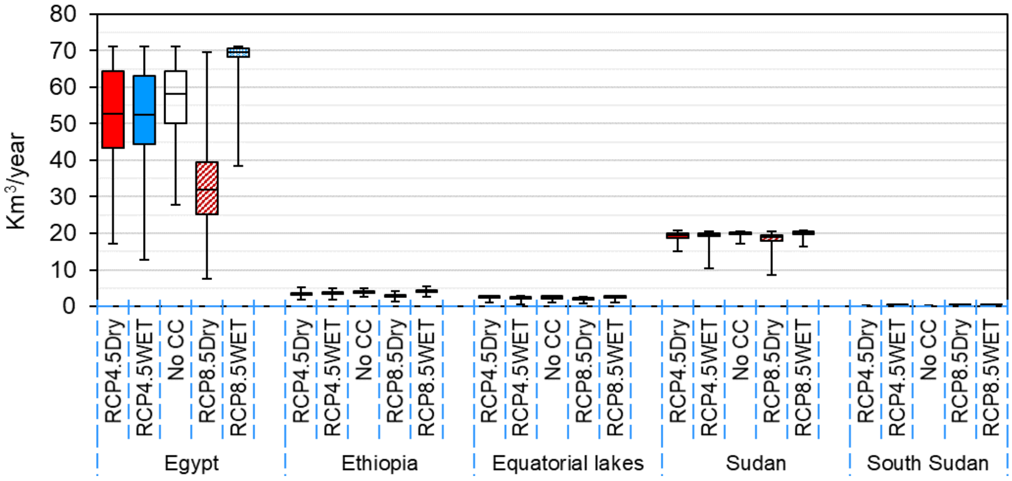


(b) Ongoing development scenario (SC0)

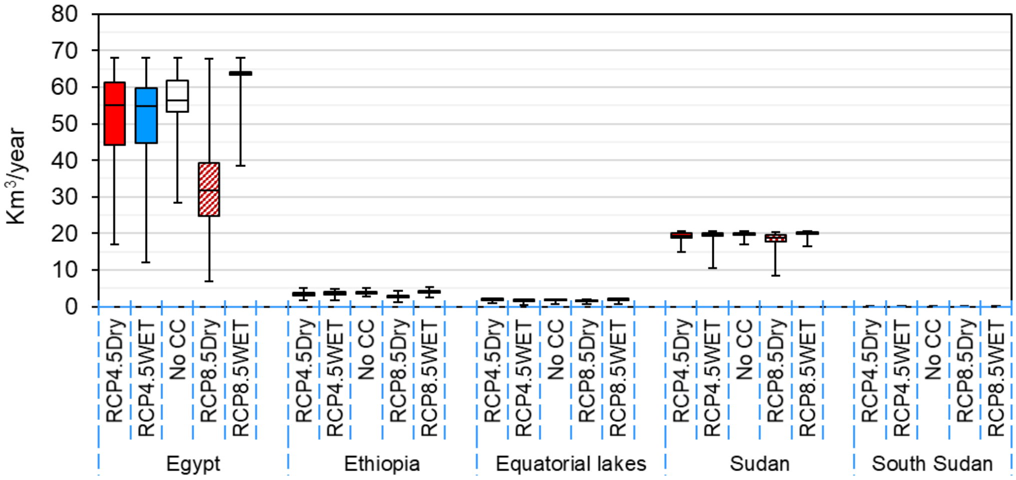


(c) Hydropower development scenario (SC1)

Figure 7.10 Irrigation water withdrawals in riparian countries for development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1), (d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies (SC3) with and without climate change



(d) Hydropower and irrigation development scenario (SC2)



(e) Hydropower and irrigation development scenario with policies (SC3)

Continue Figure 7.10 Irrigation water withdrawals in riparian countries for development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1), (d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies (SC3) with and without climate change

in general. Upstream irrigation expansions (i.e., SC2 and SC3) will impact withdrawals upstream Egypt are increased in SC2 by about 9.5 km^3, compared to the ongoing scenario (i.e., SC0), while irrigation water withdrawals in Egypt are reduced by about 5.0 km^3 (about 10% reduction). However, average annual water withdrawals in Egypt are close to its annual Nile quota under planned upstream developments, particularly SC2 and SC3 (upstream irrigation expansion scenarios) for the case of no climate change.

Irrigation water withdrawals are influenced by river flow regime and water availability in each climate model of the RCP 4.5 and RCP 8.5. The two climate models of the RCP 4.5 showed similar impacts on irrigation water withdrawals in the basin, with average irrigation water withdrawals being reduced by approximately 6%, Table 7.11. Average irrigation water withdrawals showed a wider range of change under RCP 8.5, Figure 7.9. For the driest model of the RCP 8.5, average irrigation water withdrawals are substantially reduced – by up to 32%, Table 7.11 – as a result of significant reductions in river flows under this climate model. Conversely, average irrigation water withdrawals under the wettest model of the RCP 8.5 are increased by up to 15% in SC3 and 10% for the rest of the development scenarios.

The above-shown results reveal the large uncertainty in future river flows and their impacts on irrigated agriculture in the basin. Irrigation water withdrawals in the riparian countries are affected by climate change scenarios in a similar way but with varying levels of change, Figure 7.10. Average irrigation water withdrawals are generally reduced under the climate models of the RCP 4.5 in the riparian countries, except for the ELR and South Sudan, which showed an increase under the dry model, Table 7.12. Average irrigation water withdrawals under the RCP 8.5 demonstrate a wide-ranging change in all riparian countries with a clear signal of change (i.e., reduced under the dry model, while increased under the wet model). Irrigation water withdrawals in Egypt and Ethiopia are substantially impacted by climate change compared to the rest of the riparian countries, Table 7.12. Irrigation water supplies in Ethiopia are sensitive to the Blue Nile variability, while irrigation water supplies in Egypt are impacted by changes in the Main Nile flows, which are also sensitive to the Blue Nile flows. Irrigation water withdrawals in Egypt have a similar pattern of change to the impacts of the wide-basin irrigation water withdrawal under climate change scenarios because irrigated agriculture in the basin is concentrated in Egypt. Furthermore, over 90% of the basin-wide reduction in irrigation water withdrawals occurs in Egypt, which reflects the vulnerability of irrigation water supplies in Egypt to climate change.

Table 7.11 Percent of change (%) in basin-wide irrigation water withdrawals under the climate models for the RCP 4.5 and RCP 8.5 with reference to the case of no climate change for each development scenario

Scenario	RCP 4.5 Dry	RCP 4.5 Wet	RCP 8.5 Dry	RCP 8.5 Wet
Baseline	-7	-6	-32	7
SC0	-6	-6	-32	9
SC1	-6	-6	-32	9
SC2	-6	-6	-32	15
SC3	-6	-6	-31	10

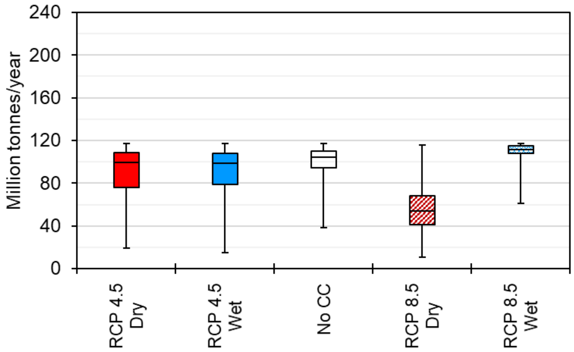
Table 7.12 Percent of change (%) in average irrigation water withdrawals in riparian countries under climate models of RCP 4.5 and RCP 8.5 for development scenarios: SC0 and SC2 with reference to the case of no climate change

Scenario	Ongoing development scenario (SC0)				Hydropower and irrigation development scenario (SC2)			
	RCP 4.5 Dry	RCP 4.5 Wet	RCP 8.5 Dry	RCP 8.5 Wet	RCP 4.5 Dry	RCP 4.5 Wet	RCP 8.5 Dry	RCP 8.5 Wet
Egypt	-8	-7	-39	9	-7	-7	-42	21
Ethiopia	-8	-3	-23	8	-13	-6	-26	7
ELR	3	-3	-4	0	5	-4	-15	4
Sudan	-1	-1	-3	0	-3	-1	-7	0
South Sudan	1	-6	-10	-18	1	0	0	0

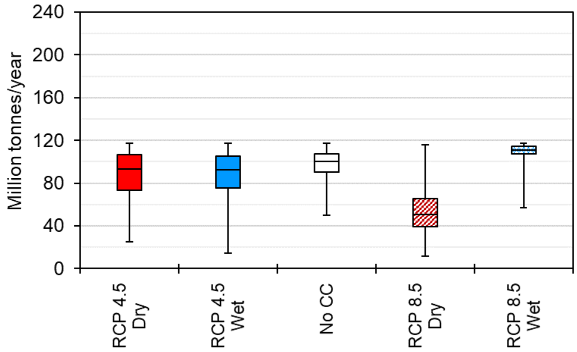
7.5.4 Food Production

Food production from irrigated agriculture in the basin is affected by the level of development and climate change. It should be noted that food production here refers to food production from irrigated agriculture in the basin. Basin-wide food production for the considered development scenarios, with and without climate change, is shown in Figure 7.11. Food production in the basin is primarily from Egypt and Sudan and to a lesser extent other riparian countries, Figure 7.12 since irrigated agriculture is predominant in Egypt and Sudan.

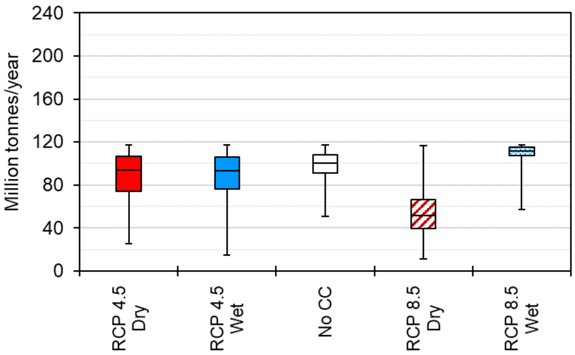
It is clear that food production is less affected by planned developments than climate change. For the case of no climate change, average food production is reduced by approximately 2% under the hydropower development scenarios (i.e., SC0 and SC1) compared to the baseline scenario. Average food production is also reduced under planned irrigation expansions in the basin (i.e., SC2); by 6%



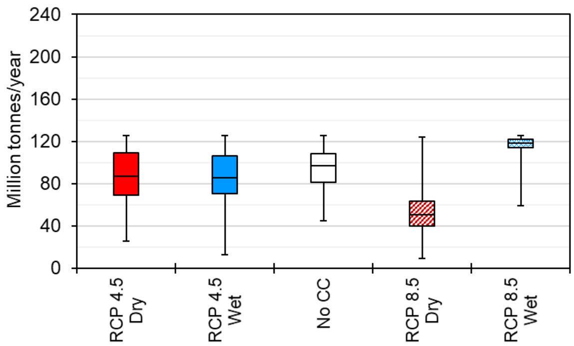
(a) No development scenario (Baseline)



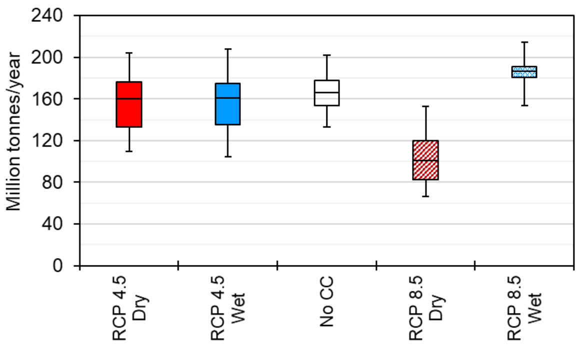
(b) Ongoing development scenario (SC0)



(c) Hydropower development scenario (SC1)



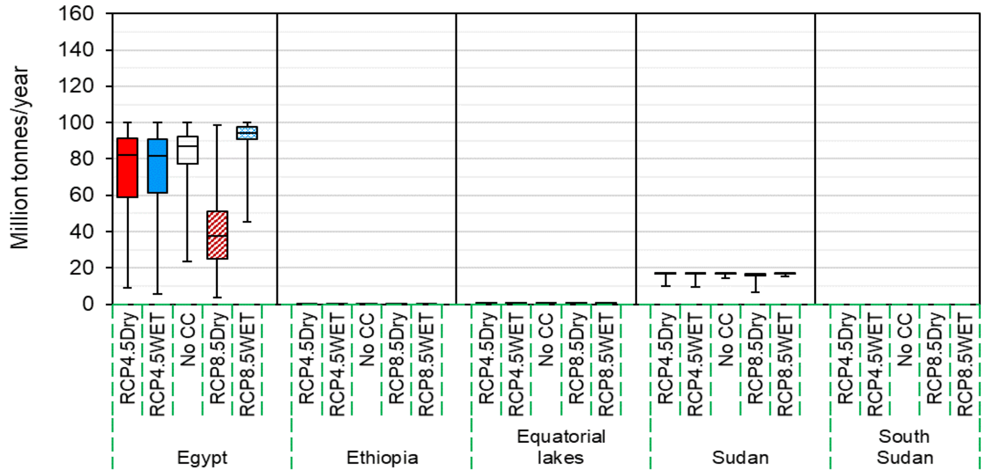
(d) Hydropower and irrigation development scenario (SC2)



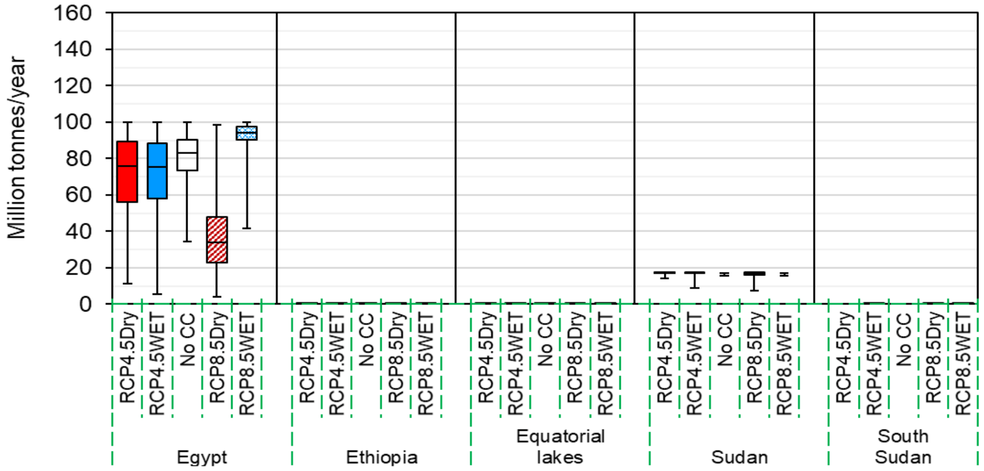
(e) Hydropower and irrigation development scenario with policies (SC3)

Figure 7.11 Basin-wide food production from irrigated agriculture under different development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1),(d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies (SC3) with and without climate change (compared to the baseline) and 3% (compared to SC0). This may seem illogical but the irrigation development scenario assumes that new irrigation projects in riparian countries are operated under existing management policies in each country (i.e., new irrigation schemes have the same irrigation efficiency and land yield of existing irrigation schemes, see Table 7.5). Therefore, the reduction in food production in Egypt outweighs the total increase in food production from new irrigation schemes outside Egypt, because crop yields in riparian countries outside Egypt are lower than those in Egypt. However, food production is likely to substantially increase as a result of achieving potential land yield and to some extent improving irrigation efficiency in the basin. This was tested in SC3, which is similar to SC2 but assumes that the riparian countries will achieve potential crop yield and improve irrigation efficiency. Results from SC3 show that average food production is significantly increased – by more than 60% – compared to other development scenarios, Figure 7.12.d, e, for the case of no climate change. This emphasises the significance of improving land productivity and irrigation efficiency for food production in the basin.

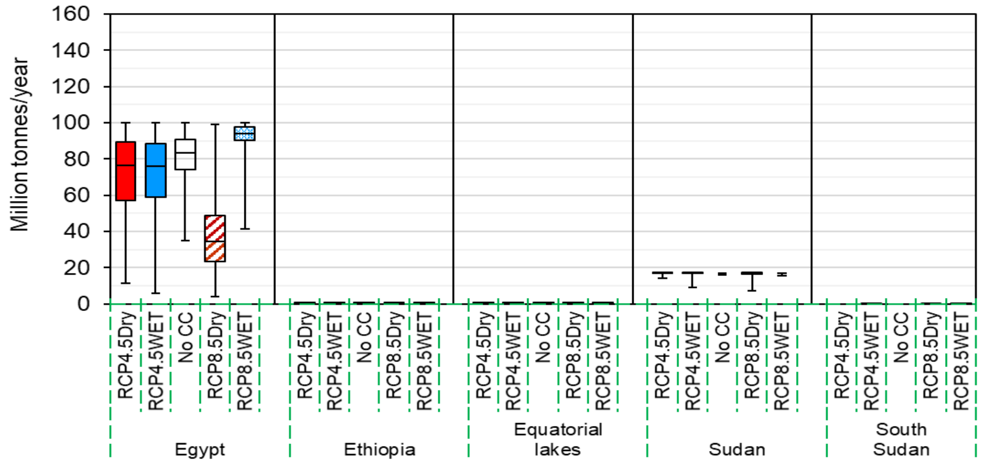
Climate change will impact food production in the basin by varying degrees depending on climate scenario and climate model as shown in Figure 7.11 and Figure 7.12. Food production is generally reduced under the two climate models of the RCP 4.5, following the overall changes of the river flows. Average food production in the basin is reduced by 7-9% in development scenarios with current management policies (i.e., Baseline, SC0, SC1 and SC2), Table 7.13, while average food production is reduced by up to 6% in the scenario of improved land yield and irrigation efficiency (SC3), Table 7.13. On the other hand, average food production varied considerably under the climate models of the RCP 8.5 as a result of the large uncertainty in future river flows under the RCP 8.5, Figure 7.11. Food production is more significantly affected by the driest model than the wettest model of the RCP 8.5, Table 7.13. Average food production in the driest model is substantially reduced by up to 45%, Table 7.13, while average food production in the wettest model is increased by up to 13% for all development scenarios except the irrigation development scenario (SC2), where it increased by 24%.



(a) No development scenario (Baseline)

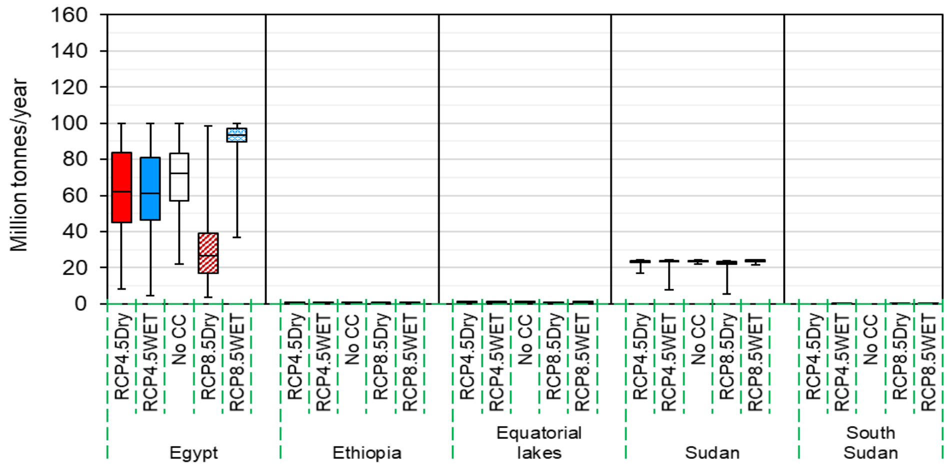


(b) Ongoing development scenario (SC0)

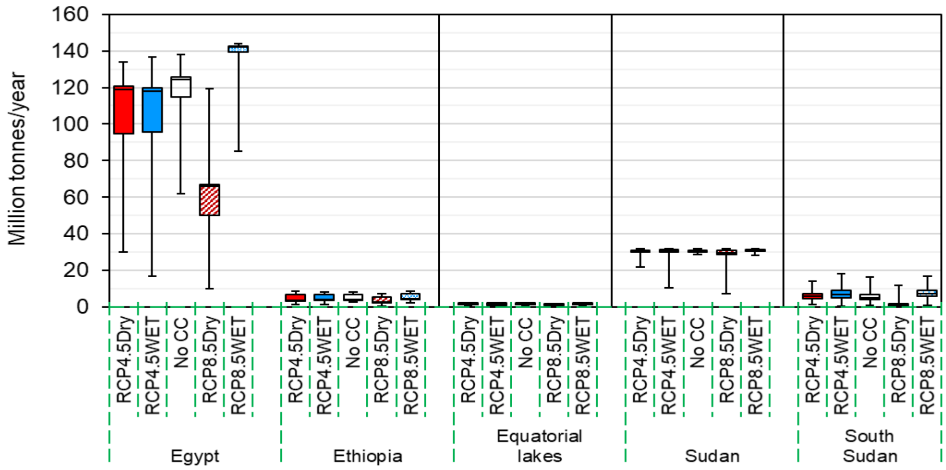


(c) Hydropower development scenario (SC1)

Figure 7.12 Food production from irrigated agriculture in riparian countries under different development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1), (d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies (SC3) with and without climate change



(d) Hydropower and irrigation development scenario (SC2)



(e) Hydropower and irrigation development scenario with policies (SC3)

Continue Figure 7.12 Food production from irrigated agriculture in riparian countries under different development scenarios: (a) No development scenario (Baseline), (b) Ongoing development scenario (SC0), (c) Hydropower development scenario (SC1), (d) Hydropower and irrigation development scenario (SC2) and (e) Hydropower and irrigation development scenario with policies (SC3) with and without climate change

Several conclusions can be drawn from the present results. For instance, although the findings from the driest and the wettest model of the RCP 8.5 represent the most extreme values, they indicate the significant impact of water availability on food production under climate change. Also, comparing food production of SC2 and SC3 for each corresponding climate model demonstrates the significance of improving crop yields and irrigation efficiency, and their capacity to boost food production in the basin. Average food production in the driest model of the RCP 8.5 increased by 90% in SC3 compared to SC2, while other climate models show an increase in food production by over 60%. Interestingly, average food production in SC3 under the driest model of RCP 8.5 (i.e., extreme case) is slightly higher than average food production in the other development scenarios (Baseline, SC0, SC1 and SC2) without climate change. This suggests the salience of improving crop productivity to combat the impacts of climate change and highlights the urgent need to develop new crop varieties that are more resistant to water shortages.

