Complexity and Uncertainty in Development of Water Demand and Supply Scenarios: A Case Study of Egypt

Mohamed Ahmed Abdelghany Nasef

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy in Geographic Information Science

The University of Leeds
Faculty of Environment - School of Geography
Centre for Spatial Analysis and Policy
August 2020

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgment.

The right of Mohamed Nasef to be identified as author of this work has been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

© 2020 The University of Leeds and Mohamed Nasef

Acknowledgements

This research would not have been possible without the help and support of numerous people. First and foremost, I would like to give my heartfelt thanks to my supervisors, Prof. Jon Lovett (Professor and Chair in Global Challenges) and Dr. Gordon Mitchell (Associate Professor, Director of Masters Education, and Leader of the master programme in Geographic Information Science), for their support, understanding and patience. They have been generous with their valuable time, guidance, and encouragement in the last four years.

In addition to my main supervisors, I would like to thank other members of my research support group, Dr. Mark Trigg and Dr. Brian Irvine, for their support and advice to improve this research.

I would also like to take this opportunity to thank Professor Alexis Comber (Professor of Geocomputation and Chair in Spatial Data Analytics) and Professor Christos Makropoulos (Professor of Hydro-Informatics *a*nd Smart Water Systems*)* - my viva examiners, for their very helpful comments and suggestions.

I would also like to thank the British Council and the ministry of higher education in Egypt for funding my PhD. I am thankful for the scholarship I received from them, which gave me the opportunity to visit a new country, meet new people, and learn new and important things. I am also thankful for the help and support that I have received from the Minister of Water Resources and Irrigation Prof. Mohamed Abdel Atty.

In addition, I would like to thank the members of the Water Resources Research Institute (WRRI), Dr. Ahmed Kamal, Prof. Gamal Abdallha, and Dr. Ahmed Shalash.

I am also thankful for the help and support that I have received from Andy Turner and Nikée Groot at University of Leeds.

This research would not have been possible without the help and support I have received from my wife, my family, and my brother Haroon. I am grateful for their patience and the love I received from them.

Abstract

Water shortage has become one of the most pressing resource issues of the last decades. Recently, Egypt's water gap has reached a stage where it is imposing restrictions on its economic development. The Egyptian water demand and supply system is consisted of many interacting components and influenced by socioeconomic and environmental factors, which are also complex and uncertain. This study represents a first attempt to deal with uncertainty and complexity in water demand and supply in Egypt. The aims of the work are to quantify uncertainty in water demand and supply modelling, assess the impacts of uncertainty factors on water demand and supply, frame the potential futures of water demand and supply, and finally evaluate the uncertainty of measures and actions to bridge the water gap. To achieve these objectives, the prediction approach, exploratory approach, scenarios analysis, and precautionary approach were employed in this study using the WEAP model, GLUE method, and Delphi technique as research tools to simulate, analyse, and manage water demand and supply. Results showed that dealing with uncertainty differs from one stage to another in the examination of the water system according to the purpose of study. In addition, selecting the way of handling the complexity in system or model is a choice made by the modeller. In this study, the choice was to use the WEAP hydrological model with fewer parameters and an understandable structure, which made dealing with uncertainty in water demand and supply easier by reducing complexity and enabling achievement of acceptable results.

Uncertainty in Egyptian Water demand and supply system is associated with the spatial variation and fluctuations of factors in the study area such as climate, agricultural area, population growth, industrial units, High Aswan Dam (HAD) outflow and human intervention. Recent changes in these factors have led to a change in the level of uncertainties in different basin areas. Model calibration and uncertainty analysis were performed with Generalized Likelihood Uncertainty Estimation (GLUE) in R software. In this study, the calibration period is (1990-2006), and the validation period is (2007-2015). The results from the uncertainty analysis indicated acceptable values of both the R-factor and P-factor over the calibration and validation periods for all gauge stations. For the calibration period, the p-factor and the r-factor values were 1 and 0.65 for Aswan station, 0.88 and 0.63 for Esna station, 0.56 and 0.45 for Assiut station, 0.72 and 0.47 for Delta station. For the validation period, the p-factor and the r-factor values were 1 and 0.94 for Aswan station, 0.78 and 1 for Esna station, 0.56 and 0.95 for Assiut station, 0.56 and 0.50 for

Delta station. When values of p-factor and r-factor are accepted, further goodness of fit can be quantified by the Nash-Sutcliff efficiency (NSE), Percent Bias (PBIAS) and Root Mean Square Error (RMSE) between the observed and the final best-simulated data. For the calibration period, the results indicated that NSE, PBIAS, and RMSE were 0.96, +0.97 and 0.61 respectively for Aswan station, 0.74, -1.20 and 2.30 for Esna station, 0.78, +1.61, and 2.11 for Assiut station, and 0.76, - 3.06, and 1.03 for Delta station. For the validation period, the results indicated that NSE, PBIAS, and RMSE were 0.97, +0.86 and 0.51 respectively for Aswan station, 0.55, +2.92 and 2.65 for Esna station, 0.57, +5.35, and 2.46 for Assiut station, and 0.53, -1.94, and 0.47 for Delta station. The results of calibration, validation and uncertainty analysis were very good and indicated a very good performance of the WEAP model in terms of the uncertainty of model structure. The rapidly growing demand for water in Egypt is due to the increasing agricultural area, population, and industrial units. The supply side fluctuates too, because of the variation of withdrawal from the reservoir, groundwater, and due to annual rainfall variability. Water shortage is not constant in the study area, and varies depending on the annual supply.

There is a high degree of uncertainty about the amount of water reaching Egypt due to the climate variability over the Nile’s upstream basin, beyond Egypt. While climate change across Egypt itself has a limited impact on water supply in Egypt because most freshwater comes from outside the country. Due to population growth, it is expected that Egypt will likely face a dramatic increase in water demand; about 9.0 BCM in 2050 with uncertainty range ± 3.4 BCM. With respect to the Grand Ethiopian Renaissance Dam (GERD), this study considers that filling of the GERD reservoir over ten years is more appropriate than filling over three to seven years, particularly in the event of droughts. The risk presented by the GERD to Egypt’s water security is not only related to the period of filling the reservoir, but also the Ethiopian policy of water release from the GERD reservoir once full.

The findings from the six scenarios presented in this thesis show that the extremely high population growth rate, increased agricultural expansion, and industrial expansion in Egypt have a crucial role in pushing the water shortage to alarming levels. By 2050, Egypt could not bridge the water gap under current policy and practice, where it would be 8.90 BCM, 0.31 BCM, and 18.09 BCM according to the Business as Usual (BAU), Critical, and Pessimistic scenarios respectively.

Obviously, Egypt's water policy does not take into account the uncertainties in supply and demand for water and in the proposed measures to close the water gap. Therefore, Egyptian policymakers and water planners may take into consideration the results of the uncertainty assessment in this study in its water policy to avoid the future water gap. In spite of the efficiency of the proposed measures in this study, Egypt should renew its water policy and management to be able to overcome the water shortage after 2050 in the case of taking place the pessimistic scenario. Unless the full representation and effective participation of stakeholders in water policy discussions are achieved, complexity and uncertainty will overshadow the management of water resources in Egypt.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

List of Equations

List of Abbreviations

BCM	Billion Cubic Meter
CAPMAS	Central Agency for Public Mobilization and Statistics
CMIP5	Climate Model Intercomparison Project
Feddan	An Egyptian unit of area equivalent to 0.42 hectare
GERD	Grand Ethiopian Renaissance Dam
GFDL	Geophysical Fluid Dynamics Laboratory Model
GISS	Goddard Institute for Space Studies
GLUE	Generalized Likelihood Uncertainty Estimation
HAD	High Aswan Dam
HADR	High Aswan Dam Reservoir
IPoE	International panel of experts on the Grand Ethiopian Renaissance Dam
IWRM	Integrated Water Resources Management
MC	Monte Carlo
MCMC	Markov Chain Monte Carlo
MF	Million Feddan
MP	Million People
MSG	Meteosat Second Generation satellites
MWRI	Egyptian Ministry of Water Resources and Irrigation
NFC	Nile Forecasting Centre
NSE	The Nash-Sutcliff efficiency
ParaSol	Parameter Solution Method
PBIAS	Percent Bias
PEST	Model-Independent Parameter Estimation and Uncertainty Analysis
RMSE	Root Mean Square Error
SA	Sensitivity Analysis
SCE-UA	Shuffled Complex Evolution Method
SNCR	Second National Communication Report
SUFI-2	Sequential Uncertainty Fitting algorithm version 2
UA	Uncertainty Analysis
UKMO	UK Meteorological Office
WEAP	Water Evaluation And Planning System