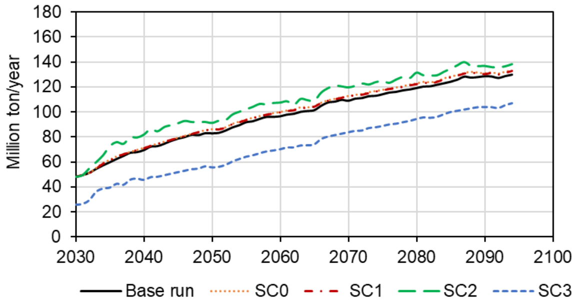
Table 7.13 Percent of change (%) in average basin-wide food production under the climate models for the RCP 4.5 and RCP 8.5 with reference to the case of no climate change per development scenario

Scenario	RCP 4.5 Dry	RCP 4.5 Wet	RCP 8.5 Dry	RCP 8.5 Wet
Baseline	-9	-8	-44	11
SC0	-9	-8	-45	13
SC1	-9	-8	-45	13
SC2	-7	-8	-43	24
SC3	-6	-5	-38	13

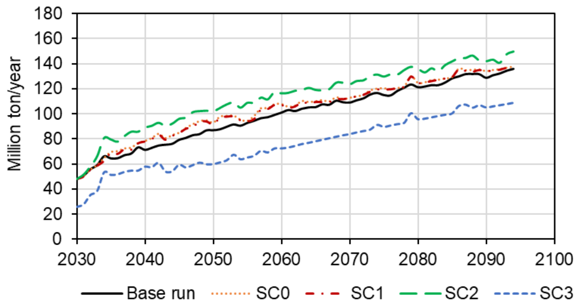
7.5.5 Food Imports in Egypt

Food imports in Egypt are projected to grow, as shown in Figure 7.13. This is because of population growth and a reduction in food production as a result of internal factors, such as the reduction in agricultural land due to urbanization, and external factors, e.g., reduction in the Nile flows from planned developments and climate change. For the case of no climate change, food imports will increase by approximately 3% under planned hydropower developments (i.e., SC0 and SC1) and 11% under the upstream irrigation expansion scenario (i.e., SC2), Table 7.14. In contrast, improving land productivity in Egypt (i.e., SC3) will significantly reduce food imports; by 27% compared to the baseline and 35% compared to SC2. This demonstrates the significance of improving land productivity in Egypt in the face of population growth and reduced water availability in Egypt.

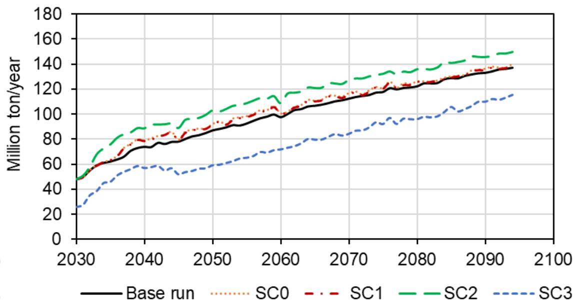
Food imports will also be impacted by climate change, depending on the climate change scenario and the level of development. Changes in food imports under climate change models for different development scenarios, with reference to the case of no climate change for the corresponding development scenario, are shown in Table 7.15. Food imports are found to increase under all climate change models except for the wettest model of the RCP 8.5, which showed a reduction in food imports. Food imports in climate models of RCP 4.5 are increased with a range of 3-7% in all development scenarios. In the driest model of RCP 8.5 (i.e., worst scenario) food imports are substantially increased; by



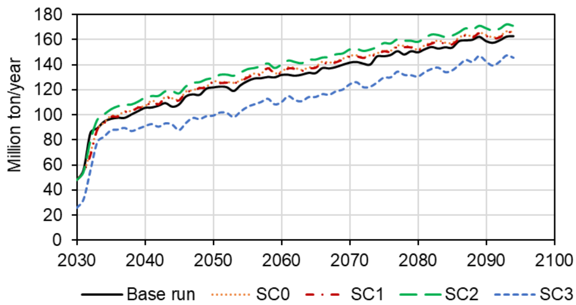
(a) No climate change



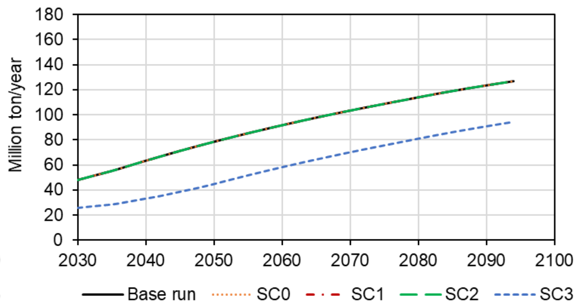
(b) RCP 4.5 Dry



(c) RCP 4.5 Wet



(d) RCP 8.5 Dry



(e) RCP 8.5 Wet

Figure 7.13 Food imports in Egypt under different development scenarios in the basin considering climate conditions: (a) no climate change, (b) RCP 4.5 dry model, (c) RCP 4.5 wet model, (d) RCP 8.5 dry model and (e) RCP 8.5 wet model approximately 35% in all development scenarios, except SC3, where they increased by 60%. In contrast, the wettest model of RCP 8.5 showed a reduction in food imports; by 6% in the baseline, 8% in hydropower development scenarios and up to 18% under upstream irrigation expansion scenarios, Table 7.15.

The impact of planned developments in the basin – considering climate conditions – on Egypt's food imports can be illustrated by comparing food imports in each development scenario with food imports in the baseline scenario for the corresponding climate condition. Similar to the case of no climate change, food imports are less affected by planned hydropower developments in the basin (i.e., SC0 and SC1) than increased upstream irrigation abstractions (i.e., SC2), Table 7.14. On the other hand, food imports are reduced by 15-37%, depending on climate condition, with improved land productivity (i.e., SC3). Interestingly, the wettest model of RCP 8.5 scenario (optimistic scenario) demonstrated that food imports are not affected by planned developments in the basin, however, they are increased due to population growth, Figure 7.13.e. Furthermore, food imports could be reduced by up to 37% on average with improved land productivity. The latter results stress the significance of improving land productivity to achieve food security in the context of a growing population in Egypt.

Table 7.14 Average percent of change (%) in food imports in Egypt under development scenarios in the basin with reference to the baseline scenario per each climate change condition

Scenario	RCP 4.5 Dry	RCP 4.5 Wet	No CC	RCP 8.5 Dry	RCP 8.5 Wet
SC0	5	4	3	2	0
SC1	4	3	2	2	0
SC2	14	14	11	7	0
SC3	-25	-25	-27	-15	-37

Table 7.15 Average percent of change (%) in food imports in Egypt under climate change scenarios with reference to the case of no climate change per each development scenario

Scenario	RCP 4.5 Dry	RCP 4.5 Wet	RCP 8.5 Dry	RCP 8.5 Wet
Baseline	3	3	36	-6
SC0	5	5	35	-8
SC1	5	4	35	-8
SC2	7	7	30	-15
SC3	7	6	60	-18

7.6 Discussion

In this chapter, the integrated model of the entire Nile basin is used to investigate and understand the WFE nexus interdependencies in the basin while considering planned developments in the basin, with and without climate change. The development scenarios considered here are used to explore the impacts of planned projects in the basin on the WFE nexus at the basin and country level. These scenarios include projects currently under construction, planned hydropower projects, and planned irrigation expansions.

Planned hydropower projects in the basin will regulate river flows e.g., Blue Nile regulation following GERD operation. However, planned hydropower projects showed insignificant changes in volumes of annual river flows. Hydropower projects in the basin will boost hydropower generation in the basin; for example, hydropower projects currently under construction in the basin, once completed will add approximately 18 TWh/year (mainly from the GERD). Furthermore, planned hydropower projects will add over 16 TWh/year once operational. Irrigation expansion projects in the upstream countries could reduce hydropower generation in the basin by 6%. HAD releases will be slightly reduced under planned hydropower projects, however, increased irrigation abstraction in the upstream countries will reduce water withdrawals in Egypt by 10%. Average annual HAD releases are expected to be close to Egypt's annual Nile quota under all development scenarios for the case of no climate change. Irrigated agriculture in the basin is dominant in Egypt and Sudan and to a lesser extent in other riparian countries. Therefore, food production in the basin is primarily concentrated in Egypt and Sudan. Food production will be reduced by approximately 2% under planned hydropower projects and by 6% for the case of increased upstream irrigation water abstractions. However, improving land productivity and irrigation efficiency in the basin are likely to boost food production in the basin.

Considering climate change, four GCMs were used based on two RCPs; RCP 4.5 and RCP 8.5 representing hydrological conditions in the basin by 2050. The WFE nexus is impacted by climate change in the basin in general and by the climate model in particular. The climate models of the RCP 8.5 indicated large uncertainties and changes in future river flows compared to climate models of the RCP 4.5. Average annual river flows are generally reduced in the RCP 4.5, unlike the climate models of RCP 8.5, which showed a wide range of change in river flows with a clear signal of change: one model showed significant reductions in average annual river flows and the other model showed an increase in average annual river flows. Irrigation water withdrawals, hydropower generation and food production in the basin are impacted by the changes in future river flows under climate change.

Interestingly, the WFE nexus is impacted by planned developments and climate change in the basin in varying degrees. For example, annual river runoff is reduced by 12% under upstream irrigation expansion projects with no climate change, while it is reduced by 7% in the RCP 4.5, and shows a wider range of change from -40% to +33% in the RCP 8.5. Following changes in river flow under climate change, hydropower generation and food production in the basin will be impacted in a similar way with varying degrees of change in sub-basins. Furthermore, improving irrigation efficiency in the basin demonstrated insignificant impacts on the river flows and hydropower generation in the basin but showed significant effects on food production. Improving land productivity and irrigation efficiency in the basin would improve food production by more than 60%.

A novel part of this work - presented here in this chapter - is introducing climate change to the nexus framework. The integrated simulation model was able to represent and account for uncertainty in hydrologic regime of the river under climate change together with basin-wide planned infrastructure projects.

This can improve our understanding of possible climate change impacts on the nexus in river basins and assist in better river basin planning and management process. The above-presented results showed that climate change has significant impacts on the nexus in the Nile basin. Therefore, climate change inclusion in the proposed nexus framework would not only promote for integrated infrastructure planning and management in river basins but will also assist in transboundary negotiations and improve management policies across scales, regions and sectors. More research is thus required to account for long-term uncertainty in river hydrology under different climate change scenarios and better understand wide impacts of climate change on the nexus in the basin.

Another novel aspect of this work is the inclusion of the socio-economic drivers in the framework. Simulation results show their impacts on the WFE nexus while considering other external elements e.g., climate change and planned developments in the Nile basin or applying policy measures. This was clear for the full application of the WFE nexus framework for Egypt, where simulation results indicate continued growth of food imports as a result of population growth. However, food imports are likely to increase due to a reduction in domestic food production as a result of planned upstream developments and/or climate change. This points out to the food security issues and the significant challenges imposed by climate change and population growth not only in Egypt but across the Nile basin. Furthermore, introducing socio-economic dynamics into the nexus framework will improve our understanding of their wide impacts on the nexus interdependencies.

Policy options regarding land productivity, improving water demands and supplies in Egypt showed significant impact in reducing food gap in Egypt. Simulation results showed that food imports could be reduced by a range of 15-37%, depending on climate conditions, when land productivity and water management policies are implemented. This reveals the significance of improving land productivity, crop varieties and improved water management policies in the face of water shortage as a result of climate change and upstream developments in the Nile basin.

CHAPTER EIGHT: CONCLUSIONS

8.1 Summary of the Work

This thesis presented a novel systems-based framework to better understand the WFE nexus interdependencies at the river basin level while taking into account interrelated themes. The presented work can be summarised as follows:

- This thesis builds on the WFE nexus approach, starts with a state of the art of the WFE nexus in river basins and identifies the gaps in the literature.
- A systems-based approach is proposed in this work to better understand the WFE nexus interdependencies in river basins, including but not limited to the challenging case of transboundary river systems.
- The approach can equip decision-makers with negotiation and policy tools to achieve cooperation among riparian countries and improve cross-sectoral management and coordination within and beyond national borders.
- The approach recognises the WFE nexus interdependencies while considering other related critical issues including long-term uncertainty of river flow regime, climate change, population growth, economic growth, planned developments and policy choices in river basins.
- An integrated simulation model was then developed for the entire Nile river basin – as a case study – using System Dynamics approach to better understand and explore the future of the WFE nexus in the basin.
- The integrated simulation model considers a full application of the framework in Egypt, while a partial application of the framework for the rest of the countries due to limited data availability.
- The integrated simulation model consists of:

(a) A comprehensive water resources model for the entire Nile basin that considers key hydrological features and activities that affect water availability, e.g., water abstractions and management infrastructure. The model represents the state of the Nile basin till the year 2015 and runs for a monthly time step. It includes 72 inflow nodes that represent basin-wide river tributaries, natural lakes, marshes, existing reservoirs with their on-site specifications and operation rules, hydropower plants and basin-wide irrigation and domestic water demands. The integrated model allows for investigating water resources and abstractions, hydropower generation and food production from irrigated agriculture in the basin. Furthermore, the model can be easily modified to include new infrastructure projects, e.g., new irrigation schemes and new reservoirs;

(b) Full WFE nexus model for Egypt that is linked to the Nile water resources model through High Aswan Dam and Nile water arriving to its reservoir. The model considers different available water resources in Egypt, e.g., agricultural drainage water reuse, and different water demands in Egypt at the national level. Food sector include domestic food production from irrigated agriculture considering various crops, food demands and food imports of different food commodities. The energy sector include: (a) energy demands in food and water sectors such as pumping for irrigation, (b) hydropower generation from High Aswan Dam. GDP per capita is used as a proxy for socio-economic state and can be calculated from population and economic sectors. Socio-economic state can be used to determine food demand at the national level. The model can provide food and water balance, while energy balance were not considered here as it was beyond the scope of the current work.

- The Nile water resources model and the full nexus model in Egypt are linked and interact with each other. They run simultaneously as a one unit in the same window in Simile software at a monthly time-step. It can run for historical time series, projected inflows of river tributaries under climate change and stochastic simulations through the use of synthetic stream flow series with and without climate change.
- Model calibrations and validations indicated that the model simulation results showed a satisfactory performance and the integrated simulation model is fit for the purpose for which it is developed.
- To account for the inherent uncertainty in river flow regime, basin-wide stochastically generated river flows were used to drive model simulations under different settings and climate conditions.
- The integrated simulation model is employed to explore the future of the WFE nexus in the basin under the GERD development in Ethiopia during first filling of the reservoir and operation phase of the dam.

- At the national level, the integrated simulation model was used to investigate policy options, such as, improving irrigation efficiency and developing new water resources, and their impacts on the WFE nexus in Egypt.
- At the regional level, the developed model was used to investigate cooperation and unilaterally motivated policies in the Nile basin over GERD development.
- The model is also utilised to explore the impacts of climate change under two RCPs scenarios; RCP 4.5 and RCP 8.5 and planned infrastructure projects in the Nile basin on the future of the WFE nexus in the basin.

8.2 Conclusions and Key Contributions

The thesis provided an in-depth understanding of the WFE nexus interdependencies and cross-sectoral, cross-regional trade-offs and synergies in transboundary river systems. Key results and conclusions from this work are presented below.

- The thesis proposes a novel systems-based approach that adequately addresses the WFE nexus interdependencies in river basins – including but not restricted to the case of transboundary river basins – while considering other critical issues, such as: (a) climate change, (b) planned developments, (c) population growth, (d) long-term uncertainty in river flow regime and (e) policy measures (Objective 1).
- Key novelties of this study lies in covering critical gaps in the literature namely uncertainty in hydrologic regime of the river with and without climate change, population growth, addressing feedback among system domains and developing a wide-basin simulation model that considers critical water, food and energy nexus linkages.
- The integrated simulation model developed here demonstrates the suitability of SD to provide cross-sectoral, cross-regional and cross-scales systems analysis when addressing the WFE nexus interdependencies with other related themes including but not limited to river basins.

- The developed model can be used in policy analysis and inform policymakers and planners to evaluate existing and future management of water, food and energy in river basins.
  - In the context of the Nile basin, the integrated simulation model covers the entire basin and considers explicit linkages among water, food and energy in the basin unlike previous models and studies appeared in literature that had rarely addressed them or were limited to certain regions and sub basins.

The simulation model was applied to explore the impacts of the GERD project on the WFE nexus in the basin during its first filling and operational phases (Objective 2). Simulation results indicate that:

- The present study quantify the nexus in the basin following GERD development using a comprehensive simulation model for the entire Nile basin.
- Simulation results showed that the GERD have a little impact on the nexus in the basin and will accelerate the fill process if it occurred during above-average years.
- The GERD filling and operation would affect the WFE nexus in Egypt, with the impact likely to be significant if the filling process occurs during a dry period.
- Food production in Egypt would be reduced on average by 9-19% during GERD filling and by about 4% during GERD operation compared to the case without GERD.
- Average hydropower generation in Egypt would reduce by 3-9% during GERD filling, while it would reduce by approximately 7% during GERD operation when compared to the case without GERD.
- In Sudan, the irrigation water supply reliability and hydropower generation will be reduced during the filling phase of GERD, but this is expected to be improved during the dam operation phase as a result of the regulation afforded by the GERD.
- During GERD filling, average hydropower generation in Sudan could be reduced by 2-29%, while it will increase by 6% during GERD operation.

- The irrigation supply reliability in Sudan could be reduced by as much as 50% during GERD filling, while it will be improved during GERD operation as a result of river flow regulation caused by GERD when the dam comes online.
- Hydropower generation in Ethiopia will increase by 360% during GERD operation, and GERD will add an average of 15,000 GWh/year.
- The annual Nile flows at Dongola will be impacted by GERD operation. The annual river flows below the level of 59 km^3 will be slightly increased compared to the case without GERD due to improved low flows following GERD regulation.
- The GERD could present an opportunity for cooperation among the riparian countries, especially during dry periods by releasing water to meet downstream demands. A potential coordinated policy among the system reservoirs could help to alleviate the risks during low flows and dry periods.
- The results presented here suggest further research regarding dynamic filling approaches by adopting higher fill polices during wet years and lower fill policies during dry years.
- The developed model in this work can be coupled to forecasting tools and assist in implementing dynamic filling strategies of the GERD.
- Another novel aspect developed in this work is that the impact of external and internal drivers of change on the nexus can be evaluated using the integrated simulation model. For example, the impact of GERD development (external factor) and the impact of population growth (internal factor) on the nexus dynamics in Egypt as discussed in chapter (4).

The full WFE nexus model in Egypt is employed to explore the impacts of policy choices on the WFE nexus at the national level (Objective 3). A set of sectoral policy measures were identified, e.g., improving irrigation efficiency and utilising potential water resources, improving land productivity and population growth. The impacts of each policy measure and different combinations of policy measures were quantified. Simulation results demonstrate that:

- Improving irrigation efficiency could increase average food production by 13%, irrigation supply reliability by 5% and energy demand in the agricultural sector by 14%. Food imports could be reduced on average by 10% and water shortages by 54%.

- Reducing the domestic water consumption rates could reduce average water and energy consumption in the domestic water sector by approximately 15%, water shortage by 15% and food imports by about 2%.
- Utilising unconventional water resources potentials could increase average food production by approximately 9%, irrigation supply reliability by 6%, while reducing food imports by 6% and water shortage by 38%. However, average energy demands in the domestic water sector could increase by 46%.
- Expansion in groundwater resources could increase on average food production by 2.8%, irrigation supply reliability by 1.7% and energy demand in the agricultural sector by 6.8%. Average water shortage would reduce by about 16% and food imports by 2.8%.
- Achieving potential crop yields could increase food production by 40% and energy demand in the agricultural sector by 17%, while reducing food imports by 32%.
- Continuation of land reclamation plans and utilising water resources potentials indicated an increase in average food production by 11%, in irrigation supply reliability by 7% and in energy demand in the domestic water sector by 46% and in the agricultural sector by 7%.
- The integrated simulation model can be used as a policy tool to assist decision makers, stakeholders and researchers to better understand the critical links among the nexus domains and other related critical issues. Furthermore, it can be used to reduce trade-offs and promote synergies among different sectors and increase resource use efficiency.
- Future national plans and strategies can substantially benefit from the work presented here. For instance, results discussed in this work suggest to give policies of improving land productivity and irrigation efficiency priority over polices of land expansion and developing new water resources. The integrated model can thus provide policy guidance and cross-sectoral management and integration at the national level.

The cooperation of the riparian countries and unilaterally motivated policies were investigated for the case of GERD development (Objective 4). The two actions were considered combined with three varying demand conditions in Egypt (1- constant demands, 2- increased demands and 3- increased demands with water resources management policies) and with various options for the operation of the Sudanese reservoirs. Results demonstrate that:

- The integrated simulation model provides a procedure to translate cooperation in shared river basin on the ground by considering joint operation of multi-reservoir systems. Furthermore, the model allows for considering dynamically varying demands in riparian countries as considered in this work for Egypt.
- Cooperation among the riparian countries over GERD could substantially alleviate the risks associated with dry years, especially prolonged droughts.
- The first and third demand scenarios suggest that:
    1. For an average year:
        1.1. The GERD has a little to negligible impacts on the WFE nexus in Egypt for both cooperation and unilateral states.
        1.2. Sudan will have more benefits in the cooperation scenario than in the unilateral scenario (i.e., increased in hydropower generation and improved water supplies) as a result of regulation of river flows offered by GERD.
        1.3. The average hydropower generation in Ethiopia – in particular GERD hydropower – will not be largely affected in cooperation state.
    2. Risks to Egypt in dry years (e.g., water shortages and food production loss) can be substantially reduced if the riparian countries agree to cooperate and sacrifice for some loss, such as hydropower generation reduction, particularly during severe droughts. For example, the maximum water shortage in Egypt will be substantially reduced in the cooperation state with negligible impacts on Sudan and Ethiopia.
    3. The Sudanese water supplies will not be impacted by the GERD operation modes. However, hydropower generation in dry periods may experience further drop, in cooperation conditions, but with less than a 1% chance.
    4. The Ethiopian hydropower generation will not be significantly impacted by cooperation conditions during dry years. However, hydropower generation in Ethiopia may experience a further drop during droughts, but with a likelihood of 1% to occur.
- The second demand condition in Egypt shows that:

1. In cooperation state, regular releases from GERD to balance the increased downstream demands are likely to substantially impact the WFE nexus in the basin and prolong the drought period.
2. Average food production, hydropower generation and water supply in Egypt have improved in cooperation state. On the other hand, average hydropower generation in Ethiopia are likely to reduce by 4-10%. In Sudan, average results of hydropower generation and water supply are not changed in this case.
3. This scenario demonstrates the limitation of cooperation among the riparian countries. For instance, excessive downstream demands are likely to increase the risk of increasing the drought periods in the basin and significantly affect the WFE nexus in the basin.

- The comparison between the second and the third scenarios indicates that the cooperation among riparian countries depends on the commitment and the success of implementing policies in Egypt to balance the growing demands and the willingness of Ethiopia to cooperate and release additional flows to Egypt when needed.
- The results of the third demand condition are conditional on the success of implementing the policy measures in Egypt. However, the difference between the results in second and third demand scenarios show the potential gains across regions that can be achieved through simultaneous actions, i.e., policy implementation in Egypt and willing of Ethiopia and Sudan to cooperate.
- Modelling results show that a high level of coordination, commitment and trust among the riparian countries are urgently required to achieve the cooperation benefits.

Another novel aspect considered in this work is to account for climate change impacts in the nexus framework. In this work, basin-wide synthetic streamflow series were generated based on basin-wide streamflow of river tributaries under four GCM of two RCPs: RCP 4.5 and RCP 8.5. The two RCPs scenarios represent the hydrological conditions in the basin by 2050. Planned infrastructure projects and climate change were considered by a number of plausible development scenarios – including hydropower and irrigation expansion projects in the basin (Objective 5). The integrated simulation model was driven by basin-wide stochastically generated stream flows with and without climate change to explore the future of WFE nexus in the basin.

- Key results from the model simulations in the case without climate change indicate that:
    1. Planned hydropower projects in the basin will regulate river flows, e.g., Blue Nile regulation following GERD operation and will have insignificant changes in volumes of annual river flows.
    2. Hydropower projects currently under construction in the basin, once completed will add approximately 18 TWh/year (mainly from the GERD). Furthermore, planned hydropower projects will add over 16 TWh/year once operational.
    3. Irrigation expansion projects in the upstream countries could reduce hydropower generation in the basin by approximately 6%.
    4. HAD releases will be slightly reduced under planned hydropower projects, however, increased irrigation abstraction in the upstream countries will reduce water withdrawals in Egypt by 10%.
    5. Average annual HAD releases are expected to be close to Egypt's annual Nile quota under all development.
- The WFE nexus is impacted by climate change in the basin in general and by the climate model in particular. Simulation results under climate change demonstrate that:
    1. The climate models of the RCP 8.5 indicated large uncertainties and changes in future river flows compared to climate models of the RCP 4.5.
    2. Average annual River flows are generally reduced in the RCP 4.5, unlike the climate models of RCP 8.5, which showed a wide range of change in river flows with a clear signal of change: one model showed significant reductions in average annual river flows and the other model showed an increase in average annual river flows.
    3. The annual river runoff is reduced by 14% under upstream irrigation expansion projects with no climate change, while it is reduced by 7% in the RCP 4.5, and shows a wider range of change from -40% to +33% in the RCP 8.5.

4. Following changes in river flow under climate change, hydropower generation and food production in the basin will be impacted in a similar way with varying degrees of change in sub-basins.
5. The inclusion of climate change in the proposed nexus framework calls for integrated infrastructure planning and management in river basins, could assists in transboundary negotiations and improve management policies across scales, regions and sectors.

- Improving irrigation efficiency in the basin demonstrated insignificant impacts on the river flows and hydropower generation in the basin but showed significant effects on food production from irrigated agriculture.
- Improving land productivity and irrigation efficiency in the basin would improve food production by more than 60%.
- The inclusion of the socio-economic drivers in the framework is another novel aspect considered in this work that assist in improving our understanding of their impacts on the WFE nexus. Simulation results from the full application of the WFE nexus in Egypt indicate a continued growth of food imports as a result of population growth.
- Food imports in Egypt are likely to increase due to a reduction in domestic food production as a result of planned upstream developments and/or climate change.
- Improving land productivity could significantly reduce food imports by 15-37%, depending on climate conditions.
- The obtained results stress the urgent need for increasing land productivity, introducing crop varieties and water management policies to sustain food production in the face of water shortage as a result of climate change and planned infrastructure projects in the basin.

At the general level, the novel approach considered in this work exploits the use of Systems Thinking method and contributes to the growing body of research that seeks to develop and diversify comprehensive frameworks and tools to better understand and quantify the nexus. The approach combines both quantitative and qualitative methods. The developed novel simulation model is beneficial and can be used in transboundary negotiations, policy analysis, promoting for cross-sectoral and cross-regional management, enhancing cooperation and trust among riparian countries. The nexus studies are case-specific, however, the modelling approach can be implemented to other river systems with adjustments to each case study. This, however, can assist in scaling up the finding from each case study from local to global scales and knowledge transfer from one region to other regions.

8.3 Future Work

The added value of the nexus, i.e., explicit multi-sectoral integration, favours the nexus over conventional integrated approaches e.g., integrated water resources management (IWRM). Holistic tools and frameworks are required to assess the WFE nexus interdependencies and their interactions with other actors and drivers of change, e.g., population growth and climate change. This study develops a novel tool to quantify the nexus and improve coordination across sectors, interested stakeholders and policymakers. However, the modelling framework presented here has limitations and can be extended in the future to overcome these shortcomings and improve our understanding of the nexus. Possible future research directions include:

- The work presented here through the case study of the Nile river basin does not include food production from rain-fed agriculture in the basin. Soil and rainfall components can be incorporated into the model to capture the soil-water interactions and assess the impacts of hydrological conditions on the rain-fed agriculture in the basin.
- Improving land productivity showed promising outcomes to boost food production in the basin. Future work can be directed to assess the impacts of improving land productivity – for both irrigated and rainfed agriculture – on food production in the basin, hence improving food security and alleviating poverty in the basin.
- Socio-economic drivers and food consumption in riparian countries outside Egypt were not included in this study. Future work should include these components to better understand the socio-economic dynamics and their impacts on the nexus in the entire Nile basin.
- Climate change was considered here in a broad context by considering a wider range of climate change scenarios, i.e., use of two extreme climate

models (a driest and a wettest model). However, multiple GCM and other RCPs should be used to better understand and assess climate change impacts on the WFE nexus in the Nile basin.

- Climate change impacts on water demands especially the agricultural sector should be incorporated in future work since evaporative demands of crops are likely to increase with projected rising temperatures in the Nile basin.
- Reservoir sedimentation and its impacts on reservoirs' capacity in the basin was not included here. This can be incorporated to assess its impacts on existing and planned reservoirs in the basin.
- Water quality is an important issue that has not been addressed in this work. Future work would benefit from including water quality in the framework and assess the interactions between the nexus domains and rivers ecosystem. Water quality issues include agriculture drainage water, and domestic and industrial wastewater returns to fresh water bodies as well as pollutants from energy industry such as fossil fuel extractions and oil refinery industry.
- The environmental impacts of planned reservoirs in the basin were not assessed in this research and can be included in future research.
- The framework developed in this thesis can be further tested-while covering the above – suggested research directions – in other river systems, such as Amazon river system, Amu Darya river system, Mekong river system, Tigris-Euphrates river system and Niger River system.

REFERENCES

Abdelhaleem, F. S. and Helal, E. Y. (2015). "Impacts of Grand Ethiopian Renaissance Dam on Different Water Usages in Upper Egypt." British Journal of Applied Science & Technology 8(5), 461-483.

Abdelkader, A., Elshorbagy, A., Tuninetti, M., Laio, F., Ridolfi, L., Fahmy, H. and Hoekstra, A. Y. (2018). "National water, food, and trade modeling framework: The case of Egypt." Science of the total environment 639, 485-496.

Abdin, A. E. l. and Gaafar, I. (2009). "Rational water use in Egypt." Technological perspectives for rational use of water resources in the Mediterranean region 88, 11-27.

Aboelata, M. (1998). "Object-oriented modeling framework for water resources policy analysis". Secondary "Object-oriented modeling framework for water resources policy analysis". Manitoba, University of Manitoba. Master.

Abu-Zeid, M. (1992). "Water resources assessment for Egypt." Canadian Journal of Development Studies/Revue canadienne d'études du développement 13(4), 173-194.

Abu-Zeid, M. (2003). "Adopted measures to face major challenges in the Egyptian water sector". Country report presented at the 3rd World Water Forum, Japan.

Ahmad, S. and Prashar, D. (2010). "Evaluating municipal water conservation policies using a dynamic simulation model." Water Resources Management 24(13), 3371-3395.

Ahmad, S. and Simonovic, S. P. (2000). "System dynamics modeling of reservoir operations for flood management." Journal of Computing in Civil Engineering 14(3), 190-198.

Al-Riffai, P., Breisinger, C., Mondal, Md. H. A., Ringler, C., Wiebelt, M. and Zhu, T. (2017). "Linking the economics of water, energy, and food: A nexus modeling approach." MENA RP Working Paper 4. Washington, DC and Cairo, Egypt.

Albrecht, T. R., Crootof, A. and Scott, C. A. (2018). "The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment." Environmental Research Letters 13(4), 043002.

Allam, M. and Eltahir, E. (2019). "Water-Energy-Food Nexus Sustainability in the Upper Blue Nile (UBN) Basin." Frontiers in Environmental Science 7(5).

Allam, M. N. and Allam, G. I. (2007). "Water Resources In Egypt: Future Challenges and Opportunities." Water International 32(2), 205-218.

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998). "FAO Irrigation and drainage paper No. 56 Crop Evapotranspiration (guidelines for computing crop water requirements)". Secondary "FAO Irrigation and drainage paper No. 56 Crop Evapotranspiration (guidelines for computing crop water requirements)". Food and Agriculture Organization of the United Nations, Rome, Italy. 56.

Andreu, J., Capilla, J. and Sanchís, E. (1996). "AQUATOOL, a generalized decision-support system for water-resources planning and operational management." Journal of Hydrology 177(3), 269-291.

Arjoon, D., Mohamed, Y., Goor, Q. and Tilmant, A. (2014). "Hydro-economic risk assessment in the eastern Nile River basin." Water Resources and Economics 8, 16-31.

Aurecon (2012). "Synthesis report: Integrated Nile Basin, Report for Water Resource Planning and Management Project". Secondary "Synthesis report: Integrated Nile Basin, Report for Water Resource Planning and Management Project", Nile Basin Initiative, Entebbe, Uganda.

Awulachew, S. B. (2012). "The Nile River Basin: water, agriculture, governance and livelihoods", Routledge.

Awulachew, S. B., Yilma, A. D., Loulseged, M., Loiskandl, W., Ayana, M. and Alamirew, T. (2007). "Water resources and irrigation development in Ethiopia", Iwmi.

Bakhshianlamouki, E., Masia, S., Karimi, P., van der Zaag, P. and Sušnik, J. (2019). "A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia Lake Basin, Iran." Science of The Total Environment.

Barlas, Y. (1989). "Multiple tests for validation of system dynamics type of simulation models." European journal of operational research 42(1), 59-87.

Barnes, J. (2017). "The future of the Nile: climate change, land use, infrastructure management, and treaty negotiations in a transboundary river basin." Wiley Interdisciplinary Reviews: Climate Change 8(2), e449.

Basheer, M., Wheeler, K. G., Ribbe, L., Majdalawi, M., Abdo, G. and Zagona, E. A. (2018). "Quantifying and evaluating the impacts of cooperation in transboundary river basins on the Water-Energy-Food nexus: The Blue Nile Basin." Sci Total Environ 630, 1309-1323.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, S. J. and Yumkellaa, K. K. (2011). "Considering the energy, water and food nexus: Towards an integrated modelling approach." Energy Policy 39(12), 7896-7906.

Beck, Michael Bruce and Villarroel Walker, Rodrigo (2013). "On water security, sustainability, and the water-food-energy-climate nexus." Frontiers of Environmental Science & Engineering 7(5), 626-639.

Behzadian, K., Kapelan, Z., Govindarajan, V., Brattebø, H. and Sægrov, S. (2014). "WaterMet2: a tool for integrated analysis of sustainability-based performance of urban water systems."

Belachew, A. and Mekonen, Z. (2014). "Eastern Nile Basin Water System Simulation Using Hec-ResSim Model". Secondary "Eastern Nile Basin Water System Simulation Using Hec-ResSim Model". CUNY Academic Works.

Benson, David, Gain, Animesh K and Rouillard, Josselin J (2015). "Water governance in a comparative perspective: From IWRM to a'nexus' approach?" Water Alternatives 8(1).

Bessler, F. T., Savic, D. and Walters, G. (2003). "Water Reservoir Control with Data Mining." Journal of Water Resources Planning and Management 129(1), 26-34.

Beyene, T., Lettenmaier, D. P. and Kabat, P. (2010). "Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios." Climatic change 100(3-4), 433-461.

Blackmore, D. and Whittington, D. (2008). "Opportunities for cooperative water resources development on the Eastern Nile: risks and rewards". Secondary "Opportunities for cooperative water resources development on the Eastern Nile: risks and rewards".

Block, P. J. (2006). "Integrated management of the Blue Nile Basin in Ethiopia: Precipitation forecast, hydropower, and irrigation modeling". Secondary "Integrated management of the Blue Nile Basin in Ethiopia: Precipitation forecast, hydropower, and irrigation modeling". Available from ProQuest Dissertations & Theses Global., University of Colorado.

Block, P. J. (2007). "Integrated management of the Blue Nile Basin in Ethiopia: hydropower and irrigation modeling". Secondary "Integrated management of the Blue Nile Basin in Ethiopia: hydropower and irrigation modeling".

Block, P. and Strzepek, K. (2010). "Economic analysis of large-scale upstream river basin development on the Blue Nile in Ethiopia considering transient conditions, climate variability, and climate change." Journal of Water Resources Planning and Management 136(2), 156-166.

Blum, A. G., Zaitchik, B., Alexander, S., Wu, S., Zhang, Y., Shukla, S., Alemneh, T. and Block, P. (2019). "A Grand Prediction: Communicating and Evaluating 2018 Summertime Upper Blue Nile Rainfall and Streamflow Forecasts in Preparation for Ethiopia's New Dam." Frontiers in Water 1(3).

Bonabeau, Eric (2002). "Agent-based modeling: Methods and techniques for simulating human systems." Proceedings of the National Academy of Sciences 99(suppl 3), 7280-7287.

Booij, M. J., Tollenaar, D., van Beek, E. and Kwadijk, J. C. J. (2011). "Simulating impacts of climate change on river discharges in the Nile basin." Physics and Chemistry of the Earth, Parts A/B/C 36(13), 696-709.

Borgomeo, E., Farmer, C. L. and Hall, J. W. (2015). "Numerical rivers: A synthetic streamflow generator for water resources vulnerability assessments." Water Resources Research 51(7), 5382-5405.

Brown, C. M., Lund, J. R., Cai, X., Reed, P. M., Zagona, E. A., Ostfeld, A., Hall, J, Characklis, G. W., Yu, W and Brekke, L. (2015). "The future of water resources systems analysis: Toward a scientific framework for sustainable water management." Water Resources Research 51(8), 6110-6124.

CAAES, Central Administration for Agricultural Extension Services (2017). Accessed May 17, 2017. http://www.caae-eg.com/.

Cai, X., Ringler, C. and Rosegrant, M. W. (2006). "Modeling Water Resources Management at the Basin Level: Methodology and Application to the Maipo River Basin". Secondary "Modeling Water Resources Management at the Basin Level: Methodology and Application to the Maipo River Basin", International Food Policy Research Institute, Washington DC (2006).

Cai, X., Wallington, K., Shafiee-Jood, M. and Marston, L. (2018). "Understanding and managing the food-energy-water nexus – opportunities for water resources research." Advances in Water Resources 111, 259-273.

CAPMAS, Central Agency for Public Mobilization and Statistics (Various years-a). "Agricultural Machinery and Equipment". Secondary "Agricultural Machinery and Equipment". Cairo, Egypt.

CAPMAS, Central Agency for Public Mobilization and Statistics (Various years-b). "Annual Bulletin of Irrigation and Water Resources Statistics". Secondary "Annual Bulletin of Irrigation and Water Resources Statistics". Cairo, Egypt.

CAPMAS, Central Agency for Public Mobilization and Statistics (Various years-c). "Annual Bulletin of Statistical Crop Area and Plant Production". Secondary "Annual Bulletin of Statistical Crop Area and Plant Production". Cairo, Egypt.

CAPMAS, Central Agency for Public Mobilization and Statistics (Various years-d). "Statistical Yearbook". Secondary "Statistical Yearbook". Cairo, Egypt.

CEDARE, Centre for Environment and Development for the Arab Region and Europe (2011). "Water use efficiency and economic approach National study Egypt". Secondary "Water use efficiency and economic approach National study Egypt". Cairo, Egypt.

Celeste, A. B. and Billib, M. (2009). "Evaluation of stochastic reservoir operation optimization models." Advances in Water Resources 32(9), 1429-1443.

Cervigni, R., Liden, R., Neumann, J. E. and Strzepek, K. M (2015). "Enhancing the Climate Resilience of Africa's Infrastructure: the Power and Water Sectors", The World Bank.

Cherre, S (2006). "Irrigation policies, strategies and institutional support conditions in Ethiopia". Best practices and technologies for small scale agricultural water management in Ethiopia. Proceedings of a MoARD/MoWR/USAID/IWMI Symposium and Exhibition held at Ghion Hotel, Addis Ababa, Ethiopia, 7-9 March, 2006., IWMI.

Clarke, R. T. (1973). "Mathematical Models in Hydrology, Irrigation and Drainage Paper 19." FAO, Rome, Italy.

Conway, D. (2005). "From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile basin." Global Environmental Change 15(2), 99-114.

Crooks, A. T. and Heppenstall, A. J. (2012). "Introduction to agent-based modelling". Agent-based models of geographical systems, Springer: 85-105.

Daccache, A., Ciurana, J. S., Rodriguez Diaz, J. A. and Knox, J. W. (2014). "Water and energy footprint of irrigated agriculture in the Mediterranean region." Environmental Research Letters 9(12), 124014.

Daher, B. T. and Mohtar, R. H. (2015). "Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making." Water International 40(5-6), 748-771.

Dai, S., Li, L., Xu, H., Pan, X. and Li, X. (2013). "A system dynamics approach for water resources policy analysis in arid land: a model for Manas River Basin." Journal of Arid Land 5(1), 118-131.

De Stercke, S., Mijic, A., Buytaert, W. and Chaturvedi, V. (2018). "Modelling the dynamic interactions between London's water and energy systems from an end-use perspective." Applied Energy 230, 615-626.

de Strasser, L., Lipponen, A., Howells, M., Stec, S. and Bréthaut, C. (2016). "A methodology to assess the water energy food ecosystems nexus in transboundary river basins." Water 8(2), 59.

Derbew, D (2013). "Ethiopia's Renewable Energy Power Potential and Development Opportunities." available from https://www.ctc-n.org/sites/www.ctc-n.org/files/resources/africa_cec_session_3_ministry_of_water_and_energy_ethiopia_beyene_220613_0.pdf.

Di Baldassarre, G., Elshamy, M., van Griensven, A., Soliman, E., Kigobe, M., Ndomba, P., Mutemi, J., Mutua, F., Moges, S. A., Xuan, Y., Solomatine, D. and Uhlenbrook, S. (2011). "Future hydrology and climate in the River Nile basin: a review." Hydrological Sciences Journal 56(2), 199-211.

Digna, R. F., Castro-Gama, M. E., Van der Zaag, P, Mohamed, Y A., Corzo, G and Uhlenbrook, S (2018a). "Optimal Operation of the Eastern Nile System Using Genetic Algorithm, and Benefits Distribution of Water Resources Development." Water 10(7), 921.

Digna, R. F., Mohamed, Y. A., van der Zaag, P., Uhlenbrook, S., van der Krogt, W. and Corzo, G. (2018b). "Impact of water resources development on water availability for hydropower production and irrigated agriculture of the eastern Nile basin." Journal of Water Resources Planning and Management 144(5), 05018007.

Djordjević, S., Prodanović, D. and Maksimović, Č (1999). "An approach to simulation of dual drainage." Water Science and Technology 39(9), 95-103.

Donia, N. (2013). "Aswan High Dam Reservoir management system." Journal of Hydroinformatics 15(4), 1491-1510.

Duckstein, L. and Opricovic, S. (1980). "Multiobjective optimization in river basin development." Water Resources Research 16(1), 14-20.

El-Din, M. M. N. (2013). "Proposed Climate Change Adaptation Strategy for the Ministry of Water Resources & Irrigation in Egypt". Secondary "Proposed Climate Change Adaptation Strategy for the Ministry of Water Resources & Irrigation in Egypt", UNESCO-Cairo Office.

El-Hefnawi, A. (2005). "Protecting agricultural land from urbanization or managing the conflict between informal urban growth while meeting the demands of the communities". Third Urban Research Symposium on Land Development, Urban Policy and Poverty Reduction, Brasilia, Brazil, World Bank Institute of Applied Economic Research (IPEA) Brasilia, DF, Brazil.

El Gafy, I., Grigg, N. and Reagan, W. (2017). "Dynamic behaviour of the water–food–energy Nexus: focus on crop production and consumption." Irrigation and Drainage 66(1), 19-33.

El Hattab, M. H., Theodoropoulos, G., Rong, X. and Mijic, A. (2020). "Applying the Systems Approach to Decompose the SuDS Decision-Making Process for Appropriate Hydrologic Model Selection." Water 12(3), 632.

El Tahlawi, M. R., Farrag, A. A. and Ahmed, S. S. (2008). "Groundwater of Egypt: "an environmental overview"." Environmental geology 55(3), 639-652.

Elarabawy, M., Attia, B. and Tosswell, P. (1998). "Water resources in Egypt: strategies for the next century." Journal of water resources planning and management 124(6), 310-319.

Elsayed, S. M., Hamed, K., Asfaw, G., Seleshi, Y., Ahmed, A. E., Deyab, D. H., Yon, B., Roe, J. D. M., Failer, E. and Basson, T. (2013). "International Panel of Experts (IPoE) on Grand Ethiopian Renaissance Dam Project (GERDP)." Addis Ababa, Ethiopia.

Elshamy, M. E., Seierstad, I. A. and Sorteberg, A. (2009). "Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios."

Endo, A., Burnett, K., Orencio, P., Kumazawa, T., Wada, C., Ishii, A., Tsurita, I. and Taniguchi, M. (2015). "Methods of the water-energy-food nexus." Water 7(10), 5806-5830.

Endo, A., Tsurita, I., Burnett, K. and Orencio, P. M. (2017). "A review of the current state of research on the water, energy, and food nexus." Journal of Hydrology: Regional Studies 11, 20-30.

ENHC, Egyptian National Hydrologic Committee (2013). "A report about the potential of the groundwater and priorities of its use in the light of excessive abstraction [In Arabic]". Secondary "A report about the potential of the groundwater and priorities of its use in the light of excessive abstraction [In Arabic]". Cairo, Egypt.

ENTRO, Eastern Nile Technical Regional Office (2009). "Eastern Nile Irrigation and Drainage Study, Component 1, Phase 1, Main Report ". Secondary "Eastern Nile Irrigation and Drainage Study, Component 1, Phase 1, Main Report ". Eastern Nile Technical Regional Office (ENTRO), Addis Ababa, Ethiopia.

FAO (2014). "The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture". Secondary "The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture". Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO (2020). "FAOSTAT database." Food and Agriculture Organization of the United Nations. Accessed January 20, 2020. http://www.fao.org/faostat/en/#data.

Farmani, R., Savic, D. and Walters, G. (2005). "Evolutionary multi-objective optimization in water distribution network design." Engineering Optimization 37(2), 167-183.