Chapter 1
Introduction

1.1 Introduction

The issue of uncertainty and complexity has received increasing interest in water resources research. A considerable part of the community was hesitant to acknowledge the crucial role of uncertainty and complexity in hydrological modelling and water management due to irrational arguments such as the difficulty of performing uncertainty analysis (UA), subjectivity of UA, and ignoring uncertainty when making final decisions (Pappenberger and Beven 2006). However, research contributing to the issue of uncertainty and complexity in water resources is currently appreciated by scientists and policy makers. Uncertainties and complexities surrounding climate change, population growth, and socio-economic factors among others make the future of water demand and supply uncertain and complicated. The need to address uncertainty and complexity in identifying the future of water demand and supply is widely recognized (Yang and Zehnder, 2005; Bharati et al., 2009; Kanta and Zechman, 2014; Beh et al., 2015; Kiefer et al., 2016; Hassan et al., 2019). In the present study, I fill the gap of addressing uncertainty and complexity in developing water demand and supply scenarios in the case study area of Egypt.

The impetus for the present study stemmed from the importance of water issues in Egypt and associated complexity and uncertainty with respect to water security. The choice of Egypt as the study area reflects the national water system, which includes complexity and uncertainty in limited water supply in the face of uncertainty about increasing socioeconomic water demand, plus the predicament Egypt faces due to the Grand Ethiopian Renaissance Dam (GERD) in the upper Nile. The expected innovation of this contribution is the interdisciplinary approach adopted to reveal and analyse uncertainty and complexity in Egypt's water demand and supply. This approach combines hydrological, economic, ecological, sociological, technical, and managerial aspects. The uncertainty and complexity of Egypt's water demand and supply in the context of uncertainty factors' impacts of population growth, climate change and variability, and socio-economic developments are significant issues that will certainly be central in the upcoming years. Therefore, the problem of uncertainty and complexity in the water demand and supply can be described in terms of: (1) uncertainties related to water demand and supply modelling, for example, uncertainty results from a limited understanding of the process, model structure uncertainty, and input data uncertainty; (2) uncertainties related to projections and potential future; and (3) efficiency of actions and measures to bridge the water gap. The challenge and intricacy state of simulation, procedures, and the multiplicity of factors, model parameters and components of water demand and supply system, and the innumerable interrelationships between them refer to complexity. This complexity arises from complex non-linear multi-scale interactions between, climate, water, soil, vegetation and human systems among others. Uncertainties and complexities can be viewed at three levels; namely, modelling of water demand and supply, the future of water demand and supply, and management of water demand and supply. Dealing with this uncertainty and complexity in water demand and supply by quantifying, identifying, and assessing properly may help decision-makers and planners avoid high-risk decisions, high cost of water utilities, water rate-payers, and the environment.

1.2 Background on Uncertainty and Complexity of Water Demand and Supply

In general, water scarcity and the associated range of uncertainties in demand and supply are mounting worldwide (Greve et al., 2018). Uncertainty refers to the hidden part that we are totally unaware of, or that we know very little about, and to reduce by obtaining more information and knowledge. Concisely, uncertainty is explained as what is not precisely known. This definition allows various forms of uncertainty to be included from different sources and activities, most of which go overlooked in the analysis (Booker and Ross, 2011). Complexity is interpreted as a property of the system that makes it difficult to understand (Vidal et al., 2011). From another point of view, Ward and Chapman (2003) identified the number of influencing factors and their interrelationships as components of complexity, which consequently contribute to uncertainty. Complexity refers to the degree of simplicity in system modelling and is connected with the extent of our understanding of the interactions and impacts of system components (Edmonds, 1999; Thunnissen, D.P., 2003; Beven et al., 2013). Uncertainty and complexity of water demand and supply is a multi-faceted issue, and it is necessary for planners to incorporate demand and supply predictions into their action plans. Demographics, climate, hydrology, economy, and other factors affect water demand and supply. A lot of research has been done on the uncertainty and complexity of the water demand and supply system (Yang and Zehnder, 2005;

Chung et al., 2009; Seifollahi-Aghmiuni et al., 2011; Guieysse et al., 2013; Kiefer et al., 2016). In general, this research has demonstrated the importance of identifying uncertainties when implementing water demand and supply projects by examining the uncertainties concerning future water demand and supply in different study areas and presenting leading strategies to manage these uncertainties. In addition, Chung et al. (2009) confirmed that the study of uncertainty and reliability are essential design factors for water supply systems. Furthermore, Seifollahi-Aghmiuni et al. (2011) reported that the evaluation of water demand uncertainty leads to the improvement of the efficiency of the network and cost savings.

Water demands are estimated from different types of water usage such as domestic, irrigation, and industrial, and gathered to give the total water demand. Water demand projections are based on a number of factors such as population growth and water consumption per capita (for domestic demand), agricultural area and water needs per feddan (an Egyptian area measure equivalent to 0.42 hectare) (for irrigation), industrial units and water consumption per unit (for industrial use). Industrial units refer to the current number of factories and the demand rate for each unit is calculated from the whole demand of the industrial sector regardless of the variation in factories' activity (CAPMAS, 2015). Water supply is represented in conventional and non-conventional resources; the conventional resources include surface water, rainfall, groundwater, while the non-conventional resources include water reuse, and desalination. The non-conventional resources are not taken into account when calculating the water gap between supply and demand. The projections of water supply depend on a number of factors such as climate change, groundwater exploitation, water treatment, seawater desalination, and inter-state cooperation in the river basin. Sources of uncertainty and complexity exist in all stages of water demand and supply, including their simulation, forecasting, and management. Uncertainty and complexity sources in water demand and supply includes models, system, simulation of demand and supply variables, projections of demand and supply variables, future of demand and supply, water demand and supply management and policy among others.

1.3 Water Crisis

The problem of water scarcity threatens many developed and developing countries. Pressure on global water resources is increasing with rising population and global economic growth driving higher water demand for domestic, agricultural, and industrial uses (Alcamo et al., 2007; Jury and Vaux, 2007; Shen et al., 2014). Uncertain future changes in water resources availability are one of the major concerns arising from both global climate change and socio-economic development (Shen et al., 2008). The current problem of water scarcity due to climate change was predicted by the 2007 IPCC report on climate change, which stated that "by 2020, between 75 and 250 million people are projected to be exposed to an increase of water stress due to climate change in Africa" (Parry et al., 2007, p.13). In addition, a water crisis is much talked about, the most noticeable manifestation of which is that 1.2 billion people need access to clean and accessible water for their domestic use (WHO, 2003). Less well documented is that most of the rural population with an income below the $1-per-day poverty line lack access to water for their livelihoods (Rijsberman, 2006). Assessing future water demand and supply is crucial for policymakers to assess the risk of water scarcity challenges for the coming generations (Hejazi et al., 2013).

As for Egypt, the situation has become worse over time and more complicated. This is for many reasons including: (i) limited supply against an ever-increasing demand, (ii) population growing dramatically, (iii) climate change over Egypt and climate variability over the Nile upstream basin, (iv) the majority of surface water comes from outside Egypt, (v) increased urbanization, industrialization, and agricultural development, and (vi) political problems with riparian countries caused by their development plans. The combined effect of these pressures leads to uncertainty and complexity in the current and future Egyptian water system.