Ferroukhi, R., Nagpal, D., Lopez-Peña, A., Hodges, T., Mohtar, R. H., Daher, B., Mohtar, S. and Keulertz, M. (2015). "Renewable energy in the water, energy & food nexus." IRENA, Abu Dhabi.

Fiering, M. B., Bund, B. and Jackson, B. B. (1971). "Synthetic streamflows", American Geophysical Union.

Fiering, Myron B (1964). "Multivariate technique for synthetic hydrology." Journal of the Hydraulics Division 90(5), 43-60.

Foran, T (2015). "Node and regime: Interdisciplinary analysis of water-energy-food nexus in the Mekong region." Water Alternatives 8(1), 655-674.

Forrester, J. W. (1997). "Industrial dynamics." Journal of the Operational Research Society 48(10), 1037-1041.

Fulp, T. and Harkins, J. (2001). "Policy Analysis Using RiverWare: Colorado River Interim Surplus Guidelines". Bridging the Gap: 1-10.

Garrote, L., Martin-C., Francisco, Flores-Montoya, F. and Iglesias, A. (2007). "Linking Drought Indicators to Policy Actions in the Tagus Basin Drought Management Plan." Water Resources Management 21(5), 873-882.

Gassman, P. W., Reyes, M. R, Green, C. H and Arnold, J. G (2007). "The soil and water assessment tool: historical development, applications, and future research directions." Transactions of the ASABE 50(4), 1211-1250.

Georgakakos, A. P. (2006). "Decision Support Systems for water resources management: Nile Basin applications and further needs". CPWF: Proceedings of the Working conference Nazareth, Ethiopia.

Gerber, A. (2015). "Agricultural Theory in System Dynamics". Secondary "Agricultural Theory in System Dynamics", System Dynamics Society.

Goor, Q., Halleux, C., Mohamed, Y. A. and Tilmant, A. (2010). "Optimal operation of a multipurpose multireservoir system in the Eastern Nile River Basin." Hydrology and Earth System Sciences 14(10), 1895-1908.

Guariso, G. and Whittington, D. (1987). "Implications of Ethiopian water development for Egypt and Sudan." International Journal of Water Resources Development 3(2), 105-114.

Guillaume, J, Kummu, M, Eisner, S and Varis, O (2015). "Transferable principles for managing the nexus: Lessons from historical global water modelling of central Asia." Water 7(8), 4200-4231.

Haberlandt, U., Hundecha, Y., Pahlow, M. and Schumann, A. H. (2011). "Rainfall generators for application in flood studies". In: Schumann A. (eds) Flood Risk Assessment and Management, Springer: 117-147.

Hagos, T. (2017). "Ethiopia: GERD Generation Capacity Increases to 6,450 MW". Secondary "Ethiopia: GERD Generation Capacity Increases to 6,450 MW".

Hamed, K. H. (2018). "Stochastic Investigation of the GERD-AHD Interaction Through First Impoundment and Beyond". In: Negm A, Abdel-Fattah S (eds) Grand Ethiopian Renaissance Dam Versus Aswan High Dam., Springer, Cham: 95-117.

Hefny, K., Farid, M. S. and Hussein, M. (1992). "Groundwater assessment in Egypt." International Journal of Water Resources Development 8(2), 126-134.

Herman, J. D., Zeff, H. B., Lamontagne, J. R., Reed, P. M. and Characklis, G. W. (2016). "Synthetic drought scenario generation to support bottom-up water supply vulnerability assessments." Journal of Water Resources Planning and Management 142(11), 04016050.

Hilhorst, B., Balikuddembe, W. O., Thuo, S. and Schütte, P. (2011a). "Food for Thought in the Nile Basin for 2030". Secondary "Food for Thought in the Nile Basin for 2030". The Food and Agriculture Organization of the United Nations, Rome, Italy.

Hilhorst, Bart, Balikuddembe, William Odinga, Thuo, Simon and Schütte, Peter (2011b). "Food for Thought in the Nile Basin for 2030". Secondary "Food for Thought in the Nile Basin for 2030", FAO, Rome.

Hilly, G., Vojinovic, Z., Weesakul, S., Sanchez, A., Hoang, D. N., Djordjevic, S., Chen, A. S. and Evans, B. (2018). "Methodological Framework for Analysing Cascading Effects from Flood Events: The Case of Sukhumvit Area, Bangkok, Thailand." Water 10(1), 81.

Hoff, H. (2011). "Understanding the Nexus: Background paper for the Bonn2011 Nexus Conference". Secondary "Understanding the Nexus: Background paper for the Bonn2011 Nexus Conference". Bonn, Germany, Stockholm Environment Institute (SEI).

Howell, P. and Allan, J. (eds) (1994). "The Nile: Sharing a Scarce Resource: A Historical and Technical Review of Water Management and of Economical and Legal Issues", Cambridge University Press.

Hussey, Karen and Pittock, Jamie (2012). "The energy-water nexus: Managing the links between energy and water for a sustainable future."

Hyun, J. Y., Huang, S. Y., Yang, Y. C. E., Tidwell, V. and Macknick, J. (2019). "Using a coupled agent-based modeling approach to analyze the role of risk perception in water management decisions." Hydrol. Earth Syst. Sci. 23(5), 2261-2278.

ICARDA&AUSAID (2011). "Water and Agriculture in Egypt". Secondary "Water and Agriculture in Egypt". Cairo, Egypt, International Center for Agricultural Research in the Dry Areas (ICARDA) and Australian Government (AUSID).

ICID, International Commission on Irrigation and Drainage (2004). "Background Report On Application of Country Policy Support Program (CPSP) for Egypt (2004)". Secondary "Background Report On Application of Country Policy Support Program (CPSP) for Egypt (2004)". Cairo Egypt.

isee systems, inc. (2019). "Stella® Architect." Accessed May 17, 2019. https://bit.ly/2LkICEy.

Jalilov, S. M., Keskinen, M., Varis, O., Amer, S. and Ward, F. A. (2016). "Managing the water–energy–food nexus: Gains and losses from new water development in Amu Darya River Basin." Journal of Hydrology 539, 648-661.

Jayakrishnan, R., Srinivasan, R, Santhi, C and Arnold, JG (2005). "Advances in the application of the SWAT model for water resources management." Hydrological Processes: An International Journal 19(3), 749-762.

Jeuland, Marc (2010). "Economic implications of climate change for infrastructure planning in transboundary water systems: An example from the Blue Nile." Water resources research 46(11).

Kahsay, T. N., Kuik, O., Brouwer, R. and van der Zaag, P. (2015). "Estimation of the transboundary economic impacts of the Grand Ethiopia Renaissance Dam: A computable general equilibrium analysis." Water Resources and Economics 10, 14-30.

Kapelan, Z S., Savic, D. and Walters, G. (2005a). "Multiobjective design of water distribution systems under uncertainty." Water Resources Research 41(11).

Kapelan, Zoran S., Savic, Dragan A. and Walters, Godfrey A. (2005b). "Multiobjective design of water distribution systems under uncertainty." Water Resources Research 41(11).

Karimi, P., Qureshi, A. S., Bahramloo, R. and Molden, D. (2012). "Reducing carbon emissions through improved irrigation and groundwater management: A case study from Iran." Agricultural water management 108, 52-60.

Karyabwite, D. R. (2000). "Water sharing in the Nile River valley." Project GNV011: Using GIS/Remote Sensing for the sustainable use of natural resources. United Nations Environment Programme, Nairobi.

Keith, B., Enos, J, Garlick, C. B., Simmons, G., Copeland, D. and Cortizo, M (2013). "Limits to population growth and water resource adequacy in the Nile River Basin, 1994–2100".

Keith, B., Ford, D. N. and Horton, R. (2017). "Considerations in managing the fill rate of the Grand Ethiopian Renaissance Dam Reservoir using a system dynamics approach." The Journal of Defense Modeling and Simulation 14(1), 33-43.

Keskinen, M., Guillaume, J., Kattelus, M., Porkka, M., Räsänen, T. and Varis, O. (2016). "The water-energy-food nexus and the transboundary context: insights from large Asian rivers." Water 8(5), 193.

Keskinen, M., Someth, P., Salmivaara, A. and Kummu, M. (2015). "Water-energy-food nexus in a transboundary river basin: The case of Tonle Sap Lake, Mekong River Basin." Water 7(10), 5416-5436.

Keskinen, Marko and Varis, Olli (2016). "Water-energy-food nexus in large Asian river basins". Secondary "Water-energy-food nexus in large Asian river basins", Multidisciplinary Digital Publishing Institute.

Khan, H. F., Yang, Y.C., Xie, H. and Ringler, C. (2017). "A coupled modeling framework for sustainable watershed management in transboundary river basins." Hydrology and Earth System Sciences 21(12), 6275-6288.

Kibaroglu, A. and Gürsoy, S. I. (2015). "Water–energy–food nexus in a transboundary context: the Euphrates–Tigris river basin as a case study." Water International 40(5-6), 824-838.

Kim, U. and Kaluarachchi, J. J. (2009). "Climate Change Impacts on Water Resources in the Upper Blue Nile River Basin, Ethiopia 1." JAWRA Journal of the American Water Resources Association 45(6), 1361-1378.

King, Andrew and Block, Paul (2014). "An assessment of reservoir filling policies for the Grand Ethiopian Renaissance Dam." Journal of Water and Climate Change 5(2), 233-243.

Kollat, J. B., Reed, P. M. and Kasprzyk, J. R. (2008). "A new epsilon-dominance hierarchical Bayesian optimization algorithm for large multiobjective monitoring network design problems." Advances in Water Resources 31(5), 828-845.

Kossieris, P., Tsoukalas, I., Makropoulos, C. and Savic, D. (2019). "Simulating marginal and dependence behaviour of water demand processes at any fine time scale." Water 11(5), 885.

Kotir, J. H., Smith, C., Brown, G., Marshall, N. and Johnstone, R. (2016). "A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana." Science of the Total Environment 573, 444-457.

Koutsoyiannis, D. (2005). "Stochastic simulation of hydrosystems." Water Encyclopedia 3, 421-430.

Koutsoyiannis, D. and Economou, A. (2003). "Evaluation of the parameterization-simulation-optimization approach for the control of reservoir systems." Water Resources Research 39(6).

Kumar, M. D., Sivamohan, M. V. K. and Narayanamoorthy, A. (2012). "The food security challenge of the food-land-water nexus in India." Food Security 4(4), 539-556.

Lawford, Richard, Bogardi, Janos, Marx, Sina, Jain, Sharad, Wostl, Claudia Pahl, Knüppe, Kathrin, Ringler, Claudia, Lansigan, Felino and Meza, Francisco (2013). "Basin perspectives on the water–energy–food security nexus." Current Opinion in Environmental Sustainability 5(6), 607-616.

Lévite, H., Sally, H. and Cour, J. (2003). "Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model." Physics and Chemistry of the Earth, Parts A/B/C 28(20), 779-786.

Levy, B. S. and Baecher, G. B. (1999). "NileSim: A Windows-based hydrologic simulator of the Nile River Basin." Journal of water resources planning and management 125(2), 100-106.

Liu, J., Hull, V., Godfray, H. C. J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., Chung, M. G. and Sun, J. (2018). "Nexus approaches to global sustainable development." Nature Sustainability 1(9), 466.

Liu, J., Yang, H., Cudennec, C., Gain, A. K., Hoff, H., Lawford, R., Qi, J., Strasser, L. de, Yillia, P. T. and Zheng, C. (2017). "Challenges in operationalizing the water–energy–food nexus." Hydrological Sciences Journal 62(11), 1714-1720.

Maasho, A. (2019). "Ethiopia expects Nile dam to be ready to start operation in late 2020". Reuters. Reuters. Accessed May 17, 2019. https://uk.reuters.com/article/us-ethiopa-dam/ethiopia-expects-nile-dam-to-be-ready-to-start-operation-in-late-2020-idUSKCN1OX0T4

MacAlister, C., Pavelic, P. l., Tindimugaya, C., Ayenew, T., Ibrahim, M. E. and Meguid, M. A. (2012). "Overview of groundwater in the Nile River Basin."

Madani, K. and Mariño, M. A. (2009). "System dynamics analysis for managing Iran’s Zayandeh-Rud river basin." Water resources management 23(11), 2163-2187.

MALR (2009). "Sustainable Agricultural Development Strategy towards 2030". Secondary "Sustainable Agricultural Development Strategy towards 2030". Ministry of Agriculture and Land Reclamation, Egypt.

Matalas, N. C. (1967). "Mathematical assessment of synthetic hydrology." Water Resources Research 3(4), 937-945.

Matalas, N. C. and Wallis, J. R. (1971a). "Statistical properties of multivariate fractional noise processes." Water Resources Research 7(6), 1460-1468.

Matalas, NC and Wallis, JR (1971b). "Statistical properties of multivariate fractional noise processes." Water resources research 7(6), 1460-1468.

McCartney, M., Alemayehu, T., Easton, Z. M. and Awulachew, S. B. (2012). "Simulating current and future water resources development in the Blue Nile River Basin." The Nile River Basin: water, agriculture, governance and livelihoods. Routledge-Earthscan, Abingdon, 269-291.

Meadows, D. L., Behrens, W. W., Meadows, D. H., Naill, R. F., Randers, J. and Zahn, E. (1974). "Dynamics of growth in a finite world", Wright-Allen Press Cambridge, MA.

MEDIWR, Ministry of Eectricity, Dams, Irrigation & Water Resources (2015). "Irrigation Development Master Plan". Secondary "Irrigation Development Master Plan". The Republic of South Sudan.

MEDIWR, Ministry of Eectricity, Dams, Irrigation & Water Resources (2020). "Energy and Dams South Sudan." Accessed January 17, 2020. http://energyanddamsgoss.com/index.html.

Mejia, Angel Jm (1972). "On the generation of multivariate sequences exhibiting the Hurst phenomenon and some flood frequency analyses". Secondary "On the generation of multivariate sequences exhibiting the Hurst phenomenon and some flood frequency analyses". Colorado State University, Fort Collins, Colorado, Colorado State University, Fort Collins, Colorado. PH.D.

Mereu, S., Sušnik, J., Trabucco, A., Daccache, A., Vamvakeridou-Lyroudia, L., Renoldi, S., Virdis, A., Savić, D. and Assimacopoulos, D. (2016). "Operational resilience of reservoirs to climate change, agricultural demand, and tourism: a case study from Sardinia." Science of the Total Environment 543, 1028-1038.

MEWNR, Ministry of Environment, Water and Natural Resources (2013). "National Water Master Plan 2030". Secondary "National Water Master Plan 2030". Nairobi, Kenya.

MHUUC, Ministry of Housing, Utilities and Urban Communities (2010). "Egyptian Code for Design and Implementation of Pipelines for Drinking Water and Sewage Networks". Secondary "Egyptian Code for Design and Implementation of Pipelines for Drinking Water and Sewage Networks". Cairo, Egypt.

Ministry of Energy and Mineral Development (2011). "Master plan study on hydropower development". Secondary "Master plan study on hydropower development". The Republic of Uganda, Ministry of Energy and Mineral Development.

Mirchi, A., Madani, K., Watkins, D. and Ahmad, S. (2012). "Synthesis of system dynamics tools for holistic conceptualization of water resources problems." Water resources management 26(9), 2421-2442.

MIT, Massachusetts Institute of Technology (2014). "The Grand Ethiopian Renaissance Dam: An Opportunity for Collaboration and Shared Benefits in the Eastern Nile Basin". Secondary "The Grand Ethiopian Renaissance Dam: An Opportunity for Collaboration and Shared Benefits in the Eastern Nile Basin", Abdul Latif Jameel World Water and Food Security Lab, Massachusetts Institute of Technology, USA: 1-17.

Molle, F., Rap, E., Al-Agha, D. E., Zaki, N., El-Gamal, T., Hassan, W., Meleha, M., Yassa, E. and Ismail, A. (2013). "An exploratory survey of water management in the Meet Yazid Canal command area of the Nile Delta."

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. and Veith, T. L. (2007). "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations." Transactions of the ASABE 50(3), 885-900.

Muetzelfeldt, R. and Massheder, J. (2003). "The Simile visual modelling environment." European Journal of Agronomy 18(3-4), 345-358.

Mulat, A. G. and Moges, S. A. (2014). "Assessment of the impact of the Grand Ethiopian Renaissance Dam on the performance of the High Aswan Dam." Journal of Water Resource and Protection 6(06), 583.

Muñoz, G. and Grieser, J. (2006). "Climwat 2.0 for CROPWAT." Water Resources, Development and Management Service, 1-5.

MWRI, Ministry of Water Resources and Irrigation (2005). "Integrated Water Resources Management Plan". Secondary "Integrated Water Resources Management Plan", Cairo, Egypt.

MWRI, Ministry of Water Resources and Irrigation (2006). "Water for the Future: Summary of the National Water Resources Plan". Secondary "Water for the Future: Summary of the National Water Resources Plan", Cairo, Egypt.

MWRI, Ministry of Water Resources and Irrigation (2011). "Water Resources Development and Management Strategy up-to 2050 Horizon". Secondary "Water Resources Development and Management Strategy up-to 2050 Horizon". Cairo, Egypt.

Napoli, C. and Garcia-Tellez, B. (2016). "A framework for understanding energy for water." International Journal of Water Resources Development 32(3), 339-361.

Nazemi, A., Wheater, H. S., Chun, K. P. and Elshorbagy, A. (2013). "A stochastic reconstruction framework for analysis of water resource system vulnerability to climate-induced changes in river flow regime." Water Resources Research 49(1), 291-305.

NBI, Nile Basin Initiative (2007). "Eastern Nile Power Trade Project". Secondary "Eastern Nile Power Trade Project".

NBI, Nile Basin Initiative (2012). "State of the River Nile Basin 2012". Secondary "State of the River Nile Basin 2012".

NBI, Nile Basin Initiative (2016a). "Nile Basin Decision Support System". Secondary "Nile Basin Decision Support System", Entebbe, Uganda.

NBI, Nile Basin Initiative (2016b). "Nile Basin Water Resources Atlas". Secondary "Nile Basin Water Resources Atlas".

NBI, Nile Basin Initiative (2016c). "Technical Note IV, Future Scenario Definition and Summary of Results". Secondary "Technical Note IV, Future Scenario Definition and Summary of Results", Nile Basin Initiative, Entebbe, Uganda.

Negm, A., Elsahabi, M. and Tayie, M. S (2018). "An Overview of Aswan High Dam and Grand Ethiopian Renaissance Dam". Grand Ethiopian Renaissance Dam Versus Aswan High Dam, Springer: 3-17.

Null, S. E. and Lund, J. R. (2006). "Reassembling Hetch Hetchy: water supply without o'shaughnessy Dam." JAWRA Journal of the American Water Resources Association 42(2), 395-408.

NWRP, National Water Research Plan Project (2000). "Crop Water Use and Water Balance in the Nile System". Secondary "Crop Water Use and Water Balance in the Nile System". Cairo, Egypt.

Omar, M. E. M. and Moussa, A. M. A. (2016). "Water management in Egypt for facing the future challenges." Journal of Advanced Research 7(3), 403-412.

Ouarda, T. B. M. J., Labadie, J. W. and Fontane, D. G. (1997). "Indexed Sequential Hydrologic Modeling for Hydropower Capacity Estimation." JAWRA Journal of the American Water Resources Association 33(6), 1337-1349.

Ouda, S., Abd El-Latif, K. and Khalil, F. (2016a). "Water Requirements for Major Crops". Major Crops and Water Scarcity in Egypt, Springer: 25-32.

Ouda, Samiha, Farge, Hanan, Noreldin, Tahany and Taha, Ahmed (2016b). "Assessment of drip irrigation system for maize to reduce food, water and energy insecurity in Egypt". Secondary "Assessment of drip irrigation system for maize to reduce food, water and energy insecurity in Egypt". Aswan, Egypt.

Passell, H. D., Aamir, M. S., Bernard, M. L., Beyeler, W. E., Fellner, K. M., Hayden, N., Jeffers, R. F., Keller, E. J. K., Malczynski, L. A., Mitchell, M. D., Silver, E., Tidwell, V. C., Villa, D., Vugrin, E. D., Engelke, P., Burrow, M. and Keith, B. (2016). "Integrated Human Futures Modeling in Egypt". Secondary "Integrated Human Futures Modeling in Egypt", Sandia National Lab. (SNL-NM), Albuquerque, NM (United States).

Pittock, J., Dumaresq, D. and Bassi, A. M. (2016). "Modeling the hydropower–food nexus in large river basins: A mekong case study." Water 8(10), 425.

Plappally, A. K. and Lienhard V, J. H. (2012). "Energy requirements for water production, treatment, end use, reclamation, and disposal." Renewable and Sustainable Energy Reviews 16(7), 4818-4848.

Pyatkova, K, Chen, A. S., Butler, D., Vojinović, Z. and Djordjević, S. (2019). "Assessing the knock-on effects of flooding on road transportation." Journal of Environmental Management 244, 48-60.

Qin, H. P., Su, Q. and Khu, S. T. (2011). "An integrated model for water management in a rapidly urbanizing catchment." Environmental modelling & software 26(12), 1502-1514.

Räsänen, T. A., Joffre, O. M., Someth, P., Thanh, C. T., Keskinen, M. and Kummu, M. (2015). "Model-based assessment of water, food, and energy trade-offs in a cascade of multipurpose reservoirs: Case study of the Sesan Tributary of the Mekong River." Journal of Water Resources Planning and Management 141(1), 05014007.

Reis, L. F. R., Bessler, F. T., Walters, G. A. and Savic, D. (2006). "Water Supply Reservoir Operation by Combined Genetic Algorithm – Linear Programming (GA-LP) Approach." Water Resources Management 20(2), 227-255.

Salas, J. D. (1980). "Applied modeling of hydrologic time series", Water Resources Publication.

Salas, J. D., Tabios III, G. Q. and Bartolini, P. (1985). "Approaches to multivariate modeling of water resources time series 1." JAWRA Journal of the American Water Resources Association 21(4), 683-708.

Savic, D. A., Burn, D. H and Zrinji, Z. (1989). "A comparison of streamflow generation models for reservoir capacity-yield analysis." JAWRA Journal of the American Water Resources Association 25(5), 977-983.

Savic, D. and Simonovic, S. P. (1991). "An Interactive Approach to Selection and Use of Single Multipurpose Reservoir Models." Water Resources Research 27(10), 2509-2521.

Savic, D. and Walters, G. (1997). "Genetic Algorithms for Least-Cost Design of Water Distribution Networks." Journal of Water Resources Planning and Management 123(2), 67-77.

Schuol, J, Abbaspour, K. C., Srinivasan, R. and Yang, H. (2008). "Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model." Journal of Hydrology 352(1), 30-49.

Sehlke, G. and Jacobson, J. (2005). "System dynamics modeling of transboundary systems: the Bear River basin model." Groundwater 43(5), 722-730.

Shahin, M. M. A. (1985). "Hydrology of the Nile basin", Elsevier.

Sharma, Ashish and O'Neill, Robert (2002). "A nonparametric approach for representing interannual dependence in monthly streamflow sequences." Water resources research 38(7), 5-1-5-10.