Egypt has an arid climate with scarce rainfall and its major freshwater source originates outside its border. Egypt is a downstream country and has a share of the Nile water estimated at 55.5 BCM as written into an agreement between Egypt and Sudan in 1959, but what reaches Egypt varies from year to year. This variation depends on the variability of rainfall over the Nile upstream and the water usage in the Nile Basin countries. Historically, the Nile River has always played a vital role in Egypt and it reflects society's reliance on the natural regenerative cycle. Egypt is extremely dependent on the River Nile, being the downstream country in the Nile basin. Egypt has hardly any other freshwater resources. Rainfall is scarce, except for a very small strip along the Mediterranean coast, and groundwater is only available in parts of the Western and Eastern deserts and the Sinai (MWRI, 2005). Rainfall over Egypt is estimated at 1.3 BCM by the Egyptian Ministry, and estimate unchanged in decades. The exploitation of deep groundwater in the desert and the Sinai reached 2.5 BCM in 2017, while the shallow groundwater under valley and delta reached 7.15 BCM in 2017 (MWRI, 2018). Egypt considers the shallow groundwater as non-conventional sources, where it infiltrates from Nile waters. In addition, desalination contributes 0.1 BCM (in 2015). Against these supply constraints, water demand increases continuously, with agricultural, domestic and industrial demands of 61.6, 10.7, and 5.4 BCM in 2017 respectively. In addition, evaporation loss from the Nile and associated canals is estimated at 2.5 BCM. In 2017, the total water supply was estimated at 59.25 BCM, while the total water demand is 80.25 BCM. Therefore, a water shortage (‘water gap’) of 21 BCM in 2017 was reported by the Egyptian Ministry of Water (MWRI, 2018). Egypt covers this deficit through water reuse and increasingly via unsustainable withdrawal from shallow groundwater (ground water ‘mining’).

In relation to this water crisis, population growth and rising demand is certainly among the most pressing challenges that Egypt faces. About 90% of the population lives on 5% of the land area around the Nile River and Delta. The remaining 95% of the country is desert (Wolters, 2016). According to CAPMAS (2020), Egypt has a population of 106 million people in 2020 with an annual growth rate of 1.9%. This population growth has led to severe pressure on water resources, decreasing the available water per capita from 2200 m^3/capita in 1960 to 570 m^3/capita in 2017 (MWRI, 2018). This means that, according to the Falkenmark Water Stress index, Egypt has gone from a position of water security (>1700 m^3/capita), to water scarcity (>500 and <1700 m^3/capita), and is quickly approaching the position of absolute water scarcity (<500 m^3/capita) (Falkenmark et al., 1989). The projections indicate that the available water per capita will be 324 m^3/capita by 2050 and population will likely vary between 145.6, 174.7 million people according to the United Nations and CAPMAS projections. This will increase the water crisis in Egypt due to the limited water supply. Furthermore, the population growth and its projections, water consumption per capita, and efficiency of water distribution network represent one aspect of the sources of uncertainty and complexity in water supply and demand in Egypt

Additionally, developing countries are vulnerable to climate change, especially those in Africa where millions continue to suffer from regular flooding and drought (Fischlin et al., 2007). Climate change represents a challenge that threatens Egyptian water resources on two aspects; climate change over Egyptian itself (its ‘inlands’) and climate variability over the Nile upstream. In the present study, climate variability refers to the natural fluctuations in Nile's upstream inflows to Egypt due to the variability of rainfall over the Nile basin. Climate change refers to changes caused by natural processes and human activity over Egypt, which can be represented by climate models projections. In terms of water supply, research discusses the impacts of climate change on the Nile upstream (e.g. Conway, 1996; Agrawala et al., 2004; Eid et al., 2007; Elsaeed, 2012). However, no study has yet addressed the impact of climate change on water resources in Egypt. The available studies discussed the impacts of climate change on sea-level rise, agriculture, economy, and environment, but not holistically. The different future scenarios for the impacts of climate change on the Nile upstream show varied projections of increase and decrease. The future of climate change over Egypt or over the Nile upstream is uncertain and complex. There is a need for more accurate and comprehensive studies to identify the impact of climate change and variability on water demand and supply of Egypt.

Another source, which contributes to the water crisis, and increases uncertainty and complexity in water demand and supply in Egypt, is the need for development in agricultural and industrial sectors. The need to bring new agricultural lands and industrial units to meet the needs of the increased population has become urgent. New lands reclamation is constrained not only by the land resources but also by the availability of water resources, which is already scarce. Moreover, there is a considerable increase in domestic and industrial water demand (Attia, 2018). The agricultural sector is the largest consumer of water in Egypt, at about 85% of total demand (MWRI, 2014). Historically, agricultural expansion has increased continuously. The agricultural area in 1990 was 6.9 million feddans, approximately 7.7 million feddans in 2000, and was estimated to be 11.0 million feddans by 2017 due to the mega projects, the El-salam canal and Toshka New Valley irrigation project (MWRI, 2005). The El-salam canal and Toshka New Valley are two mega land reclamation projects that have been launched to provide the base for population resettlement and further economic development (Sallam et al., 2014). The El-Salam canal is located west of the Suez Canal to reclaim about 620,000 feddans and the second project is Toshka New Valley south of Egypt, which is called Toshka project, which will reclaim some 540,000 feddans (MWRI, 2005) (Figure 1.1). The failure of these projects meant that agricultural lands in Egypt recorded a reduced 9.1 million feddans in 2017 and consumed 61.6 BCM of water. For the industrial sector, the industrial units reached 7590 units in 2015 and consumed 5.4 BCM. The increased development in agriculture and industry to meet the demands of population causes more pressure on Egyptian water resources. In addition, the agricultural area and industrial units and their projections, water consumption per feddan, and water consumption per unit are considered as sources of uncertainty.

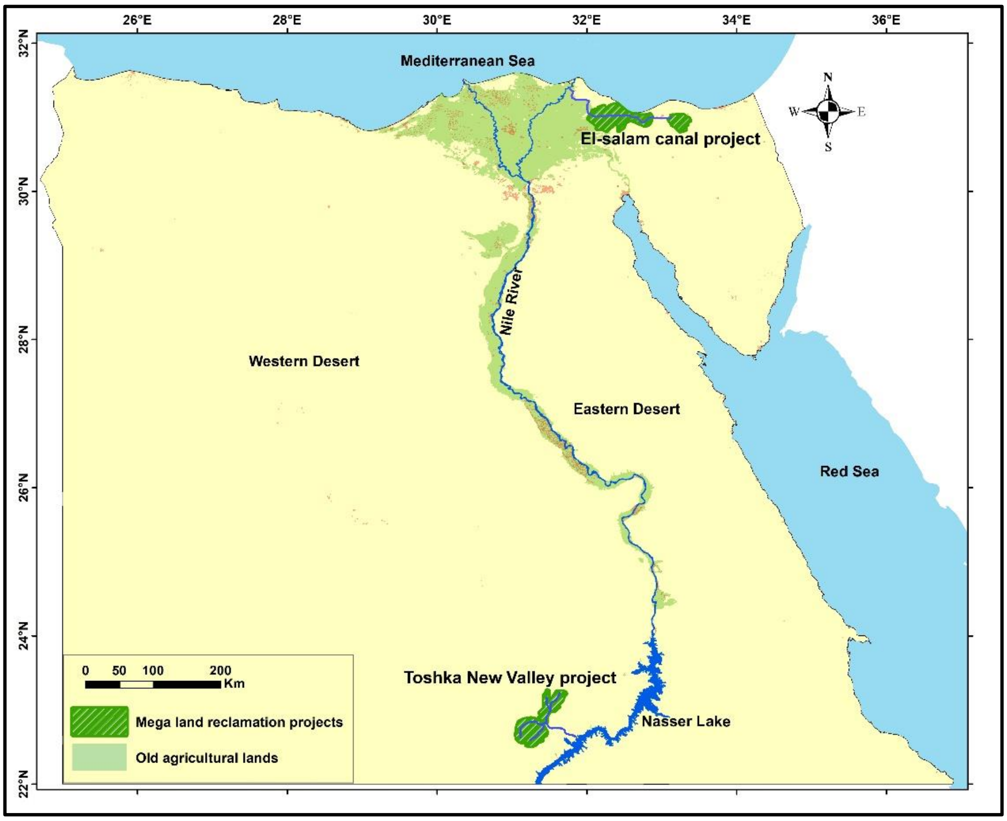


Figure 1.1 Location map of mega land reclamation projects in Egypt. (MWRI, 2005)

The political issues in riparian countries related to the Nile water help worsen the water crisis and lead to more uncertainty and complexity in Egyptian water demand and supply. These issues are often associated with the developmental plans of the riparian countries. One of these issues is the Grand Ethiopian Renaissance Dam (GERD). According to the International Panel of Experts (IPoE), the capacity of GERD is 74 BCM (IPoE, 2013). This means a deduction of a large percentage of the Blue Nile water, which provides Egypt with 59% of its water.