Siam, M. S. and Eltahir, E. A. B. (2017). "Climate change enhances interannual variability of the Nile river flow." Nature Climate Change 7(5), 350-354.

Siderius, C., Van Walsum, P. E. V., Roest, C. W. J., Smit, A. A. M. F. R., Hellegers, P. J. G. J., Kabat, P. and van Ierland, E. C. (2016). "The role of rainfed agriculture in securing food production in the Nile Basin." Environmental science & policy 61, 14-23.

Sieber, J. (2006). "WEAP water evaluation and planning system."

Sileet, T., El Shamy, M. and Sharaky, A. (2014). "Downstream Impact of Blue Nile Basin Development." Nile Basin Water Science & Engineering Journal Vol.7(1), 18.

Simonovic, S. P. and Fahmy, H. (1999). "A new modeling approach for water resources policy analysis." Water resources research 35(1), 295-304.

Simonovic, S. P. and Rajasekaram, V. (2004). "Integrated analyses of Canada's water resources: a system dynamics approach." Canadian Water Resources Journal/Revue canadienne des ressources hydriques 29(4), 223-250.

Simulistics, Ltd (2019). “Simile.” Accessed January 07, 2019. http://www.simulistics.com/.

Soliman, I. and Migahed, M. (1994). "Economic Efficiency for agricultural Tractor operation". Proceedings Fifth Conference of Agricultural Development Research, The Faculty of Agriculture, Ain Shams University, Cairo, Egypt.

Srinivas, V. V. and Srinivasan, K. (2005). "Hybrid moving block bootstrap for stochastic simulation of multi-site multi-season streamflows." Journal of Hydrology 302(1-4), 307-330.

Stagge, J. H. and Moglen, G. E. (2013). "A nonparametric stochastic method for generating daily climate-adjusted streamflows." Water Resources Research 49(10), 6179-6193.

Steduto, P., Hsiao, T. C., Fereres, E. and Raes, D. (2012). "Crop yield response to water", FAO, Rome, Italy.

Stephan, T. D. (1992). "The use of statistical measures to validate system dynamics models". Secondary "The use of statistical measures to validate system dynamics models", Naval postgraduate school Monterey CA.

Sterman, J. D. (2000). "Business Dynamics: Systems Thinking and Modeling for a Complex World", Irwin McGraw-Hill

Sun, S., Djordjević, S. and Khu, S. (2011). "A general framework for flood risk-based storm sewer network design." Urban Water Journal 8(1), 13-27.

Sun, S., Fu, G., Djordjević, S. and Khu, S. (2012). "Separating aleatory and epistemic uncertainties: Probabilistic sewer flooding evaluation using probability box." Journal of Hydrology 420-421, 360-372.

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Baumert, N., Kloos, J., Renaud, F. G., La Jeunesse, I., Mabrouk, B., Savić, D., Kapelan, Z. and Ludwig, R. (2015). "Interdisciplinary assessment of sea-level rise and climate change impacts on the lower Nile delta, Egypt." Science of the Total Environment 503, 279-288.

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Savić, D. and Kapelan, Z. (2012). "Integrated System Dynamics Modelling for water scarcity assessment: Case study of the Kairouan region." Science of the total environment 440, 290-306.

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Savić, D. and Kapelan, Z. (2013). "Integrated modelling of a coupled water-agricultural system using system dynamics." Journal of Water and Climate Change 4(3), 209-231.

Sutcliffe, J. V. and Parks, Y. P. (1999). "The hydrology of the Nile", International Association of Hydrological Sciences Wallingford, Oxfordshire, UK.

Svanidze, G. G. (1964). "Principles of estimating river flow regulation by the Monte Carlo method." Metsniereba, Tbilisi, 271.

Talaat, W. (2018). "The targeting effectiveness of Egypt's Food Subsidy Programme: Reaching the poor?" International Social Security Review 71(2), 103-123.

Tan, C. C., Erfani, T. and Erfani, R. (2017). "Water for Energy and Food: A System Modelling Approach for Blue Nile River Basin." Environments 4(1), 15.

Tate, E. L., Sene, K. J. and Sutcliffe, J. V. (2001). "A water balance study of the upper White Nile basin flows in the late nineteenth century." Hydrological sciences journal 46(2), 301-318.

Teegavarapu, R. S. V. and Simonovic, S. P. (2014). "Simulation of Multiple Hydropower Reservoir Operations Using System Dynamics Approach." Water Resources Management 28(7), 1937-1958.

The World Bank 2019. "The World Bank Open Data." Accessed May 17, 2019. https://data.worldbank.org/.

Thomas, H. A. and Fiering, M. B. (1962a). "Mathematical synthesis of streamflow sequences for the analysis of river basin by simulation." Design of water resources-systems, 459-493.

Thomas, H.A. and Fiering, M. P. (1962b). "Mathematical synthesis of streamflow sequences for the analysis of river basins by simulation. Chapter 12 in: Design of water resources systems". Harvard University Press, Cambridge, Massachusetts, USA.

Tidwell, V. C, Passell, H. D, Conrad, S. H and Thomas, R. P (2004). "System dynamics modeling for community-based water planning: Application to the Middle Rio Grande." Aquatic sciences 66(4), 357-372.

Tilmant, A., Arjoon, D. and Marques, G. F. (2012). "Economic value of storage in multireservoir systems." Journal of Water Resources Planning and Management 140(3), 375-383.

Tsoukalas, I., Efstratiadis, A. and Makropoulos, C. (2017). "Stochastic simulation of periodic processes with arbitrary marginal distributions". Proceedings of the 15th International Conference on Environmental Science and Technology, Rhodes, Greece.

Tsoukalas, I., Efstratiadis, A. and Makropoulos, C. (2018a). "Stochastic periodic autoregressive to anything (SPARTA): Modeling and simulation of cyclostationary processes with arbitrary marginal distributions." Water Resources Research 54(1), 161-185.

Tsoukalas, I., Efstratiadis, A. and Makropoulos, C. (2019). "Building a puzzle to solve a riddle: A multi-scale disaggregation approach for multivariate stochastic processes with any marginal distribution and correlation structure." Journal of Hydrology 575, 354-380.

Tsoukalas, I. and Kossieris, P. (2019). "anySim: Stochastic simulation of processes with any marginal distribution and correlation structure.R package.". from Available at: http://www.itia.ntua.gr/en/softinfo/33/.

Tsoukalas, I., Kossieris, P., Efstratiadis, A. and Makropoulos, C. (2016). "Surrogate-enhanced evolutionary annealing simplex algorithm for effective and efficient optimization of water resources problems on a budget." Environmental modelling & software 77, 122-142.

Tsoukalas, I. and Makropoulos, C. (2015a). "Multiobjective optimisation on a budget: Exploring surrogate modelling for robust multi-reservoir rules generation under hydrological uncertainty." Environmental Modelling & Software 69, 396-413.

Tsoukalas, I. and Makropoulos, C. (2015b). "A surrogate based optimization approach for the development of uncertainty-aware reservoir operational rules: the case of nestos hydrosystem." Water resources management 29(13), 4719-4734.

Tsoukalas, I., Papalexiou, S., Efstratiadis, A. and Makropoulos, C. (2018b). "A cautionary note on the reproduction of dependencies through linear stochastic models with non-gaussian white noise." Water 10(6), 771.

UEGCL, Uganda Electricity Generation Company Limited (2020). "Uganda Electricity Generation Company Limited." Accessed January 17, 2020. https://uegcl.com/business-operations/projects/karuma-hydro-power-project.html.

UNECE, The United Nations Economic Commission for Europe (2018). "A nexus approach to transboundary cooperation". Secondary "A nexus approach to transboundary cooperation", United Nations.

United Nations (2017). "World Population Prospects 2017." Accessed April 23, 2018. https://population.un.org/wpp/.

Valencia, Darío R and Schakke, John C (1973). "Disaggregation processes in stochastic hydrology." Water resources research 9(3), 580-585.

Ventana Systems, inc. (2019). "Vensim." Accessed May 17, 2019. http://vensim.com/.

Water Technology. net (2014). "Grand Ethiopian Renaissance Dam Project, Benishangul-Gumuz, Ethiopia."

Webber, J. L., Gibson, M. J., Chen, A. S., Savic, D., Fu, G. and Butler, D. (2018). "Rapid assessment of surface-water flood-management options in urban catchments." Urban Water Journal 15(3), 210-217.

Wheater, H. S., Chandler, R. E., Onof, C. J., Isham, V. S., Bellone, E., Yang, C., Lekkas, D., Lourmas, G. and Segond, M-L. (2005). "Spatial-temporal rainfall modelling for flood risk estimation." Stochastic Environmental Research and Risk Assessment 19(6), 403-416.

Wheeler, K. G., Basheer, M., Mekonnen, Z. T., Eltoum, S. O., Mersha, A., Abdo, G. M., Zagona, E. A., Hall, J. W. and Dadson, S. J. (2016). "Cooperative filling approaches for the Grand Ethiopian Renaissance Dam." Water International, 1-24.

Whittington, D. and McClelland, E. (1992). "Opportunities for regional and international cooperation in the Nile basin." Water International 17(3), 144-154.

Whittington, D., Wu, X. and Sadoff, C. (2005). "Water resources management in the Nile basin: the economic value of cooperation." Water Policy 7(3), 227-252.

Xu, W., Zhang, C., Peng, Y., Fu, G. and Zhou, H. (2014). "A two stage Bayesian stochastic optimization model for cascaded hydropower systems considering varying uncertainty of flow forecasts." Water Resources Research 50(12), 9267-9286.

Xu, Z. X., Takeuchi, K., Ishidaira, H. and Zhang, X. W. (2002). "Sustainability analysis for Yellow River water resources using the system dynamics approach." Water Resources Management 16(3), 239-261.

Yang, J., Yang, Y. C. E., Khan, H. F., Xie, H., Ringler, C., Ogilvie, A., Seidou, O., Djibo, A. G., van Weert, F. and Tharme, R. (2018). "Quantifying the Sustainability of Water Availability for the Water-Food-Energy-Ecosystem Nexus in the Niger River Basin." Earth's Future 6(9), 1292-1310.

Yang, Y. C. E., Ringler, C., Brown, C. and Mondal, Md. A. H. (2016a). "Modeling the agricultural water–energy–food nexus in the Indus River Basin, Pakistan." Journal of Water Resources Planning and Management 142(12), 04016062.

Yang, Y. C. E., Wi, S., Ray, P. A., Brown, C. M. and Khalil, A. F. (2016b). "The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories." Global Environmental Change 37, 16-30.

Yang, YC Ethan, Wi, Sungwook, Ray, Patrick A, Brown, Casey M and Khalil, Abedalrazq F (2016c). "The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories." Global Environmental Change 37, 16-30.

Zagona, E. A., Fulp, T. J., Shane, R., Magee, T. and Goranflo, H. M. (2001). "Riverware: a generalized tool for complex reservoir system modeling". Secondary "Riverware: a generalized tool for complex reservoir system modeling", Wiley Online Library.

Zarghami, M. and Akbariyeh, S. (2012). "System dynamics modeling for complex urban water systems: Application to the city of Tabriz, Iran." Resources, Conservation and Recycling 60, 99-106.

Zarghami, M., Fotookian, M. R., Safari, N. and Aslanzadeh, A. (2016). "Reservoir operation using system dynamics under climate change impacts: a case study of Yamchi reservoir, Iran." Arabian Journal of Geosciences 9(16), 678.

Zhang, C., Chen, X., Li, Y., Ding, W. and Fu, G. (2018). "Water-energy-food nexus: Concepts, questions and methodologies." Journal of cleaner production 195, 625-639.

Zhang, Y., Erkyihum, S. T. and Block, P. (2016). "Filling the GERD: evaluating hydroclimatic variability and impoundment strategies for Blue Nile riparian countries." Water international 41(4), 593-610.

Zhang, Ying, Block, Paul, Hammond, Michael and King, Andrew (2015). "Ethiopia’s Grand Renaissance Dam: Implications for downstream riparian countries." Journal of water resources planning and management 141(9), 05015002.

Zhuang, Y. (2014). "A system dynamics approach to integrated water and energy resources management". Secondary "A system dynamics approach to integrated water and energy resources management", University of South Florida.

APPENDICES

Appendix A

A.1 Surface area – Elevation – Storage relationships

A.1.1 White Nile Basin Reservoirs

Bujagali RoR		
Elevation (m)	Surface area (km^2)	Storage (MCM)
1096.00	3.08	0.00
1109.50	3.78	41.20
1111.50	3.88	54.00

Sondu Mirriu RoR		
Elevation (m)	Surface area (km^2)	Storage (MCM)
1405.00	0.00	0.00
1410.00	1.00	3.00

Gogo Falls RoR		
Water level (m)	Surface area (km^2)	Storage (MCM)
0.00	0.00	0.00
19.00	10.00	1000.00

Sang'oro RoR		
Water level (m)	Surface area (km^2)	Storage (MCM)
0.00	0.00	0.00
62.20	10.00	1000.00

Isimba RoR		
Water level (m)	Surface area (km^2)	Storage (MCM)
0.00	0.00	0.00
13.30	10.00	1000.00

Karuma RoR		
Elevation (m)	Surface area (km^2)	Storage (MCM)
1019.00	0.00	0.00
1028.00	17.90	34.34
1030.00	27.37	79.87

Magwagwa Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
1560.00	0.00	0.00
1611.00	5.00	107.00
1645.00	13.00	400.00
1665.00	22.50	750.00
1670.00	26.00	850.00

Nandi Forest Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
1786.00	0.00	0.00
1790.00	2.00	5.00
1811.50	6.50	100.00
1831.00	8.80	275.00

Fula Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
570.00	0.00	0.00
580.00	3.07	10.22
590.00	8.64	66.39
600.00	16.25	188.87
610.00	30.85	420.52
620.00	50.07	821.30

Shukoli Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
537.00	0.00	0.00
540.00	0.77	0.77
550.00	5.59	28.94
560.00	11.69	113.51

Lakki Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
513.00	0.00	0.00
520.00	4.74	11.07
530.00	17.80	116.85
535.00	25.23	223.89

Bedden Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
473.00	0.00	0.00
480.00	9.36	21.83
490.00	34.43	227.63
500.00	76.55	768.71
510.00	138.78	1830.05

Baro 1 Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
1439.00	0.00	0.00
1440.00	0.50	0.20
1450.00	2.90	17.40
1460.00	5.60	59.30
1470.00	9.60	134.50
1480.00	15.20	259.00
1490.00	21.50	445.00
1500.00	27.40	690.00
1510.00	32.50	989.00
1520.00	36.80	1337.00
1525.00	38.70	1525.00

Baro 2 Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
1293.00	0.00	0.00
1295.00	0.22	0.15
1300.00	0.78	2.50
1305.00	1.32	7.69
1310.00	2.61	17.40
1315.00	5.26	36.60
1320.00	9.62	73.30
1325.00	13.25	130.20

Genji RoR		
Elevation (m)	Surface area (km²)	Storage (MCM)
1185.00	0.00	0.00
1190.00	0.06	0.10
1195.00	0.14	0.60
1200.00	0.22	1.50
1205.00	0.33	2.87
1210.00	0.46	4.82

Geba II Dam		
Elevation (m)	Surface area (km²)	Storage (MCM)
1670.00	0.00	0.00
1680.00	1.00	1.00

Geba I Dam		
Elevation (m)	Surface area (km²)	Storage (MCM)
2140.00	0.00	0.00
2142.00	3.50	18.00
2144.00	7.50	26.00
2146.00	10.50	39.00
2148.00	12.50	68.00
2150.00	16.50	89.00
2152.00	19.50	137.00
2154.00	23.50	169.00
2156.00	27.50	222.00
2158.00	31.50	286.00
2160.00	35.00	352.00
2162.00	40.75	432.00
2164.00	46.50	520.00
2166.00	52.25	634.00
2168.00	59.00	746.00
2170.00	68.00	860.00
2172.00	76.00	1010.00
2174.00	86.00	1170.00

Geba R Dam		
Elevation (m)	Surface area (km²)	Storage (MCM)
920.00	1.00	0.00
930.00	1.50	10.00
940.00	2.00	20.00
950.00	4.00	50.00
960.00	5.00	100.00
970.00	7.00	190.00
980.00	10.00	280.00
990.00	12.00	380.00
1000.00	14.00	500.00
1010.00	16.00	650.00
1020.00	18.00	850.00
1030.00	21.00	1000.00
1040.00	23.50	1250.00
1050.00	26.00	1500.00
1060.00	29.00	1780.00
1070.00	32.00	2100.00
1080.00	36.00	2400.00
1090.00	40.00	2800.00
1100.00	44.00	3200.00
1110.00	50.00	3700.00
1120.00	56.00	4200.00

Kirra Dam		
Elevation (m)	Surface area (km²)	Storage (MCM)
1131.54	0.00	0.00
1131.55	0.10	0.10
1132.00	0.20	5.00

Alwero Dam		
Water level (m)	Surface area (km^2)	Storage (MCM)
428.00	0.00	0.00
430.00	0.20	0.00
432.00	0.40	0.00
434.00	0.60	1.00
436.00	0.80	3.00
438.00	1.00	6.00
440.00	1.50	8.00
442.00	2.00	12.00
444.00	2.60	16.00
446.00	3.40	22.00
448.00	4.40	30.00
450.00	5.20	40.00
452.00	6.40	52.00
454.00	8.20	66.00
455.00	9.20	75.00
458.00	12.60	110.00
460.00	15.00	136.00
462.00	18.20	170.00

Jebel Aulia Dam		
Water level (m)	Surface area (km^2)	Storage (MCM)
360.00	0.00	0.00
366.00	50.00	75.00
370.00	80.00	100.00
373.29	131.00	305.00
373.70	216.00	501.00
374.68	319.00	803.00
375.41	560.00	1424.00
376.00	820.00	1925.00
376.27	888.00	2125.00
376.75	1060.00	2702.00
377.25	1220.00	3125.00
377.27	1225.00	3178.00
377.50	1326.29	3377.01
378.00	1494.79	3903.51
378.50	1663.29	4430.01
379.00	1831.79	4956.51

A.1.2 Blue Nile, Atbara and Main Nile Reservoirs

Koga Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
2003.00	0.00	0.00
2006.00	0.94	1.10
2007.00	1.85	2.40
2009.00	4.35	8.50
2010.00	6.83	14.00
2011.00	9.32	22.10
2012.00	11.06	32.20
2013.00	13.45	44.50
2014.00	15.44	58.90
2015.00	17.24	75.20
2016.00	19.06	93.40
2017.00	20.72	113.30
2018.00	22.36	134.80
2019.00	24.00	158.00
2020.00	25.82	182.90

Tis Abbay		
Elevation (m)	Surface area (km^2)	Storage (MCM)
534.00	0.00	0.00
535.20	0.40	0.25
536.40	7.69	5.18
537.60	31.16	28.86
538.90	59.09	83.87
540.10	91.87	175.89
541.30	106.03	296.52
542.50	138.00	445.27
543.70	174.02	635.47
545.00	231.89	882.90
545.60	260.22	1032.89
546.20	325.78	1211.49

Fincha Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
2212.00	0.00	0.00
2213.00	16.00	8.00
2214.00	69.00	51.00
2215.00	147.00	159.00
2216.00	206.00	335.00
2217.00	238.00	557.00
2218.00	266.00	809.00
2219.00	345.00	1115.00
2220.00	425.00	1500.00
2221.00	455.00	1940.00
2222.00	473.00	2404.00
2223.00	485.00	2883.00

Amerti-Neshe Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
2223.00	0.00	0.00
2224.00	0.40	0.20
2225.00	2.10	1.50
2226.00	4.20	4.70
2227.00	5.60	9.60
2228.00	8.10	16.50
2229.00	9.90	25.50
2230.00	11.90	36.40
2231.00	14.70	49.70
2232.00	17.40	65.80
2233.00	20.00	84.50
2234.00	22.80	105.90
2235.00	25.60	130.10

El Roseires Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
465.00	9.10	0.00
466.00	10.50	13.00
467.00	14.40	30.10
467.70	18.50	50.70
468.00	20.60	61.80
468.50	24.50	83.20
469.00	29.00	108.80
470.00	39.70	172.40
471.00	52.30	253.20
472.00	67.40	351.90
473.00	84.30	469.00
474.00	103.40	605.00
475.00	124.50	760.40
476.00	147.60	935.50
477.00	172.70	1130.80
478.00	199.80	1346.50
478.50	214.10	1462.10
479.00	228.90	1583.00
479.50	244.20	1709.20
480.00	260.00	1840.60
480.50	276.30	1877.50
481.00	293.00	2119.70
482.00	327.70	2458.32
483.00	363.30	2832.06
484.00	398.60	3241.23
485.00	433.40	3685.45
486.00	465.70	4163.23
487.00	498.60	4673.63
488.00	532.20	5217.31
489.00	566.90	5795.10
490.00	603.00	6408.31

Sennar Dam		
Elevation (m)	Surface area (km^2)	Storage (MCM)
411.90	89.00	0.84
412.00	90.00	0.85
412.30	140.00	1.07
412.60	210.00	1.45
413.00	320.00	2.30
413.30	430.00	3.30
413.60	570.00	4.60
414.00	780.00	7.00
414.30	960.00	9.50
414.60	1170.00	12.60
415.00	1560.00	17.60
415.30	1780.00	22.40
415.60	2080.00	27.90
416.00	2530.00	36.90
416.30	2890.00	44.80
416.60	3300.00	53.90
417.00	3880.00	67.90
417.30	4350.00	80.10
417.60	4860.00	93.70
418.00	5580.00	114.20
418.30	6170.00	131.70
418.60	6780.00	150.90
419.00	7660.00	179.50
419.30	8350.00	203.30
419.60	9690.00	229.30
420.00	10130.00	267.60
420.30	10940.00	299.00
420.60	11790.00	340.00
421.00	12990.00	382.50

TK5 Dam		
Elevation (m)	Surface area (km²)	Storage (MCM)
965.00	0.00	0.00
975.00	0.00	0.00
1000.00	5.00	69.00
1010.00	8.10	134.00
1030.00	21.60	423.00
1050.00	39.60	1023.00
1070.00	61.80	2036.00
1090.00	81.90	3480.00
1110.00	106.90	5353.00
1130.00	139.70	7810.00
1140.00	156.90	9293.00
1150.00	176.10	10958.00

Khashm Elgirba Dam		
Elevation (m)	Surface area (km²)	Storage (MCM)
430.00	0.00	0.00
440.00	0.00	0.00
445.00	1.50	5.00
455.00	3.00	23.00
461.00	6.00	43.00
464.00	10.80	70.00
467.50	35.00	165.00
470.00	63.00	308.00
473.60	95.00	580.00
474.00	100.00	657.00
484.00	100.00	1657.00

Upper Atbara and Setit Dam		
Elevation (m)	Surface area (km²)	Storage (km³)
500.00	0.00	0.00
509.00	16.50	1180.00
510.00	33.00	1311.00
511.00	49.50	1482.00
512.00	66.00	1653.00
513.00	82.50	1823.00
514.00	99.00	1994.00
515.00	115.50	2165.00
516.00	132.00	2404.00
517.00	148.50	2642.00
518.00	165.00	2881.00
519.00	181.50	3119.00
520.00	198.00	3358.00
521.00	214.50	3688.00
521.50	231.00	3853.00
522.00	247.50	4018.00
522.50	264.00	4183.00
523.00	280.00	4347.00
523.50	297.00	4512.00

Grand Ethiopian Renaissance Dam		
Elevation (m)	Surface area (km²)	Storage (km³)
500.00	3.00	0.00
510.00	11.00	10.00
520.00	29.00	20.00
530.00	61.00	50.00
540.00	111.00	750.00
550.00	180.00	2000.00
560.00	272.00	3000.00
570.00	387.00	6000.00
580.00	531.00	9800.00
590.00	703.00	15000.00
600.00	905.00	21500.00
610.00	1133.00	31000.00
620.00	1380.00	42500.00
630.00	1638.00	57000.00
640.00	1904.00	74000.00

Merowe Dam		
Elevation (m)	Surface area (km²)	Storage (MCM)
249.90	0.00	0.00
250.00	1.00	3.00
260.00	35.00	143.00
265.00	65.00	389.00
270.00	108.00	817.00
275.00	174.00	1520.00
280.00	256.00	243.20
284.90	353.00	4119.00
285.00	354.00	4120.00
290.00	476.00	6170.00
295.00	620.00	8900.00
298.00	724.00	11050.00
300.00	803.00	12450.00

High Aswan Dam		
Elevation (m)	Surface area (km²)	Storage (MCM)
107.00	0.00	0.00
120.00	450.00	5200.00
125.00	600.00	7800.00
130.00	749.00	11300.00
135.00	988.00	15600.00
140.00	1242.00	21200.00
145.00	1589.00	28300.00
147.00	1738.20	31860.00
150.00	1962.00	37200.00
155.00	2414.00	48100.00
160.00	2950.00	61500.00
165.00	3581.00	77900.00
170.00	4308.00	97600.00
175.00	5168.00	121300.00
180.00	6118.00	149500.00
183.00	6751.60	169420.00

Rumela Dam		
Elevation (m)	Surface area (km²)	Storage (km³)
465.00	0.00	0.00
508.40	59.80	1317.00
508.50	60.00	1319.00
509.00	66.00	1392.00
510.00	72.00	1554.00
512.00	84.00	1898.00
514.00	100.00	2259.00
516.00	116.00	2711.00
517.00	124.00	2892.00
517.50	132.00	3000.00
520.00	172.00	3614.00

A.1.3 Natural Lakes

Lake Victoria		
Elevation (m)	Surface area (km^2)	Storage (MCM)
0.00	0.00	0.00
1125.00	60660.00	2396600.00
1127.00	61820.00	2517920.00
1128.00	62593.00	2579740.00
1129.00	63367.00	2642330.00
1130.00	64140.00	2705700.00
1131.00	64914.00	2769840.00
1132.00	65392.00	2834760.00
1134.00	66935.00	2968000.00
1135.00	67717.00	3034140.00
1136.00	68471.00	3102150.00
1137.00	88014.00	3170800.00

Lake Tana		
Elevation (m)	Surface area (km^2)	Storage (MCM)
1772.00	0.00	0.00
1773.00	300.00	250.00
1774.00	900.00	1000.00
1775.00	1400.00	2000.00
1776.00	1700.00	4000.00
1777.00	2000.00	5500.00
1778.00	2250.00	7500.00
1779.00	2500.00	10000.00
1780.00	2550.00	12000.00
1781.00	2650.00	15000.00
1782.00	2750.00	17000.00
1783.00	2875.00	20000.00
1784.00	2931.97	23147.00
1785.00	2978.00	26096.00
1786.00	3024.03	29097.00
1787.00	3070.05	32098.00
1788.50	3116.08	35099.00
1790.00	3116.08	38215.00

Lake Albert		
Elevation (m)	Surface area (km^2)	Storage (MCM)
572.00	0.00	0.00
575.00	390.00	488.00
580.00	1851.00	6391.00
585.00	2567.00	17634.00
590.00	3078.00	31791.00
595.00	3398.00	48011.00
600.00	3664.00	65667.00
605.00	4020.00	84832.00
610.00	4276.00	105560.00
615.00	4626.00	127745.00
618.60	5062.00	144993.00
621.70	5869.00	162041.00
625.20	6188.00	183246.00
640.00	6878.00	280176.00
664.00	7839.00	456855.00

Lake Kyoga		
Elevation (m)	Surface area (km^2)	Storage (MCM)
0.00	0.00	0.00
1027.00	677.00	576.00
1028.00	945.23	1253.00
1028.20	1075.26	1442.00
1028.40	1230.30	1657.00
1028.60	1410.34	1903.00
1028.80	1583.46	2185.00
1029.00	1770.43	2505.00
1029.20	1950.47	2856.00
1029.40	2125.52	3246.00
1029.60	2310.56	3671.00
1034.60	4941.24	22725.00
1034.80	5005.11	23713.00
1035.00	5203.91	24715.00
1036.00	6331.82	29924.00

A.2 Net Evaporation from Reservoirs and Lakes (cm/month)

Month	Koga Dam	Fincha Dam	Amerti - Neshe Dam	Roseires Dam	Sennar Dam	TK5 Dam	Khashm Elgirba Dam
Jan.	15.0	3.0	3.0	18.0	19.0	14.0	16.0
Feb.	13.0	10.0	10.0	18.0	21.0	14.0	16.0
Mar	13.0	14.0	14.0	19.0	27.0	17.0	20.0
Apr	10.0	10.0	10.0	19.0	28.0	16.0	22.0
May	1.0	10.0	10.0	13.0	24.0	17.0	25.0
Jun	-10.0	1.0	1.0	3.0	22.0	18.0	23.0
Jul	-34.0	-21.0	-21.0	4.0	7.0	11.0	19.0
Aug	-33.0	-19.0	-19.0	-3.0	12.0	-8.0	6.0
Sep	-14.0	-26.0	-26.0	7.0	0.0	-10.0	3.0
Oct	4.0	-10.0	-10.0	12.0	18.0	9.0	14.0
Nov	11.0	3.0	3.0	18.0	20.0	18.0	18.0
Dec	15.0	10.0	10.0	18.0	19.0	15.0	18.0

Month	Alwero Dam	Jebel Aulia Dam	Merowe Dam	High Aswan Dam	Upper Atbara and Setit Dam	GERD	Fula Dam
Jan.	13.0	19.0	13.0	13.0	18.0	12.1	17.0
Feb.	13.0	21.0	14.0	11.6	18.5	11.0	17.0
Mar	12.0	27.0	19.0	12.9	23.3	15.1	16.0
Apr	10.0	28.0	21.0	14.7	24.0	13.2	11.0
May	-2.0	24.0	23.0	16.7	22.3	7.3	7.0
Jun	-8.0	23.0	22.0	20.1	14.4	0.4	2.0
Jul	-12.0	17.0	22.0	20.2	4.3	-4.8	-3.0
Aug	-11.0	13.0	21.0	21.2	0.9	-4.7	-5.0
Sep	-8.0	15.0	20.0	20.9	10.5	-2.4	2.0
Oct	3.0	22.0	19.0	19.0	16.7	6.9	8.0
Nov	9.0	20.0	14.0	14.8	18.0	9.7	13.0
Dec	11.0	19.0	12.0	14.8	17.7	10.3	16.0

Month	Baro1 Dam	Baro2 Dam	Geba Dam	Lake Tana	Lake Victoria	Lake Albert
Jan.	10.9	12.5	10.9	13.0	0.0	9.0
Feb.	11.4	13.2	11.4	15.0	1.0	7.0
Mar	8.8	11.5	8.8	19.0	-7.0	5.0
Apr	6.5	9.8	6.5	17.0	-16.0	-1.0
May	-6.9	-1.6	-6.9	16.0	-9.0	3.0
Jun	-13.4	-7.2	-13.4	13.0	4.0	2.0
Jul	-18.7	-11.8	-18.7	6.0	7.0	9.0
Aug	-18.0	-11.1	-18.0	-6.0	7.0	5.0
Sep	-14.9	-8.6	-14.9	-26.0	6.0	-3.0
Oct	-1.1	2.8	-1.1	-6.0	0.0	6.0
Nov	6.9	9.0	6.9	14.0	-6.0	9.0
Dec	9.5	11.1	9.5	14.0	-5.0	7.0

A.3 Operation Rules of Main Reservoirs

<table>
<tr><th></th><th colspan="3">Tis Abbay</th><th colspan="3">Fincha Dam</th></tr>
<tr><th>Month</th><th>Minimum operation level (m)</th><th>Target power (MW)</th><th>Flood control level (m)</th><th>Minimum operation level (m)</th><th>Target power (MW)</th><th>Flood control level (m)</th></tr>
<tr><td>Jan</td><td rowspan="12">540</td><td rowspan="12">1.2</td><td rowspan="12">543</td><td rowspan="12">2214</td><td rowspan="12">86</td><td>2219</td></tr>
<tr><td>Feb</td><td>2219</td></tr>
<tr><td>Mar</td><td>2218</td></tr>
<tr><td>Apr</td><td>2218</td></tr>
<tr><td>May</td><td>2217</td></tr>
<tr><td>Jun</td><td>2217</td></tr>
<tr><td>Jul</td><td>2218</td></tr>
<tr><td>Aug</td><td>2218.5</td></tr>
<tr><td>Sep</td><td>2219</td></tr>
<tr><td>Oct</td><td>2219</td></tr>
<tr><td>Nov</td><td>2219</td></tr>
<tr><td>Dec</td><td>2219</td></tr>
<tr><td colspan="7">* Note rules are prioritized from left to right</td></tr>
</table>

	Amerti Neshe Dam			Sennar Dam			
Month	Minimum operation level (m)	Target power (MW)	Flood control level (m)	Minimum downstream release (m^3/sec)	Irrigation Gezira-Managil Demand	Flood control level (m)	Target power (MW)
Jan	2230	27.82	2235	92.6	845.76	421.8	10 MW before 1967 15 MW since 1967
Feb					519.01	421.8	
Mar					62.56	421.8	
Apr					75.52	421.8	
May					94.14	421.8	
Jun					149.27	421.8	
Jul					349.05	421.8	
Aug					685.1	417.2	
Sep					780.73	417.2	
Oct					898.84	421.8	
Nov					455.01	421.8	
Dec					984.99	421.8	

* Note rules are prioritized from left to right

	Khashm ElGirba Dam		Merowe Dam		HAD	
Month	Target Power (MW)	Flood Control Level (m)	Target Power MW	Flood Control Level (m)	Downstream deamdns	Power demand (MW)
Jan	7.6	474	520	300	Calcuated indigenously	By product
Feb				300		
Mar				300		
Apr				300		
May				300		
Jun				295		
Jul				289		
Aug				289		
Sep				295		
Oct				300		
Nov				300		
Dec				300		

* Note rules are prioritized from left to right

	Gebel Aulia Dam		El Roseires Dam			TK5 Dam	
Month	Flood control level (m)	Target Power (MW)	Supply Sennar dam levels (m)	Flood control level (m)	Target power (MW)	Target power (MW)	Flood control level (m)
Jan	377.4	28.8	421.8	490	221.8	170	1140
Feb	377.22	28.8	421	490	221.8	190	1140
Mar	376.76	28.8	420.3	485	221.8	190	1140
Apr	375.38	28.8	419.5	480	221.8	190	1140
May	374	28.8	418.7	475	221.8	190	1140
Jun	374.92	28.8	418	470	221.8	180	1140
Jul	376.3	28.8	417.2	467	221.8	135	1140
Aug	376.9	28.8	417.2	480	221.8	135	1140
Sep	377.12	28.8	417.2	490	221.8	135	1140
Oct	377.4	28.8	421.8	490	221.8	135	1140
Nov	377.4	28.8	421.8	490	221.8	135	1140
Dec	377.4	28.8	421.8	490	221.8	150	1140

* Note rules are prioritized from left to right

Appendix B

B.1 Historical VS Simulated River Flows at Gauge Stations in the Nile Basin

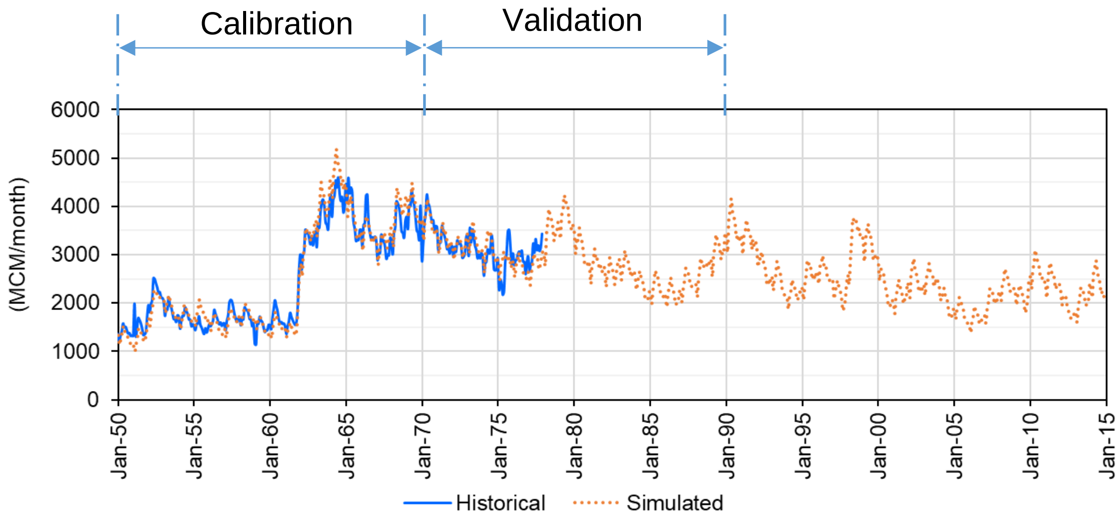


Figure B.1 Historical VS Simulated monthly flows of Lake Victoria at Jinga gauge

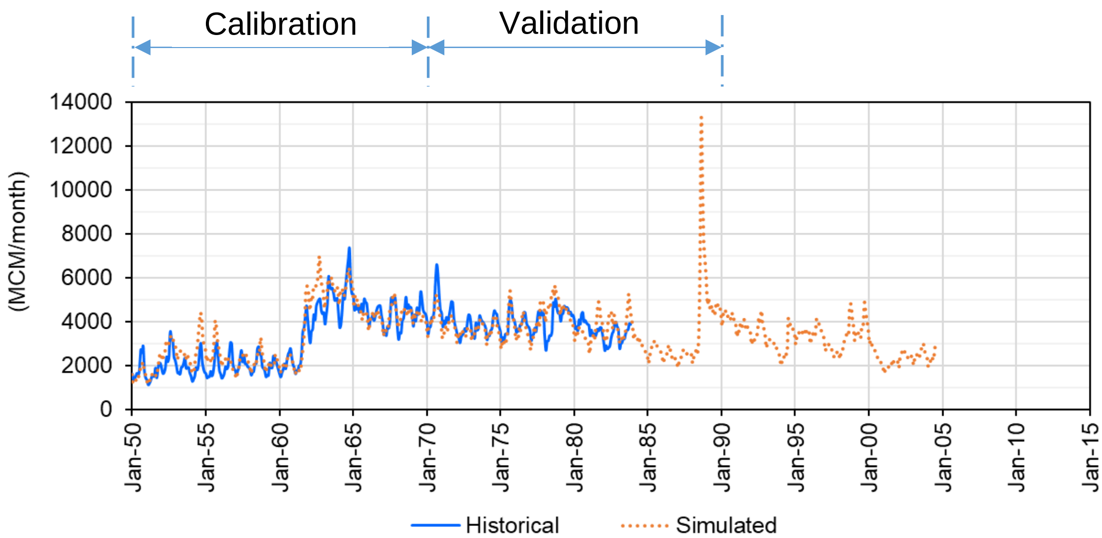


Figure B.2 Historical VS Simulated monthly flows of Bahr El Jebel at Mongolla gauge

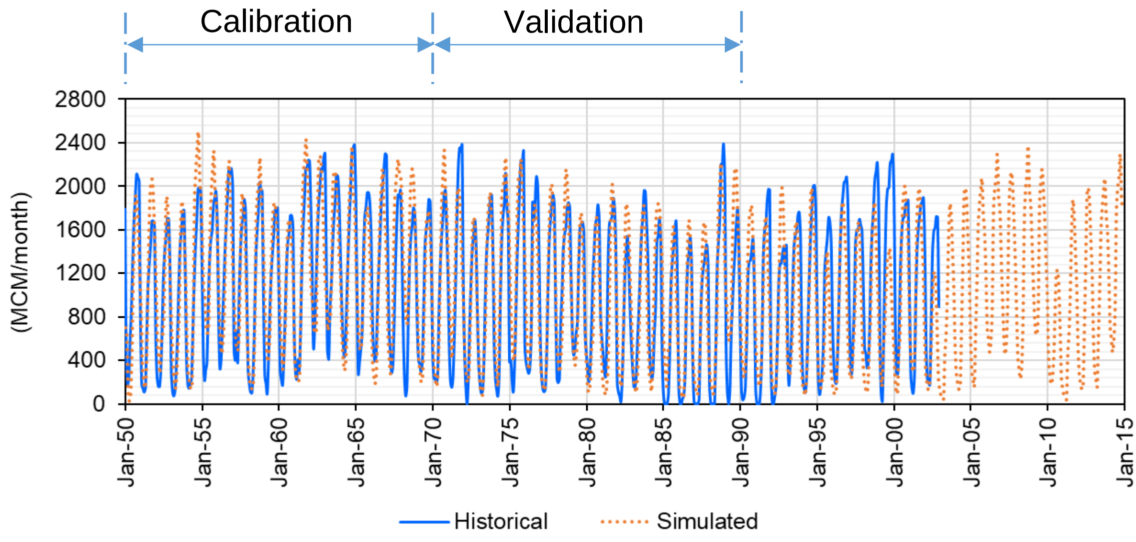


Figure B.3 Historical VS Simulated monthly flows of the Sobat River at Hillel Doleib gauge

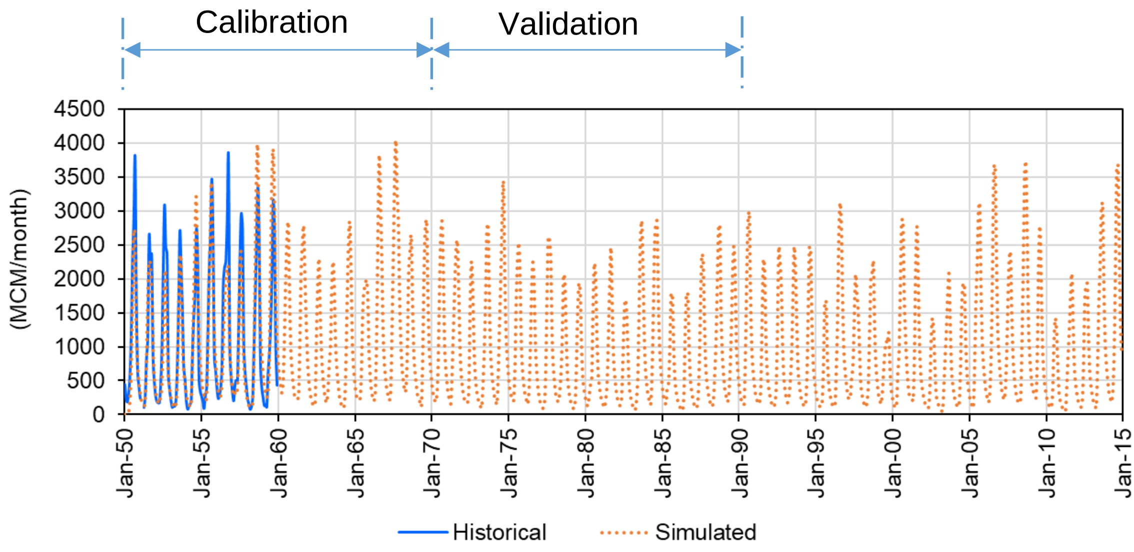


Figure B.4 Historical VS Simulated monthly flows of the Baro River at Gambella gauge

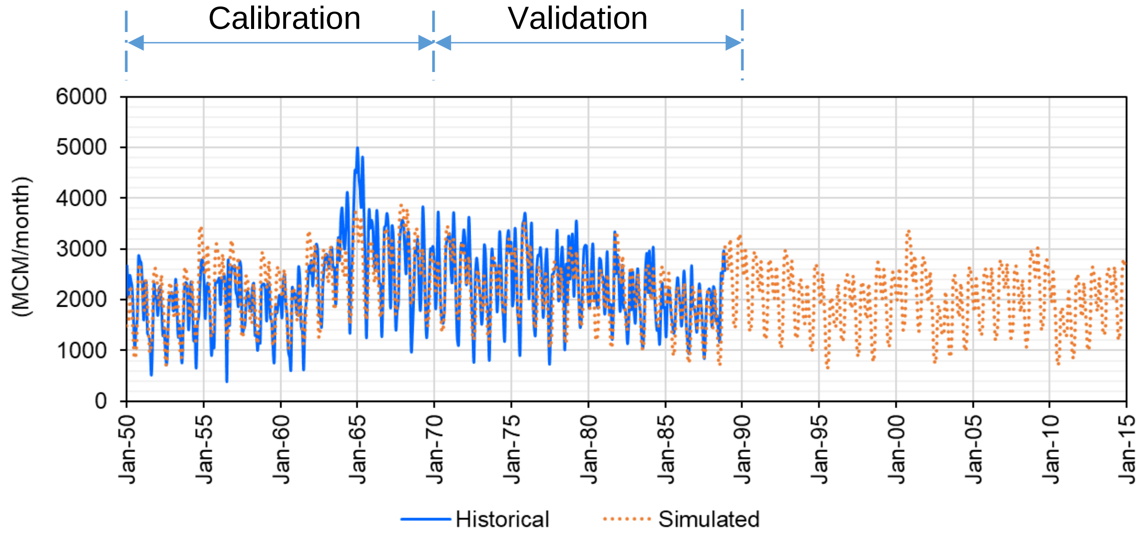


Figure B.5 Historical VS Simulated monthly flows of the White Nile River at Mogren gauge