In addition, Egyptian water policies and plans, developed since 1975, need to be enhanced by assessing their uncertainty, and assumptions made about related measures. These policies and plans completely ignore uncertainty and have no metrics to identify the likelihood of proposed measures to manage water demand and supply effectively. The policies and plans also lack any feasibility assessment of planned measures. It is necessary to report that water shortages that such actions were intended to prevent still exist and indeed, and are increasing in spite of these policies.

These characteristics of Egypt: high population growth; development activities; climate change; an arid environment; Nile River flow and dependency; and the trans-boundary problem with upstream countries presents Egypt as a complex water system with a clear complexity and uncertainty challenge this research seeks to address.

1.4 Research Questions

The uncertain and complex characteristics of water demand and supply create a number of problems for policy makers that can be formulated as a series of basic research questions (we demonstrate approaches to answering these problems for the case of Egypt):

1. How can we deal with uncertainty and complexity in water demand and supply modelling?

2. How can we assess the impacts of future uncertainty factors on water demand and supply?

3. What are the expected future water demand and supply, and water gap?

4. How can we deal with uncertainty and complexity in water demand and supply management?

These questions can be elaborated by turning them into research objectives, as described in the next section.

1.5 Research Objectives

The intention of this study is to contribute to dealing with uncertainty and complexity in water demand and supply. Consequently, the objectives of the study are as follows:

1. Identifying a method to deal with uncertainty and complexity in water demand and supply assessment in Egypt for establishing a primary understanding of the basin hydrology.

This objective aims to quantify and address the uncertainty sources (input data and variables, model structure, parameters, outputs) in water demand and supply modelling. In addition, identifying the types of uncertainty related to water demand and supply. Furthermore, developing a subjective scale to judge the complexity in water demand and supply modelling. This objective covers the scope of the current research to establish an efficient model for the Nile Basin in Egypt, using the available historical data, with the ultimate goal of simulating and modelling water demand and supply processes. Finally, after calibrating this model and measuring its reliability, it will be used to achieve the remaining objectives of this study.

2. Assessing the impacts of future uncertainty factors on water demand and supply in Egypt.

Assessing the impacts of different future uncertainty factors related to climate change, climate variability, population growth, land-use change and the GERD on water demand and supply in Egypt as part of a risk assessment. The purpose of assessing the impact of these factors is to provide the decision-maker with a range of uncertainty about the risks of these factors to help in developing appropriate water policies.

3. Framing the future of water demand and supply in Egypt.

To achieve this objective, I will develop a set of plausible scenarios for future water demand and supply to identify uncertainty in these factors for Egypt. These scenarios include assumptions related to hydrological fluctuations of climate, potential policies, technology and infrastructure development, socio-economic drivers, and human behaviour change. The main purpose of these scenarios is framing the future of Egypt’s water demand and supply in the light of uncertainty and complexity.

4. Identifying the optimal methods to bridge the future water gap.

The final objective is to determine the optimal measures to bridge the future water gap through addressing uncertainties about these measures, and so help planners and decision-makers to find alternative, efficient solutions. Identifying a method depends on a precautionary approach for integrated water demand and supply management using the Delphi technique with the WEAP modelling framework.

1.6 Thesis Structure

This thesis comprises eight chapters, of which the first and the last chapters give a general introduction and conclusion, respectively. Chapter 2 covers the literature review on issues, theories, and methods and approaches of dealing with uncertainty in water demand and supply, and identify the gaps in knowledge. Chapter 3 provides the methodology of this thesis and specific details of how the study will be conducted.

The remaining chapters respond to the study's objectives as shown in Figure 1.2.

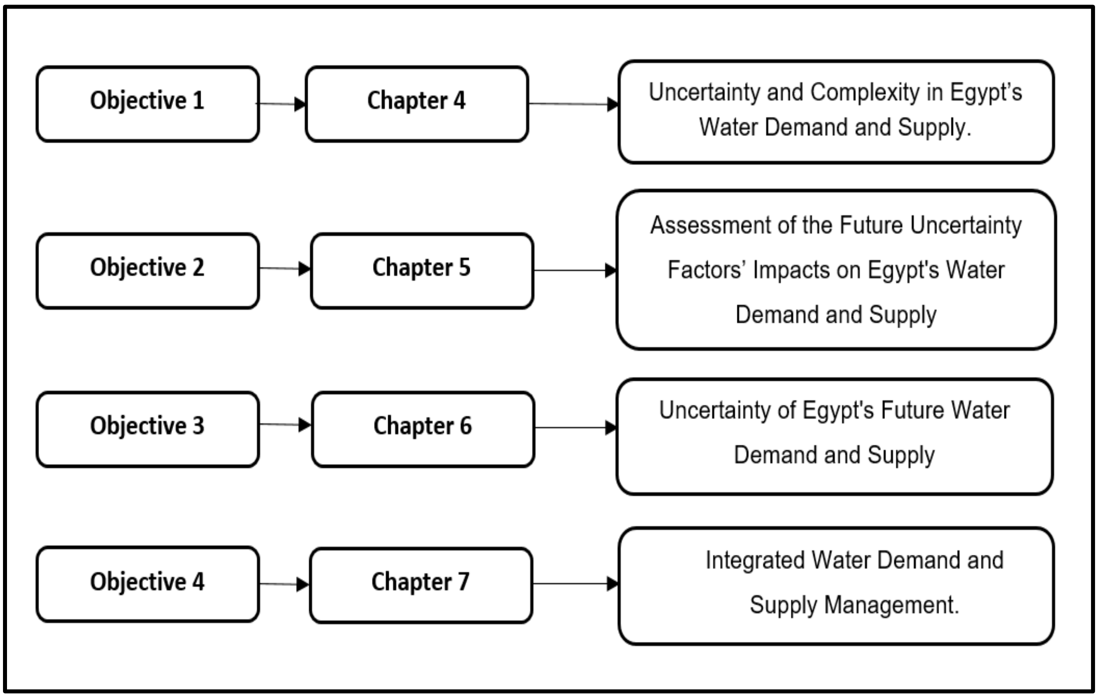


Figure 1.2 Organization of the thesis.

Chapter 2
Literature Review

2.1 Introduction

Taking action amongst an uncertain future and complex real world is one of the most difficult challenges we face today. The need to address uncertainty and complexity in the development of water demand and supply scenarios has been identified as the most haunting problem facing the policy makers of water resources on a national and global scale (Ako et al., 2010; Cosgrove and Loucks, 2015; Larson et al., 2015; Thissen et al., 2017; Tantoh and Simatele, 2018). In general, uncertainty is interpreted as what is not precisely known (Booker and Ross, 2011; Heal and Millner, 2014; Kern-Isberner and Lukasiewicz, 2017; McMillan et al., 2018). This description allows various forms of uncertainty to be defined from different sources and activities, most of which go overlooked in the analysis (Booker and Ross, 2011); While complexity is defined as property of the system that makes it difficult to understand (Vidal et al., 2011). In addition, Ward and Chapman (2003) have identified the “number of influencing factors and their interrelationships” as components of complexity, which consequently contribute to uncertainty.

Dealing with uncertainty and complexity in water demand and supply scenarios using the methods of reduction, identification or quantification can improve the reliability of estimates of water need, and reduce the cost of implementation. In addition, this helps policymakers to develop water plans that adapt more effectively to the unexpected changes under climate change, population growth and different development activities. Nearly, all the environmental issues faced today, including those of water resources, involve some elements of uncertainty. Uncertainty and complexity have wide applicability to many diverse fields; making both topics fertile ground for research.

In this literature review, recent studies are highlighted that focus on the problem of uncertainty and complexity in water demand and supply system on the global scale, for the Nile basin, and for Egypt. However, no study has holistically discussed the uncertainty and complexity issue in water supply and demand system for Egypt though a few researchers address uncertainty of climate change and its impacts (Conway, 2005; Elshamy et al., 2009a; Elshamy et al., 2009b; Kingston and Taylor, 2010; SNCR, 2010; Di Baldassarre et al., 2011; El Ganzori, 2012).

Uncertainty and complexity are associated with water scarcity issues, especially in arid regions such as Egypt, where they are steadily increasing in various sectors due to increasing demand and limited supply. Water scenarios are usually applied in Egypt in deterministic terms, where reference values (average, low, high) are used to represent key factors of population growth, development activities, climate change, and the flow of the Nile, given the fact that those values may be uncertain. As for the management side, Egypt is not exempt from uncertainty; every proposed water plan to manage the water scenarios contains some degree of uncertainty. However, each proposed plan ignores this uncertainty and deal with the system as a normal system, where each factor is knowable and wholly predictable, but in fact, the Egyptian model is a completely complex system. To have a clear picture of uncertainty and complexity issues in such water systems, I must first recognize some foundational and scientific concepts related to the issue.

2.2 Uncertainty and Complexity: The Idea and Concept

Uncertainty plays a crucial role in the analysis and evaluation of a wide and varied set of fields. Understanding uncertainty and complexity is one of the major scientific issues of our time. It affects many crucial problems facing the world today - from climate change projections, to economic modelling, to the interpretation of medical data (Brodlie, 2012). In order to better illuminate the concept of uncertainty, this section of the chapter sets out to do three things. First, it provides historical overviews of the concept of uncertainty in general. Second, it provides some conceptual discussion of uncertainty in different fields. Third, it illustrates conceptual issues linked to uncertainty such as risk and complexity.

Historically, the precursors of ideas and concepts of uncertainty have long been associated with gambling and games. The earliest-known form of gambling was a kind of dice game played with astragals in 3500 BC Egypt (Bernstein, 1998). It is clear that the idea and concept of uncertainty have been around for a long time; beginning with Socrates and Plato, where the philosophers at that time doubted whether scientific knowledge is adequately represented reality (Tannert et al., 2007). In the late 1800s, the English statistician Karl Pearson was the first one describing the idea and concept of uncertainty as a measure of data variation (Salsburg, 2001). Before Pearson, scientists knew that uncertainty is variability and was embedded into their measurements, but thought that it was only due to error. Pearson presented his revolutionary idea about the interpretation of uncertainty that is inherent in nature and this is not due to the limitations of technology in measurement (Carpi and Egger, 2008). In 1927, The German physicist Werner Heisenberg put forward the uncertainty principal in quantum mechanics field referring to the location and the speed of an object ‘electron’ cannot be precisely measured, simultaneously, even in theory (Peat, 2002; Busch et al., 2007). Later, the term of uncertainty was widely used and developed to include multiple and different definitions according to each field and the term has come to encompass a multiplicity of concepts. For example, scientists agree on the tenor of their definitions that the uncertainty can be described as a situation in the system involving incomplete or unknown information. While, Antunes and Vicente (2015) defined the uncertainty is an ambiguous expression with no clear explanation.

Obviously, many definitions of uncertainty have been proposed according to different fields (Knight, 1921; Moellering, 1988; Beard et al., 1991; Taylor and Kuyatt, 1993; Goodchild et al.,1994; Klir and Wierman, 1999; Thunnissen, 2003; McManus and Hastings, 2006; Montanari, 2007; Booker and Ross, 2011; Beven et al., 2013; Antunes and Vicente, 2015; Nearing et al., 2016). Thunnissen (2003), tried hard to come up with a comprehensive definition of uncertainty that is “doubtfulness or vagueness”, “want of assurance or confidence; hesitation, irresolution”, “liability to chance or accident”, and “something not definitely known or knowable”. While Dungan et al. (2002) defined uncertainty as a multi-faceted description of data or predictions using data that may include different aspects, for example, error, precision, validity, goodness, confidence and reliability. Luce and Raiffa (1957) and Resnik (1987) supported the concept that uncertainty is that specific acts and outcomes have a range of potential results whilst the probabilities of these results are uncertain or insignificant. Klir and Wierman (1999) noted that uncertainty itself has many types and dimensions, and may include concepts such as fuzziness or ambiguity, discrepancy and conflict, inaccuracy and lack of specificity. Kase and Cantón (2013) confirmed that uncertainty has been defined as the lack of certainty and identified the uncertainty as a situation where the present condition, the potential result, or more than one possible outcome cannot be represented accurately. Nearing et al. (2016) tended to the philosophical direction in their definition of uncertainty, where they stated that uncertainty is an epistemological subject in the sense that any scientific interpretation of uncertainty demands a theory of knowledge. Therefore, the uncertainty arising from scientific activities can be fully understood only in the light of a well-defined scientific philosophy. The following listed sources, which address uncertainty definitions, indicate that there is no consensus or widely recognized concept:

In **economics**, uncertainty was described by the American economist Frank Knight in his work published in 1921, “Uncertainty must be taken in a fundamentally different context from the common concept of Risk, from which it has never been adequately distinguished.” Knight refers to "risk" as circumstances in which the decision-maker may allocate statistical probabilities to the randomness with which he is confronted.

In **environmental science**, uncertainty was defined as associated with different types of environmental variability: that could be known and that could be simulated; that which could be known but that we cannot simulate; and the error inherent in nature's representations and calculations (Pang, 2001). In addition, Hunsaker (2001) expressed the uncertainty in a broad concept as to the variation between phenomena in the real world and the description of these phenomena. While for **climate science**, the IPCC reported that the uncertainty indicates circumstances where the relevant data could be incomplete or inaccessible (IPCC, 2007).

In geographic information science, several works were dedicated to the ideas and concepts of uncertainty. These works represented the uncertainty in several terms like error, inaccuracy, validity, and data quality (Moellering, 1988; Goodchild et al., 1994; Hunter, 1999; Crosetto and Tarantola, 2001; Deren, 2006; Hong et al., 2013). Regarding the uncertainty of data quality, Beard et al. (1991) identified three parameters for data quality: variable that consists of goodness or statistical measure, application or model resolution, and purpose such as analysis or communication. Consequently, Beard et al. determined the data uncertainty sources as source errors, process errors, and use errors. Within the same area, Mowrer and Congalton (2000) identified spatial uncertainty for both attribute and position values to include accuracy, the statistical precision and bias in initial values, as well as the estimation of errors.

In **physical sciences**, uncertainty has mainly focused on error analysis and quantum physics. Commonly, error analysis uncertainty linked to the measurement uncertainty, where represents the variation between the actual value and measured value (Thunnissen, 2003). Similarly, in **dynamical systems**, uncertainty refers to the difference between modelled values and observed values. **Statistically**, uncertainty is expressed as the sum of difference between the outcomes and the observation, and can be described by the equation:

$$\mathbf{U = E - A} \qquad \text{(Equation 2.1)}$$

Where U is uncertainty, E is estimated value, and A is actual value (Pang, 2001).

In **computational modelling and simulation**, uncertainty is characterised as a possible lack of knowledge or incomplete information in any stage or operation of the modelling process (Oberkampf et al., 1999). Within the same field, Melchers (1999) stated that model uncertainty is the accuracy of a mathematical model to simulate the real physical system.