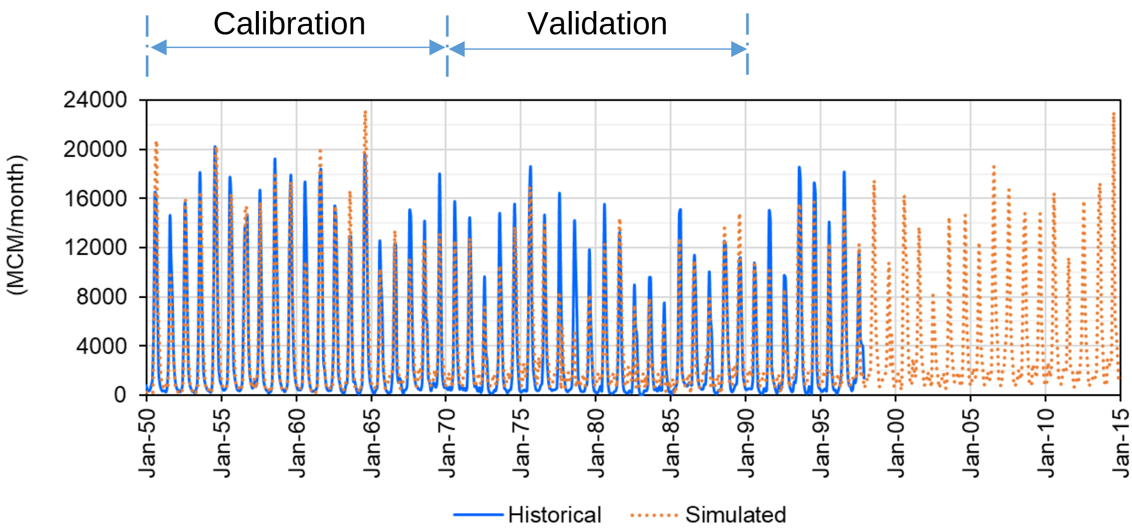


Figure B.6 Historical VS Simulated monthly flows of the Blue Nile River at Soba gauge

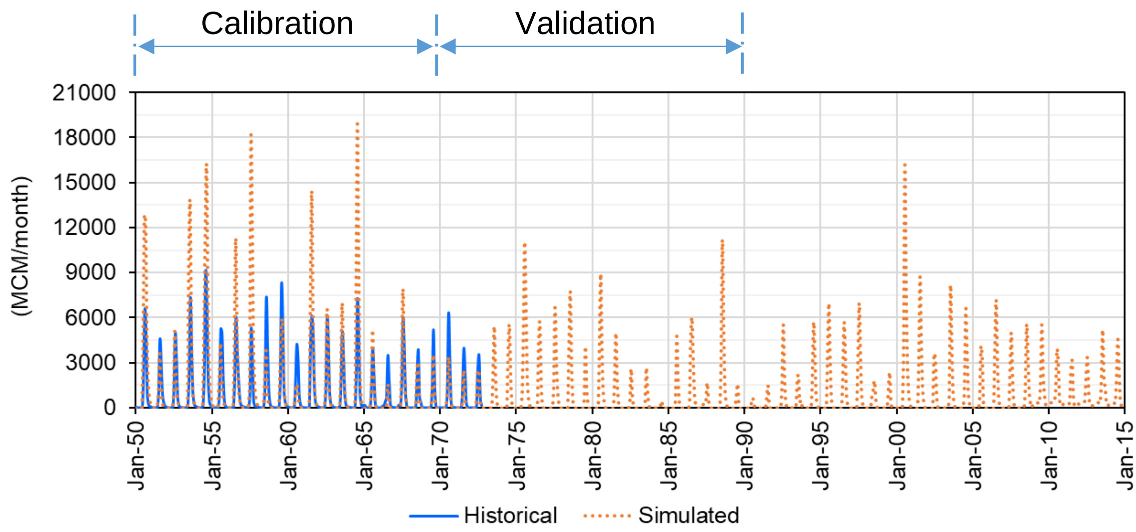


Figure B.7 Historical VS Simulated monthly flows of the Atbara River at Atbara mouth gauge

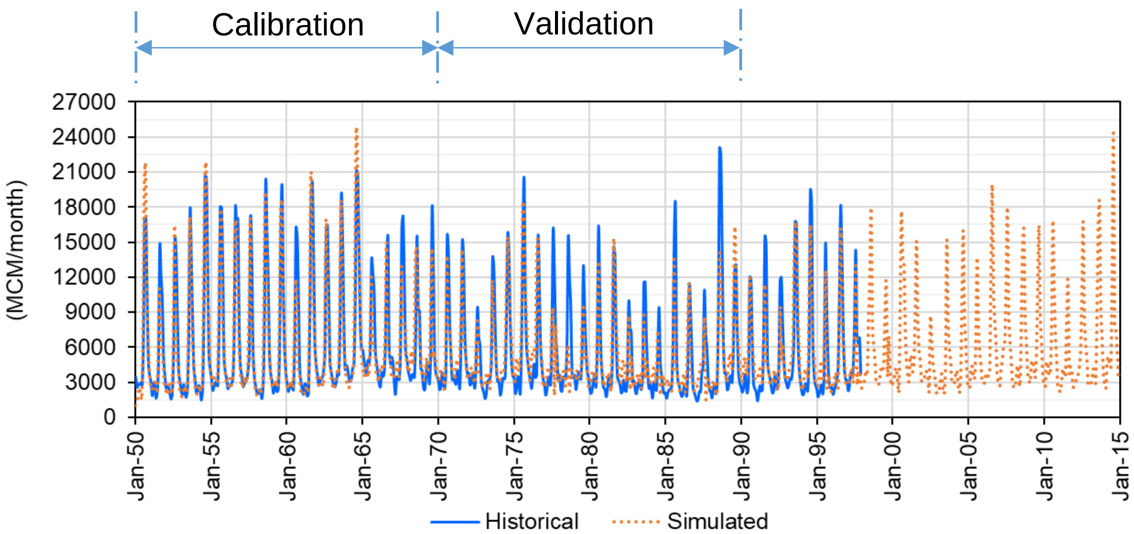


Figure B.8 Historical VS Simulated monthly flows of the main Nile at Tamaniat gauge

Appendix C

C.1 Crop Sowing, Harvesting Date and Growing Length in Egypt

Table C.1 Development data for winter crops in Egypt

Crop	Growing period (days)	Sowing date in Egypt's regions			Crop development stages			
		Delta	Middle	Upper	L_{ini}	L_{dev}	L_{mid}	L_{late}
Tomato	155		01-Sep		35	40	50	30
Potato	120		01-Nov		25	30	35	30
Onion (dry)	180		01-Sep		20	25	95	40
Onion (green)	120		01-Oct		25	55	25	15
Lentil	165		16-Oct		25	35	65	40
Faba bean (dry)	150		10-Nov		65	35	30	20
Wheat	165		15-Nov		20	52	63	30
Sugar beet	180		10-Nov		30	55	60	35
Short clover	90		01-Oct		10	30	40	10
Long clover	190		01-Nov		15	25	150	0
Garlic	153		15-Sep		38	55	46	14

Table C.2 Development data for summer crops in Egypt

Crop	Growing period (days)	Sowing date in Egypt's regions			Crop development stages			
		Delta	Middle	Upper	L_{ini}	L_{dev}	L_{mid}	L_{late}
Tomato	155		01-Mar		35	40	50	30
Potato	120		01-Feb		25	30	35	30
Maize	110		15-May		20	30	36	24
Rice	150		14-May		30	30	60	30
Sorghum	120		16-May		20	30	40	30
Sugar cane	365		15-Feb		35	80	190	60
Cotton	190		10-Mar		30	50	55	55
Sunflower	95		01-May		20	25	30	20
Sesame	110		01-May		20	30	40	20
Watermelon	75		01-Mar		10	20	20	25

Continued, Table C.2 Development data for summer crops in Egypt

Crop	Growing period (days)	Sowing date in Egypt's regions			Crop development stages			
		Delta	Middle	Upper	L_{ini}	L_{dev}	L_{mid}	L_{late}
Soybean	100		01-May		15	20	45	20
Alfalfa	365		01-Apr		10	30	315	10
Eggplant	130		01-Apr		30	40	40	20
Beans	110		15-Feb		20	30	40	20
Pepper	120		15-Mar		25	35	40	20

Table C.3 Development data for Nili crops in Egypt

Crop	Growing period (days)	Sowing date in Egypt's regions			Crop development stages			
		Delta	Middle	Upper	L_{ini}	L_{dev}	L_{mid}	L_{late}
Tomato	155		01-Aug		35	40	50	30
Potato	120		15-Sep		25	30	35	30
Onion (dry)	180		01-Jul		20	25	95	40
Maize	110		01-Jul		20	30	36	24
Eggplant	130		01-Jul		30	40	40	20
Beans	106		15-Aug		20	30	40	16

Table C.4 Development data for Fruits in Egypt

Crop	Growing period (days)	Sowing date in Egypt's regions			Crop development stages			
		Delta	Middle	Upper	L_{ini}	L_{dev}	L_{mid}	L_{late}
Citrus	365		01-Feb		60	90	120	95
Olives	270		01-Feb		30	90	60	90
Banana	365		01-Feb		120	60	180	5
Date palms	365		01-Feb		135	31	193	6
Deciduous orchards	270		01-Feb		30	90	60	90
Grapes	240		14-Feb		20	40	120	60

C.2 Crop Consumptive Water Demands in Egypt

Table C.5 Calculated crop consumptive water demands (m^3/month/feddan) for the winter season in Egypt

Month	Wheat	Sugar beet	Long Clover	Winter Vegetables	Other Winter
January	292.51	255.46	244.92	279.22	250.88
February	392.39	407.47	305.79	142.97	366.32
March	603.26	627.16	475.21	0.00	491.40
April	452.98	674.24	600.95	0.00	207.31
May	0.00	160.61	220.93	0.00	0.00
June	0.00	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00
September	0.00	0.00	0.00	215.74	0.00
October	0.00	0.00	0.00	339.30	37.95
November	121.14	83.77	165.55	302.23	134.46
December	207.92	117.88	225.57	267.48	205.94

Table C.6 Calculated crop consumptive water demand (m^3/month/feddan) for the summer season in Egypt

Month	Maize	Sorghum	Rice	Sugar cane	Summer vegetables	Other summer
January	0.00	0.00	0.00	265.39	0.00	0.00
February	0.00	0.00	0.00	144.35	44.45	0.00
March	0.00	0.00	0.00	282.38	312.37	30.20
April	0.00	0.00	0.00	580.90	598.58	75.30
May	134.03	124.53	347.41	1079.50	750.71	488.34
June	529.62	510.74	789.59	1246.30	454.04	949.35
July	985.52	934.81	856.10	1162.65	212.88	870.96
August	732.09	840.88	824.91	1100.00	9.30	296.23
September	26.82	226.52	643.10	950.34	0.00	59.89
October	0.00	0.00	171.14	750.88	0.00	0.00
November	0.00	0.00	0.00	521.94	0.00	0.00
December	0.00	0.00	0.00	346.46	0.00	0.00

Table C.7 Calculated crop water consumptive demand (m^3/month/feddan) for the Nili season and fruits in Egypt

Month	Maize	Nili vegetables	Fruits
January	0.00	29.39	130.86
February	0.00	0.00	228.52
March	0.00	0.00	389.98
April	0.00	0.00	556.91
May	0.00	0.00	724.56
June	0.00	0.00	770.04
July	379.98	205.46	760.81
August	727.19	405.62	712.33
September	705.58	440.03	569.55
October	196.62	488.55	397.82
November	0.00	375.37	170.99
December	0.00	235.77	128.39

C.3 Comparison between Calculated and MWRI Estimates of Crop Consumptive Water Demands

(a)

(b)

(c)

(d)

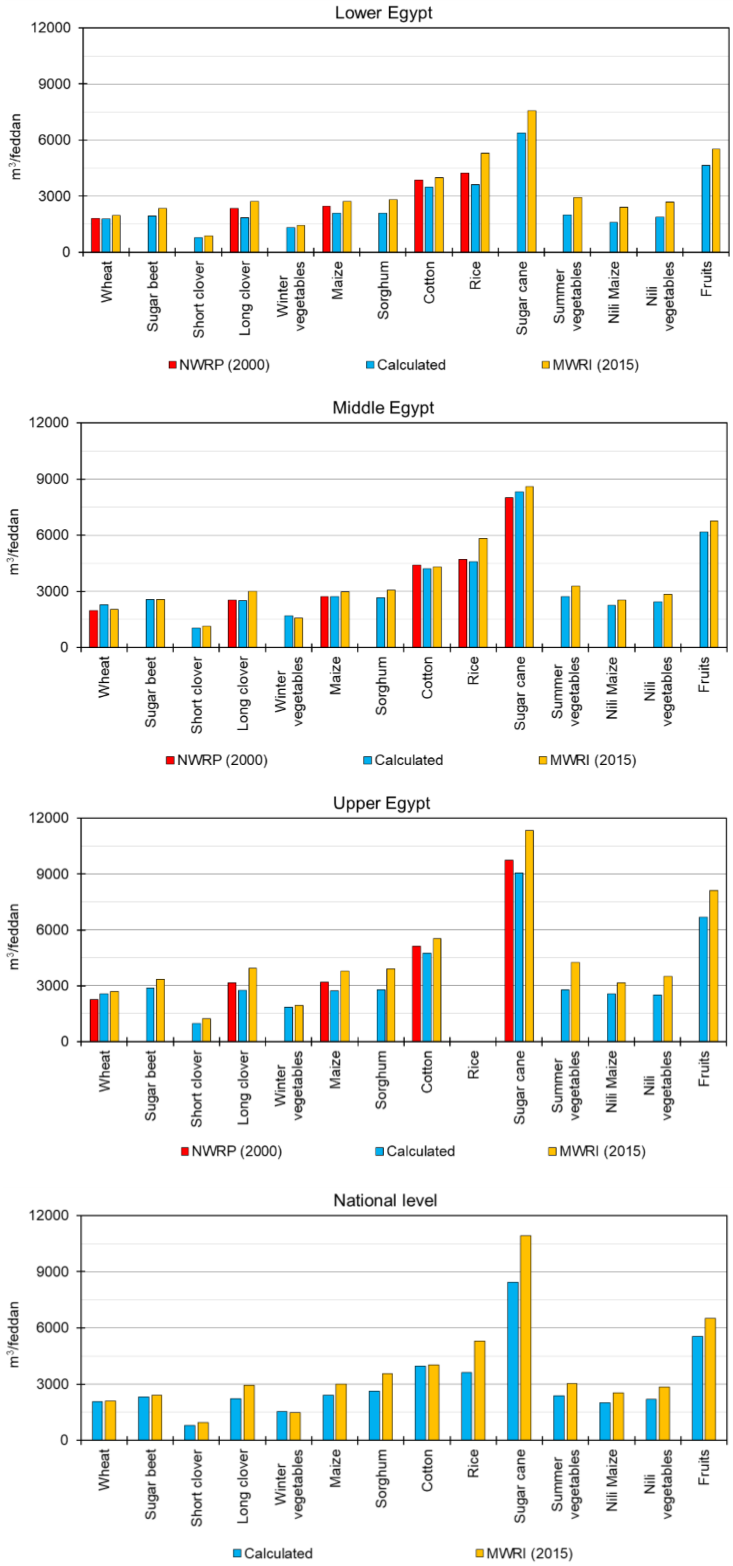
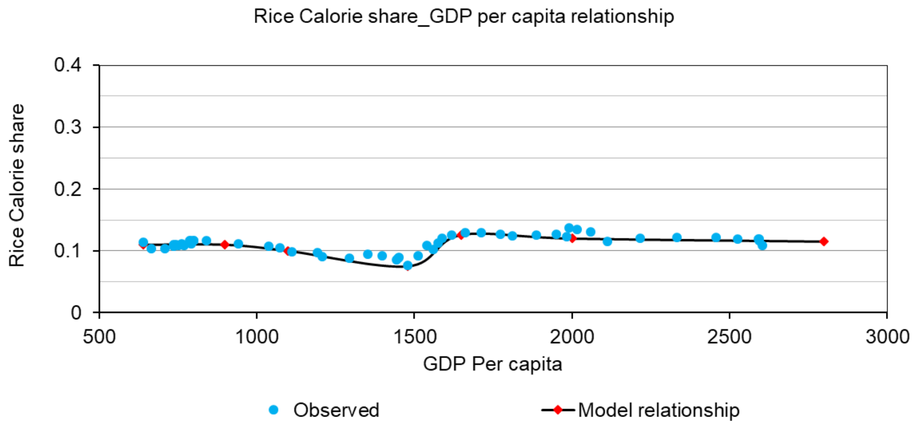


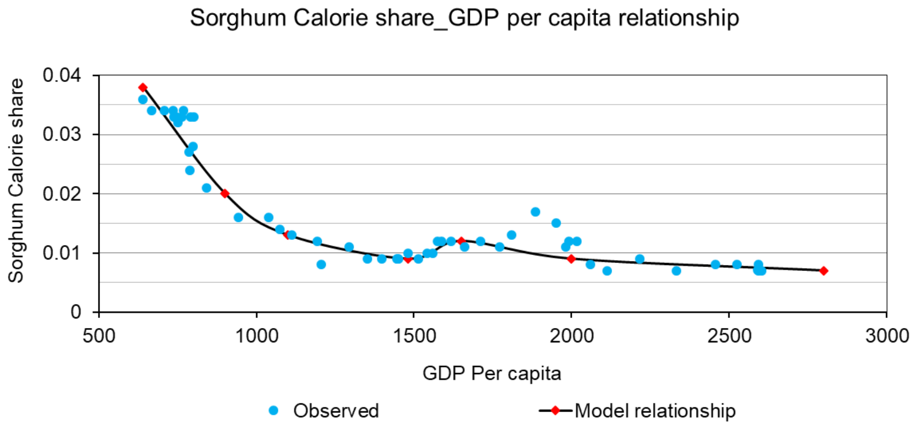
Figure C.1 Calculated vs MWRI estimates of crop consumptive water demands in: (a) Lower Egypt, (b) Middle Egypt, (c) Upper Egypt and (d) at the national level in Egypt

C.4 Relationship Between Food Commodity and GDP per Capita

(a)



(b)



(c)

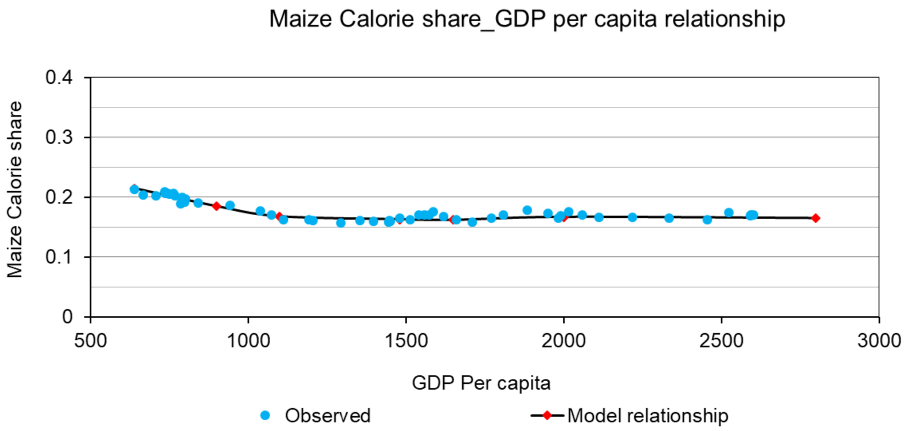
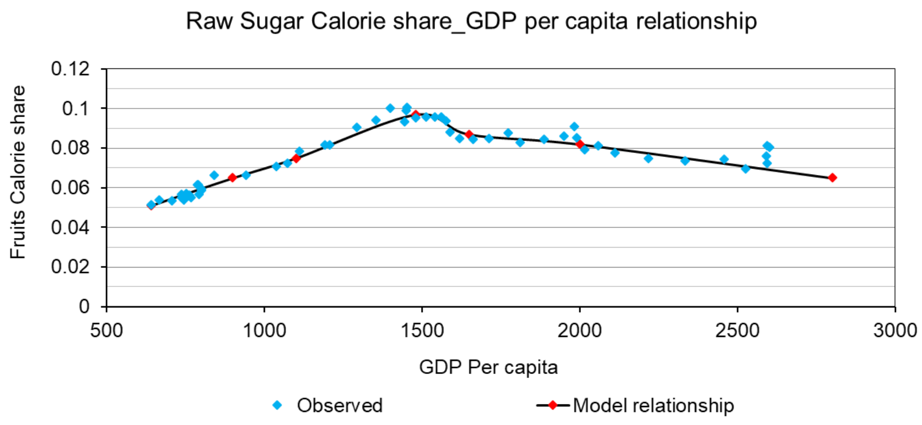
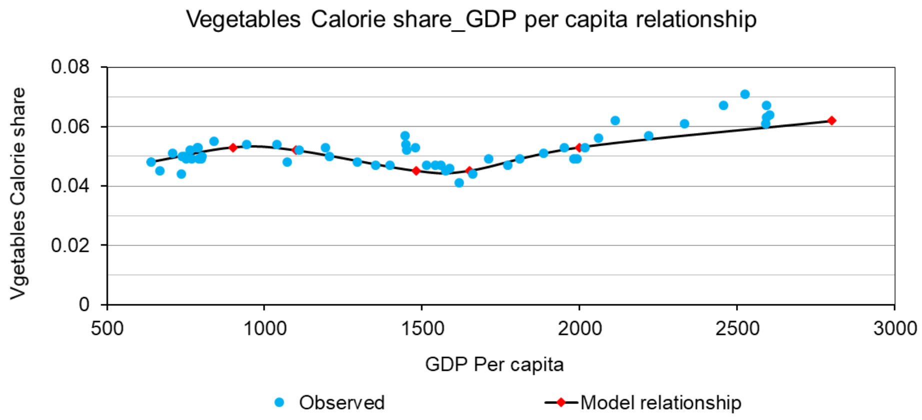


Figure C.2 Daily kcal consumption-GDP per capita relationship for: (a) Rice, (b) Sorghum, (c) Maize, (d) Raw Sugar, (e) Vegetables and (f)

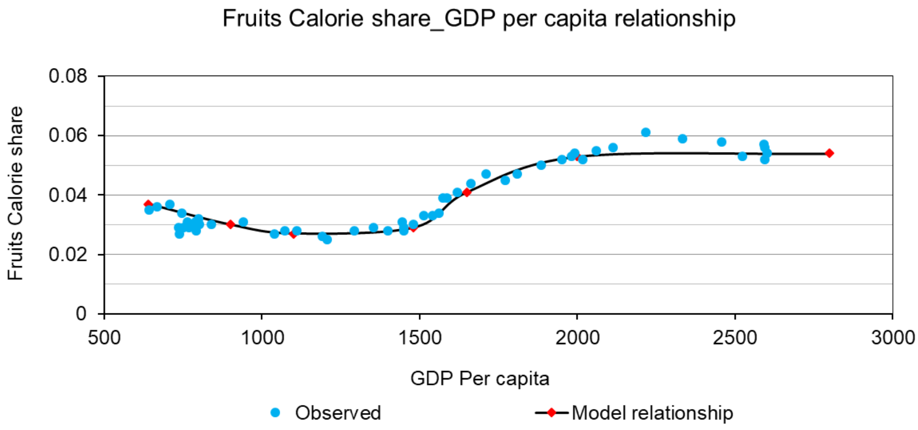
(d)



(e)



(f)



Continued, Figure C.2 Daily kcal consumption-GDP per capita relationship for: (a) Rice, (b) Sorghum, (c) Maize, (d) Raw Sugar, (e) Vegetables and (f) Fruits

C.5 Egypt Sub-Model Testing

The following equations are used in estimating statistical measures of the: Percent bias (*PBIAS*), Root Mean Square Percent Error (*RMSPE*), Theil Inequality Coefficient (*TIC*), and Theil Inequality Statistics: bias (U^M), variance (U^S) and covariance (U^C).

$$\mathrm{PBIAS}(\%) = \frac{\sum_{i=1}^{n}(S_t\text{-}A_t)}{\sum_{i=1}^{n} A_t} \quad \text{(C1)}$$

Where, *n* denotes the number of observations, S_t is the simulated value at time (*t*) and $A_t$is the actual value at time (*t*).

$$\mathrm{RMSPE}(\%) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{(S_t\text{-}A_t)}{A_t}\right)^2} \quad \text{(C2)}$$

$$\mathrm{TIC} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_t\text{-}A_t)}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n} S_t^2} + \sqrt{\frac{1}{n}\sum_{i=1}^{n} A_t^2}} \quad \text{(C3)}$$

$$U^M = \frac{(\bar{S}\text{-}\bar{A})^2}{\frac{1}{n}\sum(S_t\text{-}A_t)^2} \qquad U^S = \frac{(S_s\text{-}S_A)^2}{\frac{1}{n}\sum(S_t\text{-}A_t)^2} \qquad U^C = \frac{2(1\text{-}r)S_s\,S_A}{\frac{1}{n}\sum(S_t\text{-}A_t)^2} \quad \text{(C4)}$$

$$\bar{S} = \frac{1}{n}\sum S_t, \text{ and } \bar{A} = \frac{1}{n}\sum A_t \quad \text{(C5)}$$

Where, $\bar{S}$, $\bar{A}$ denotes the average of simulated and actual values, r is the correlation coefficient between the simulated and actual values, and $S_{s\,,}S_A$are the standard deviations of simulated and actual values.