As for **hydrology and water systems**, the concept of uncertainty in hydrological modelling has been getting increasing attention in recent years within the hydrological community. Montanari (2007) pointed out the subject of uncertainty and its evaluation in hydrology suffers from the lack of consistent terms and a clear approach. In the context of the philosophical basis for hydrological uncertainty, Nearing et al. (2016) reported that uncertainty means the difference between the (unknown) actual truth-value of some assumptions and our state of perception about that truth-value. Nearing et al. (2016) tried to associate the concept of uncertainty with the state of knowledge we possess, our own beliefs, and the state of available information that can be manipulated and processed. While Honti et al. (2014) give more accurate concept to the hydrological uncertainty by defining it as the uncertainty of discharge predictions, which are produced when the outcomes of a hydrological model are made depending on the actual climate data. This uncertainty can be quantified by comparing model results to observed discharge data. Within the same area of hydrological modelling, Klein et al. (2016) clarified the concept of predictive uncertainty in the hydrological model as the likelihood of occurrence of variable, subject to all knowledge provided. In this context, predictions and forecasts for hydrological models are regarded to be available but still uncertain knowledge.

For this part of the literature review, it is difficult to find a consistent concept of uncertainty in the literature, where the idea and concept of uncertainty is different based on the field of application. This difference may be attributed to much of the varied discussions around these foundational concepts of uncertainty in terms of usage, classification, sources, different model structure, desired model outcomes, and scientific explanation of results. For the present study, I may define uncertainty in a broad sense as lack of knowledge, information, data, understanding, which arise from errors in input data, imperfect hydrological representation, inadequacy of model structure, and observed object data error.

It is worthy to note that ***risk and uncertainty*** are terminologically confounded due to their convergence of meaning and their presence in the same event. Thunnissen (2003) clarified the difference between risk and uncertainty such that risk indicates that all potential actions are known, all potential outcomes resulting from each action are known, and the probabilities can be attributed to each action. While uncertainty indicates that all potential actions and outcomes are unknown or it makes no logical sense to appoint probabilities to them. In addition, Frank Knight (1921) distinguished between ‘risk’ and ‘uncertainty’, where risk refers to cases where the likelihood of results can be confirmed by means of well-established hypotheses with valid complete data, while uncertainty refers to situations where the relevant data may be incomplete or unavailable. The IPCC (2007) reported that risk indicates the mixture of the likelihood of occurrence of an event and its effects. Hill et al. (2013) reshaped the IPCC definition by reporting that risk is an indicator of both the probability of an unexpected result and the degree of harm that happens due to that result. They supported that risks emerge from a lack of knowledge or uncertainty regarding events that have not yet taken place. To demonstrate the relationship between uncertainty and risk, Hayes et al. (2006) stated that uncertainty analysis is the core of risk assessment and it is the base of risk assessment components. Bark et al. (2013) summarized the relationship between risk and uncertainty, where it should understand well the sources of uncertainty to minimize the risks of undesirable outcomes. Hence, it can be inferred that reducing the risk could reduce the uncertainty. In addition, managing risk is easier than managing uncertainty because we can identify the risk but the uncertainty is too difficult to predict due to limited knowledge.

Within the water resources sciences, the concept of uncertainty is associated with ***complexity*** and both of them have long been of interest, particularly in areas concerned with hydrological modelling, decision-making, and management. In very broad terms, uncertainty occurs at the limits of knowledge, while complexity occurs due to the reasons that affect the uncertainty. Although complexity is considered an element of uncertainty as supported by Atkinson et al. (2006), others support that uncertainty is an element of complexity (e.g. Geraldi and Adlbrecht, 2007; Brady and Davies, 2010; Geraldi et al., 2011). For the relationship between uncertainty and complexity, Baccarini (1996) considers complexity as “forming of several varied interconnected elements”, while Williams (1999) views “number of elements” and “interrelationship of elements” as components of “structural uncertainty” which is proposed as an element of complexity.

Complexity and uncertainty are broadly confounded in the literature due to the strong interrelationship between complexity and uncertainty. This confusion may result from addressing the problem of complexity in each source of uncertainty individually. For instance, there are researchers who attribute complexity to the model used (e.g. Grassberger, 1989; Raccoon, 1995; Edmonds, 1999; Custovic, 2015); others address complexity of system understanding (e.g. Perminova et al., 2008; Vidal et al., 2011; Custovic, 2015), and others define complexity in the light of the huge numbers of variables and interrelationships (e.g. Baccarini, 1996; Lubchenco, 1998; Clark, 2007; Liu et al., 2007; Leonard, 2009; Leichenko, 2011). However, recent papers confirm that the concept of complexity remains ambiguous (Saunders et al., 2015; Qureshi and Kang, 2015).

Complexity is the property of a model that increases the difficulty of expressing its general behaviour in a particular language, even if it provides adequately comprehensive information about its elements and their interrelationships (Grassberger, 1989, Custovic, 2015). In the same context, Edmonds (1999) argued that complexity is the difficulty of obtaining an explanation of the general behaviour of a model. Raccoon (1995) emphasized the previous concept, which defines complexity as the model status with respect to the structure and the influence of the variables and parameters within the model. Complexity often reflects the disparity between the ease of representation of the different components and the difficulty with respect to the overall system behaviour.

In terms of model complexity, Farmer et al. (2003) views that the user or modeller may need to increase the complexity of the model when model predictions are shown to be incorrect. Consequently, the level of model complexity needed would rise with decline in the spatial and temporal resolutions at which simulating hydrological processes and with increments in the number of simulated hydrological processes (Atkinson et al., 2002). However, complex models can represent and simulate precise hydrological processes, but large input data and parameters requirements lead to uncertainty and inaccuracy (Her et al., 2015). Therefore, Wagener et al. (2001) and Kirchner (2006) recommended that the complexity of the used model should be adjusted with the number of obtainable observation points, measurements, and information that may restrict the model's behaviour. For example, Jakeman and Hornberger (1993) determined that only five parameters would be sufficient to simulate rainfall-runoff processes whilst ensuring a suitable sensitivity of the model and low correlation between parameters. Drawing upon the literature on hydrological modelling, it can be noted that the number of parameters and selected model may depend on the belief and experience of the modeller, understanding of the system, purpose and nature of the study, and previous research on the study area.

On the backdrop of the complex systems, complexity could be in system understanding, where it may emerge from various circumstances and dynamic processes that include interrelationships through sub-systems of the environment (e.g. land, vegetation, water) and human (e.g. culture, economy, infrastructure, technology, society) (Lubchenco, 1998; Leichenko, 2011). Nonetheless, experts or decision-makers do not completely grasp the nature of relationships between human and natural systems (Liu et al., 2007; Clark, 2007). Whilst Fenemor (2014) views that the complexity of the system implies that the evaluation of past system behaviour or probabilistic reasoning is required even to make a semi-rational decision. On the other hand, Beven (2018) links the complexity of systems and models by supporting that the complexity of hydrological systems refers to those models, which reflect that concept, and will have many elements and parameters, although we have a relatively poor understanding of many aspects.

It is clear that complexity characterises the behaviour of a system or model and it may arise from system understanding due to multi interactions between the components, the structure of the selected model due to large number of parameters, a large number of variables, large number of required data by the model, and even the model’s outputs. In addition, complexity is judged and described usually through estimating or evaluating the number of variables, form and number of their interrelationships according to the explanation of complexity in the business dictionary. Moreover, Edmonds (1999) explained that scientific modelling includes many different types of complexity. Merging of the following elements into a single "complexity" in simulation of a given system would usually contribute to uncertainty. There might be a complexity of data, complexity of the informal model, complexity of using the formal model to predict, and complexity of using the formal model to explain.

2.2.1 Classifications of Uncertainty

In the 1920s, Frank Knight suggested a distinction between the uncertainties that could be handled as probabilities and what he termed the “true uncertainties” that could not be probabilistically quantified (Knight, 1921). Since then, there have been a lot of effort to outline the different types of uncertainty in various disciplines (Morgan and Henrion, 1990; Oberkampf et al., 1999; Regan et al., 2002; Thunnissen, 2003; Apel et al., 2004; Tannert et al., 2007; Beven and Smith, 2015; Di Baldassarre et al., 2016; Beven, 2016). There are significant similarities between the classifications of uncertainty due to focus on one facet of the uncertainty that affects a particular field and most of them depend on the practical aspects.

In general, uncertainty has been classified as either fundamental uncertainty or ambiguity. Fundamental uncertainty means that it is impossible to know some relevant information, not even in principle and that something unimaginable may happen (Dequech, 2000). While ambiguity characterizes as uncertainty about probability, produced by missing information that is relevant and it is possible to know (Camerer and Weber, 1992). The policy and risk analysis society has sorted uncertainty into quantity types and model form uncertainty. The quantity type involves empirical quantity, decision variables, value parameter, model domains, and outcomes criteria (Morgan and Henrion, 1990). Ayyub and Chao, (1997) assigned three types of uncertainty in the civil engineering field comprising abstracted, non-abstracted and unknown uncertainty. Abstracted uncertainties emerge from components of a real system that are represented by a model. Unknown uncertainties are due to all unknown sources that may affect the system. While the non-abstracted uncertainties may include physical randomness, vaguely parameters, conflict in information, and errors of human and organizations. Factually, Ayyub and Chao, (1997) included the same aspects into the abstracted and non-abstracted uncertainties and he did not give a clear distinction between them.

In the computational modelling and simulation field, Oberkampf et al. (1999) classified uncertainty to uncertainty, error, and variability. The uncertainty appears in a lack of knowledge and incomplete information, and the error may be acknowledged or unacknowledged. While variability is the inherent variation linked to the given physical system or the environment. Thunnissen (2003) provided four types of uncertainty for the design and development of complex systems: ambiguity, epistemic, aleatory, and interaction. Ambiguity implies design imprecision and vagueness of terms. Epistemology is originated from the Greek "episteme", implying “knowledge”, and epistemic uncertainty exists due to human knowledge limitations. Aleatory derives from the Latin "Alea", meaning a dice game, and so relates to probabilistic uncertainty. Aleatory uncertainty is an inherent fluctuation in the physical system (Koutsoyiannis, 2010). Interaction uncertainty emerges from unanticipated or foreseeable interaction of events and/or disciplines. Interaction uncertainty is essential in complex systems, which includes many components, variables, and involved experts in the design and development.

As for ecology, Hayes et al. (2006) distinguished three types of uncertainty in ecological risk assessment: linguistic uncertainty, variability and incertitude. Linguistic uncertainty appears due to the terms or statements used to characterize interactions and processes that suffer from ambiguity and vagueness. Variability is a natural variation or the uncertainty resulted from inherent fluctuations. Incertitude is uncertainty which results from incomplete description or information.

Tannert et al. (2007) divided the uncertainties to objective and subjective uncertainty according to the ethical field. He divided objective uncertainty into epistemological and ontological uncertainty clarifying that the epistemological uncertainty results from gaps in knowledge, while ontological uncertainty results from the stochastic characteristics of the system. Subjective uncertainty results from the difficulty of applying suitable moral laws and rules. These kinds of uncertainty can bring social worriment or conflict.

As for hydrology and water systems, Di Baldassarre et al. (2016) categorized the uncertainty based on lack of knowledge to three types: *known unknown* "things we know we don’t know"; *unknown unknowns* "things we don’t know we don’t know", and *wrong assumptions* "things we think we know, but we actually don’t know". Although this classification popularized by Rumsfeld in 2002, it dates back to the American psychologists, Joseph Luft and Harrington Ingham in 1955. In fact, this classification is an explanation of the epistemic and ontological uncertainty, where Beven (2016) identified various types of aleatory, epistemic, semantic, and ontological uncertainty. Aleatory type is uncertainty with stationary statistical characteristics but may be minimized to a stationary random distribution. Epistemic uncertainty has resulted from limited information about representation, model efficiency, insufficient data, incorrect data, and model outcomes assessment. Semantic or linguistic uncertainty implies the similarity and variation in terms of words or quantities where in various contexts or scales, the quantities with the same name have different meanings. Ontological uncertainty is linked to beliefs and assumptions, which could lead to various estimations of uncertainty.

The chaos of terms forms a problem in standardizing uncertainty classifications. It has seemed that all uncertainties are associated with knowledge limitations, our lack of knowledge or misunderstanding of system and processes due to unknown events in the future. Due to our limited knowledge, there is always unquantifiable uncertainty. In addition, the similarity and difference between the terms of uncertainty and its classification increase the complexity and cause confusion in understanding the meaning, sources, and dealing with uncertainty.

2.2.2 Sources of Uncertainty

If we need to solve a problem, we should start to understand the reasons and sources of that problem. Determining the sources of uncertainty facilitates the selection of appropriate methodologies for dealing with uncertainty and supporting the decision-making process (Klir, 2006).

Moss and Schneider (2000) determined three major sources for uncertainty: data problems, model problems and other sources. Data problem appears in missing data, error, incomplete observations, sampling error and biases. Model problems may be in unknown functional relationships, errors in model structure, incorrect values of parameters, error in model behaviour to predict the system, or the model’s approximation techniques. The other sources such as ambiguous terminology, inappropriate spatial and temporal units, human behaviour, and natural sources such as climate change. While Schneider et al. (2002) reported that uncertainties emerge from such sources as linguistic vagueness, statistical difference, measurement error, approximation, variability, and subjective judgment.

In hydrology and water systems, Beven (2005) demonstrated that there are multiple sources of uncertainty in the analysis and modelling of hydrological systems, and the impact of different uncertainties cannot be separated without developing very reasonable assumptions about the nature of these different sources. Consequently, Beven (2006) presents equifinality as one of the main sources of uncertainty in hydrological modelling. Equifinality means the presence of a lot of parameter sets and multiple model structures linked to the same ‘optimal’ measure of efficiency (Beven and Freer, 2001). Her and Chaubey (2015) reported that equifinality reduces with increasing the number of observations and decreasing the number of calibration parameters.

In terms of climate change and hydrological modelling, Ludwig et al. (2009) emphasize climate projections and modelling tools as the source of uncertainty and the limiting factors to form the adaptation strategy. According to Foley (2010) and Anwar et al. (2013) uncertainty in modelling of climate change may be linked to the inability to predict with climate patterns and anthropogenic greenhouse gas emissions

In addition, Singh et al. (2010) grouped uncertainty sources in the planning framework into two categories of uncertain factors: unpredictable factors (natural disasters, acts of terrorism, advancement in technology, and legislative and policy change), and predictable factors (climate change, and demand and supply projections). They divided uncertainties in the water demand and supply system in the same study into three main categories: supply uncertainty, demand uncertainty, and uncertainty in water management strategies for overcoming the water deficit. Therefore, they reported the uncertainty sources that impact on water demand and supply such as impact of climate on water supply, uncertainty in population projections, the per-capita usage rates, variability in water usage, feasibility of the permitting process, societal concerns, cost of implementation, and reliability of different water management strategies for meeting water deficit.

Arnold et al. (2012) identified three sources of uncertainty to include the error in input data (e.g. rainfall and temperature), the error in observed data used in model calibration (e.g. river streamflow and sediment load), and the error in the conceptual model and model parameters. Within the same context, Honti et al. (2014) determined three elements as sources of hydrological model uncertainty, defined as a combined result of input uncertainty (actual climate data are not accurate), the uncertainty of the calibration data observation, and the structural uncertainty of the model (hydrological models are incomplete). Some researchers have reported that uncertainties of hydrological models are less important than those emerging from climate change (Prudhomme and Davies, 2009; Chen et al., 2011). This tends to underestimate the importance of hydrological models as a source of uncertainty; this may be acceptable for a simple model of a simple system, but the representation and simulation of complex systems requires a complex model to some extent, to represent a large numbers of variables and multiple interrelationships. This increases the complexity of the model, which may lead to increased uncertainty, where climate change will be just a predictable element among many components.

Nobody can deny that sources of uncertainty are subject to human influence on the hydrological system, of which Savenije et al. (2014) determined four major types of human impacts on hydrology: water supplies to domestic, industrial, and agricultural sectors; building dams and reservoirs; changing characteristics of the river basin due to land-use change and urbanization;

and climate change over the basin. It seems that Savenije et al. depend on the uncertainty arising from the hydrological system to identify these sources.

From the hydrological model point of view, Abbaspour et al. (2015) divided the sources of uncertainties into six sources:

a) Model uncertainties due to simplifications in the model,
b) Model uncertainties due to processes occurring in the watershed but not included in the model,
c) Model uncertainties due to processes that are included in the model, but their occurrences in the watershed are unknown to the modeller or unaccountable,
d) Model uncertainties due to processes unknown to the modeller and not included in the model,
e) Uncertainties due to input data quality,
f) Uncertainties due to the model's parameters for modelling hydrological processes.