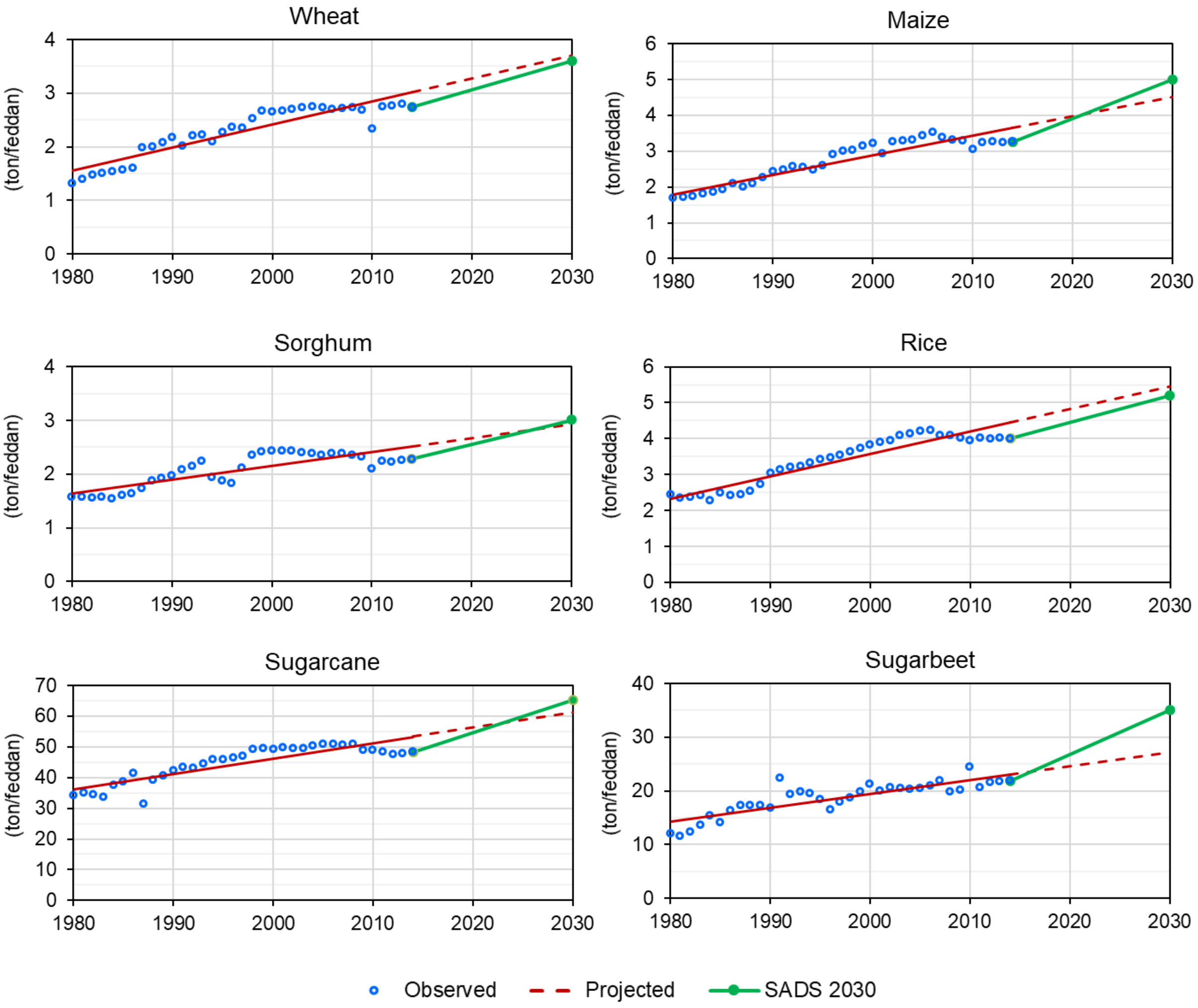


Figure C.3 Observed crop yields trends and projections vs potential

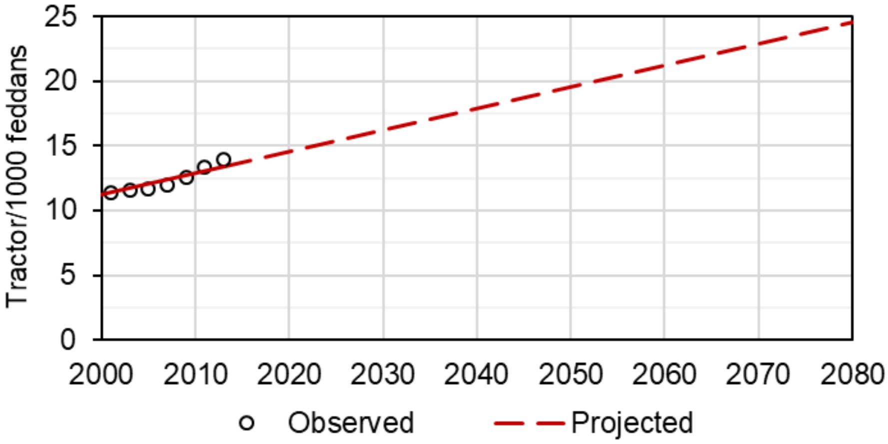


Figure C.4 Current and projected numbers of tractors per unit land

Appendix D

D.1 Statistics of Synthetic Flows (without Climate Change)

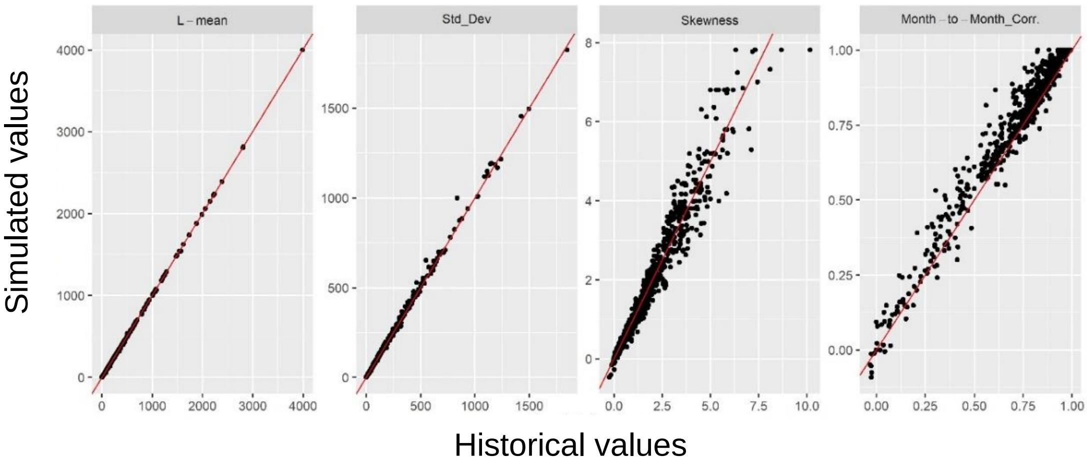


Figure D.1 Simulated VS historical statistical characteristics (mean, standard deviation, skewness, lag-1 month to month correlation) of the 72 streamflows of river tributaries

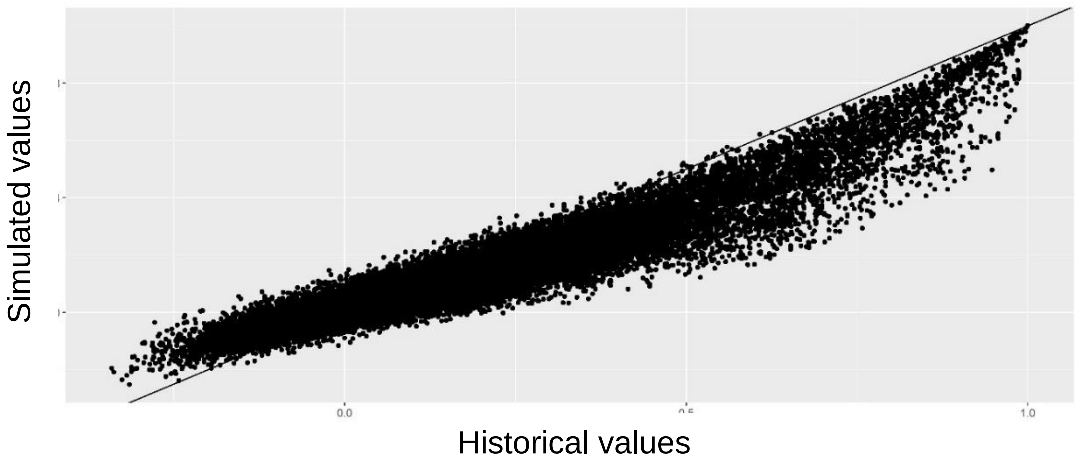


Figure D.2 Simulated VS historical lag-0 cross-correlation coefficient of monthly flows of the 72 river tributaries

D.2 Probability of Non-Exceedance of Hydropower Generation in Egypt, Ethiopia and Sudan

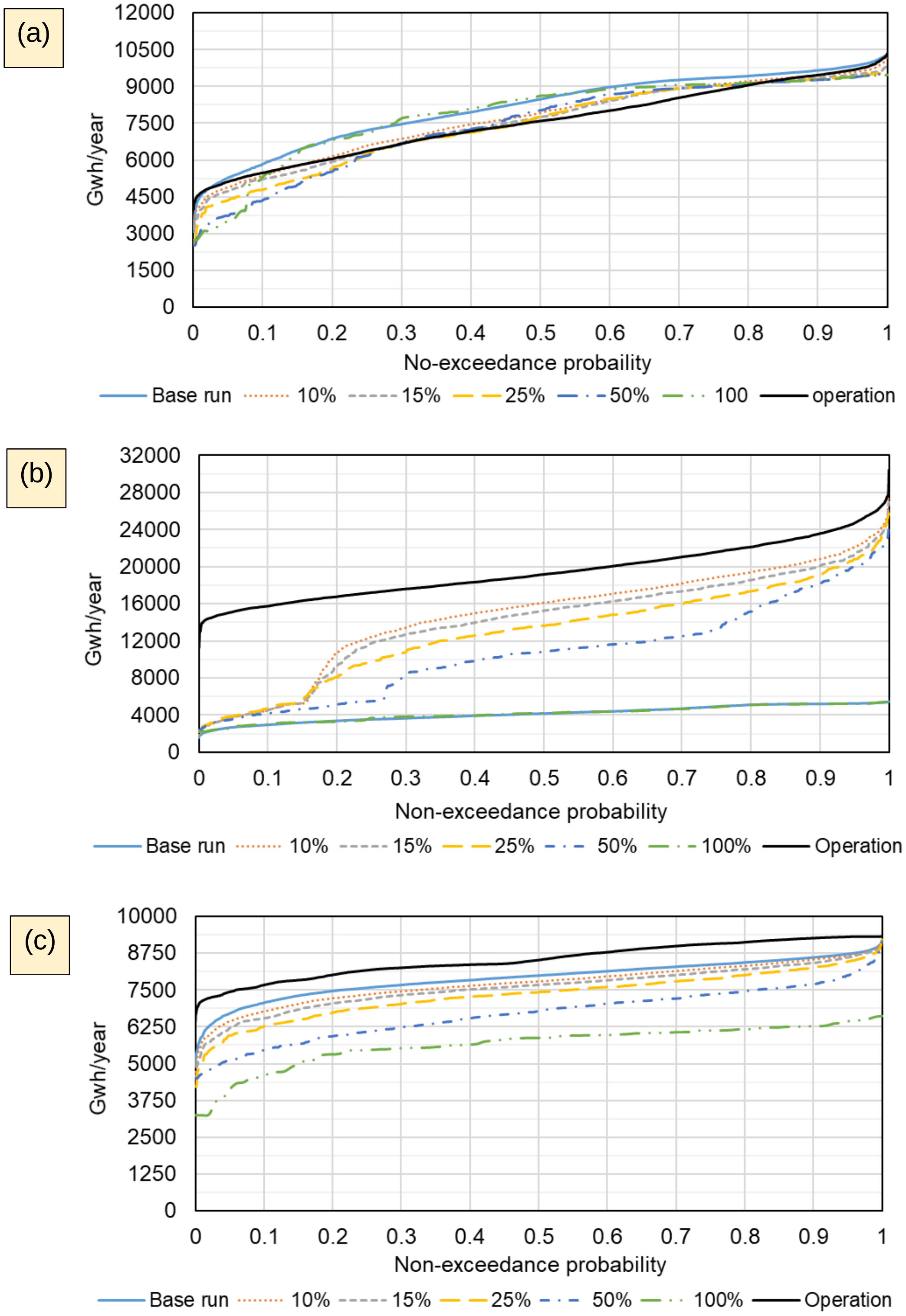


Figure D.3 Non-exceedance probability of hydropower generation in (a) Egypt, (b) Ethiopia and (c) Sudan with GERD (filling and operation) and without GERD

D.3 Statistics of Synthetic Flows (under Climate Change)

D.3.1 RCP 4.5 Dry Climate Model

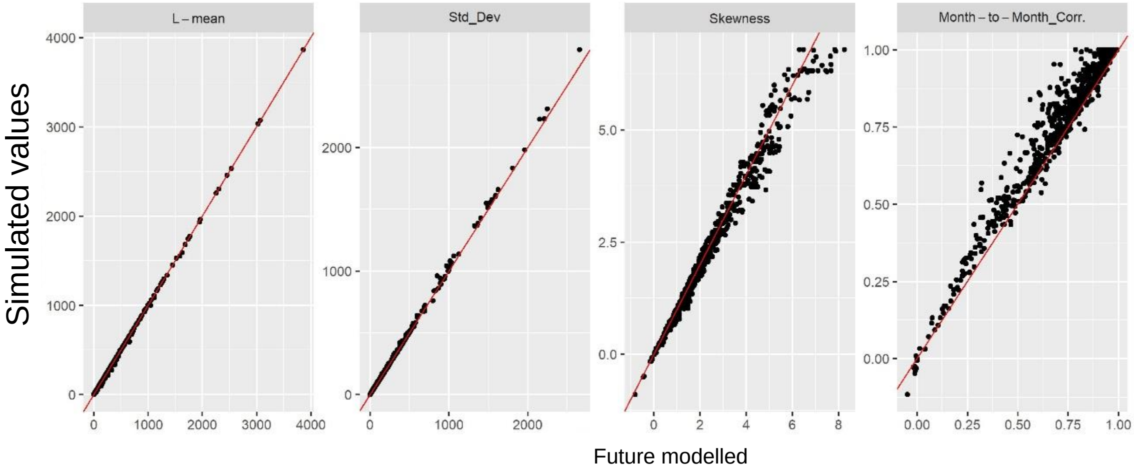


Figure D.4 Simulated VS future modelled statistical characteristics (mean, standard deviation, skewness, lag-1 month to month correlation) of the 72 streamflows of river tributaries of RCP 4.5 Dry climate model

D.3.2 RCP 4.5 Wet Climate Model

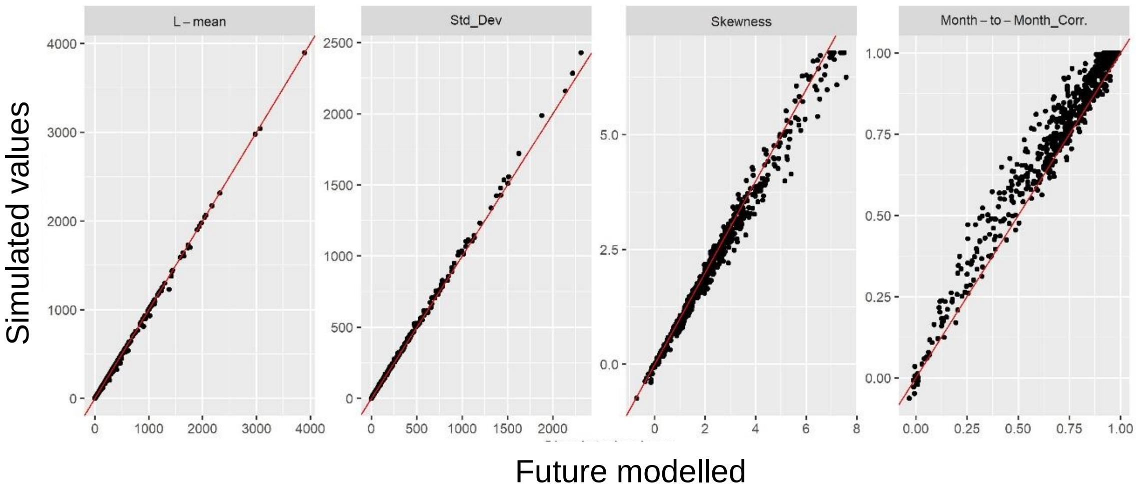


Figure D.5 Simulated VS future modelled statistical characteristics (mean, standard deviation, skewness, lag-1 month to month correlation) of the 72 streamflows of river tributaries of RCP 4.5 Dry climate model

D.3.3 RCP 8.5 Dry Climate Model

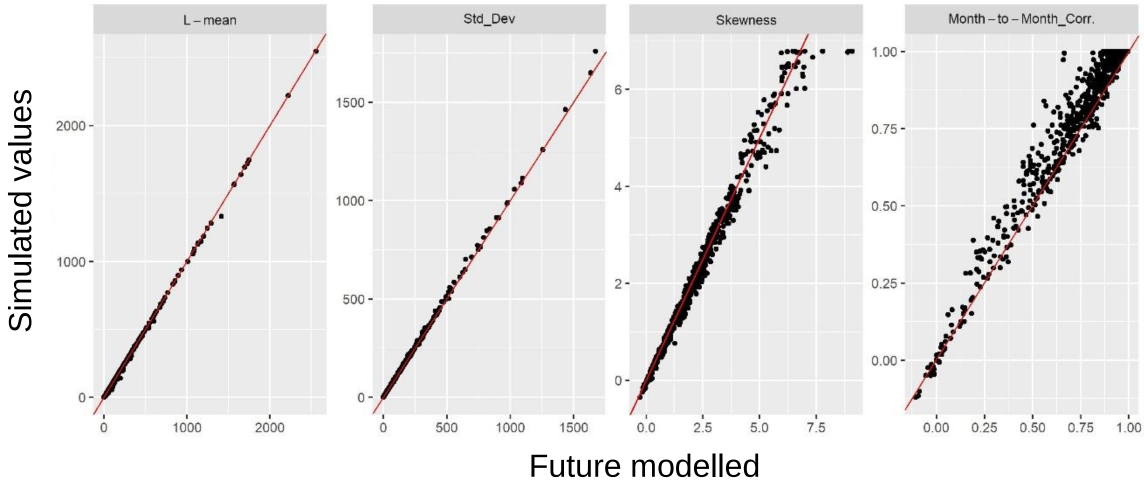


Figure D.6 Simulated VS future modelled statistical characteristics (mean, standard deviation, skewness, lag-1 month to month correlation) of the 72 streamflows of river tributaries of RCP 8.5 Dry climate model

D.3.4 RCP 8.5 Wet Climate Model

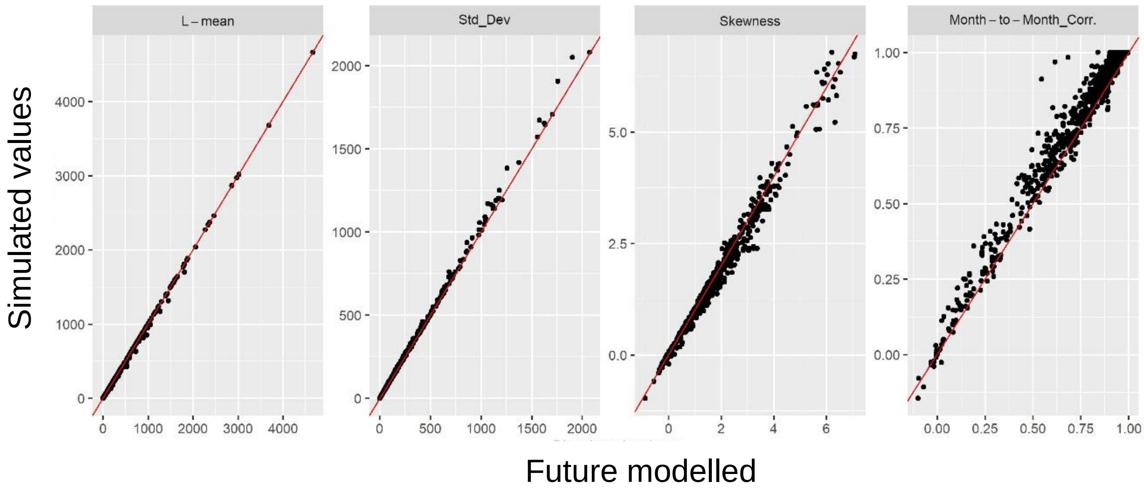


Figure D.7 Simulated VS future modelled statistical characteristics (mean, standard deviation, skewness, lag-1 month to month correlation) of the 72 streamflows of river tributaries of RCP 8.5 Wet climate model