Nearing et al. (2016) classified the sources of hydrological uncertainty to fundamental and proximal sources. The fundamental sources involved the problem of the limited experiment, and the problem of finite hypotheses (this implies our ability to examine only a limited number of models). While the Proximal sources included model uncertainty, observation uncertainty, and misinformation.

From the preceding review, uncertainty in water resource systems can be categorized into four main sources according to system, data, model and modeller, and can be summarized as follows:

1- *Uncertainty sources related to the system*
   - Uncertainty in water demand projections such as population growth, per-capita water consumption, and industrial and agricultural water consumption,
   - Uncertainty in water supply projections such as climate change projections, water availability, and drought conditions,
   - Uncertainty in water management such as feasibility of process and strategies to bridge the water gap, cost of implementation, acceptability of decision makers and society, and feasibility of permitting, policy, and legislature,
   - Human interventions as an uncertainty source, such as constructing dams, land-use change and urbanization, updating infrastructure, and human behaviour in water usages,

- Lack of system understanding due to complexity of the system, and
- Unknown elements and unexpected events.

2- *Uncertainties sources related to data*
- Data limitations,
- Lack of information about the system and disinformation,
- Lack of data availability and incomplete time series, and
- Errors in input data.

3- *Uncertainties sources related to the model*
- Appropriateness of the model to simulate the system in term of usage flexibility, structure, and parameters,
- Lack of knowledge about model structure and parameters,
- Model performance and efficiency, and
- Lack of understanding of the outcomes.

4- *Uncertainties sources related to the modeller*
- Lack of experiences and skills,
- Human error,
- Wrong assumptions, and
- Reliance on prior beliefs, subjectivity and bias.

2.2.3 Dealing with Uncertainty

Uncertainty and complexity, and how the actors and researchers can assess, negotiate, and handle it has long been a highly significant topic in the water resources field (e.g. Erlenkotter et al.,1989; Frey, 1992; Beven and Binley, 1992; Dudley and Hearn, 1993; Jakeman and Hornberger, 1993; Beven and Freer, 2001; Atkinson et al., 2002; Butts et al., 2004; Mantovan and Todini, 2006; Ludwig et al., 2009; Shrestha et al., 2009; Prudhomme and Davies, 2009; Chung et al., 2009; Singh et al., 2010; Chen et al., 2011; Dessai and van der Sluijs, 2011; Bark et al., 2013; Elshamy et al., 2013; Guieysse et al., 2013; Gal et al., 2014; Honti et al., 2014; Mirzaei et al., 2015; Beh et al., 2015; Her and Chaubey, 2015; Larson et al., 2015; Tsoukalas and Makropoulos, 2015a; Tsoukalas and Makropoulos, 2015b; Barnes, 2016; Klein et al., 2016; Kundzewicz et al., 2018; Elsayed et al., 2020).

Dealing with uncertainty and complexity has evolved from using simple statistical measures (such as standard deviation and least squares techniques) to sophisticated and complex algorithms (such as generalized likelihood uncertainty estimation (GLUE), sequential uncertainty fitting algorithm (SUFI-2), and parameter solution (ParaSol) method), as well as scientific objective judgments. It may be better to depend on the sources and places of uncertainty and complexity to select the optimal method of addressing uncertainty and handling the complexity. For example, dealing with uncertainties and complexities in hydrological modelling requires methods that may differ from addressing uncertainty and complexity in future factors or in water management. In addition, some sources of uncertainty can be avoided through suitable handling, others can be minimized through data collection, while others cannot be removed or reduced but can only be better represented, simulated and interpreted (Hayes et al., 2006).

Uusitalo et al. (2015) view that selecting an effective way to deal with the uncertainty depends on the determination of the used models and the availability and quality of information to the modeller. That is, the uncertainty results differ with the method used to estimate them (Pappenberger et al., 2006). Beven et al. (2014) supports this by reporting that there is no accurate result in uncertainty estimation; each estimation depends on the developed assumptions and in most applications there are many assumptions that need to be developed.

Addressing uncertainty is related to what we are doing to predict the future. To deal with the unknown future, scientists assume that this future is like the past, then they have to choose from several techniques: (i) probability theory, (ii) developing a limited number of plausible scenarios to better understand the potential future and determine the actions that should be taken on that basis, and (iii) expert judgment (Dwivedi et al., 2006; Singh et al., 2010; Mastrandrea et al., 2010; Li et al., 2012; Uusitalo et al., 2015; Hoogduin, 2016; Mach et al., 2017; Khosravi and Jha-Thakur, 2019). Probability theory can treat both epistemic and aleatory uncertainty, where random experiments usually deal with natural fluctuations, which is sufficient to define the aleatory uncertainty (Li et al., 2012). Scenario analysis strategy can manage the uncertainty that relates to future events; scenario analysis is a way for creating responses to different future events with the aim of overcoming uncertainty through being prepared for any eventuality, a process called "alertness" (Wilson and Ralston, 2006; Zhu et al., 2011; Hoogduin, 2016). Scenarios may help policymakers and planners to be sensitive to what might happen, and be aware of opportunities and threats. Expert judgment is widely used in assessment of uncertainties in data, model, simulation, outcomes, and future predictions (Mastrandrea et al., 2010; Aspinall and Cooke, 2013; Oppenheimer et al., 2016; Mach et al., 2017).

To deal with the linguistic uncertainty that occurs due to ambiguous terms in describing processes and events, Hayes et al. (2006) support identifying the terms carefully to overcome this ambiguity. Uncertainty due to inherent fluctuations cannot be minimized but can be interpreted and better understood by representation and simulation. Uncertainty due to incomplete knowledge can be dealt with by collecting additional data and information.

In hydrological literature, the estimation of uncertainty has been the topic of significant debate. Some believe that formal statistics are the only way to get an unbiased estimate of probability uncertainty (e.g. Mantovan and Todini, 2006, Stedinger et al., 2008) or that the only way to address the unpredictable is through probabilistic variability (Montanari, 2007, Montanari and Koutsoyiannis, 2012). The fields of mathematics, statistics and physics have helped hydrologists by developing many methods to deal with uncertainty such as frequentist probability distributions, subjective probability, belief statements of Bayesian statistics, Monte Carlo simulation, sensitivity analysis, and interval analysis (Ayyub et al., 1992; Tonn, 1991; Frey, 1992; Yager, 1992). These methods present a reasonable way to quantify, manage, and understand uncertainty.

Mastrandrea et al. (2010) in the fifth IPCC report emphasized that the use of statistical analysis to deal with uncertainties in complex systems helps to bring verifiable evidence into policy-making. In addition, they divide the measures addressing uncertainty into two types: (i) Qualified measures where they are expressed qualitatively such as the degree of agreement and confidence in the validity of results, based on mechanistic understanding, theory, data, models, expert judgement, and (ii) Quantified measures where they are expressed probabilistically based on a statistical analysis of observations or model results, or expert judgment. It is worth noting that Beven (2016) concluded the traditional statistical methods were not sufficient to address the complex sources of uncertainty in the hydrological modelling process.

As stated above, uncertainty stems from different sources. Following the classification of Thunnissen (2003), who classified the uncertainty in complex system to ambiguity, epistemic, aleatory, and interaction uncertainty, it can be summarized that efforts of scientists to deal with these types of uncertainties can be grouped as follows:

For **ambiguity,** semantic or linguistic uncertainty emerges when, as Beven (2016) called it, words have more than one meaning. It is easy to eliminate this source of uncertainty by clearly defining terms in the assessment (Hayes et al., 2006). In my view, ambiguity will remain in the human discourse and can be treated by issuing standard definitions for every term and process, which researchers, modellers, and developers then adhere to.

According to Beven and Young (2013) and Beven (2016), the **epistemic uncertainty** that is related to the lack of knowledge can be dealt with by increasing knowledge or information, selecting the best model, removing the approximation errors and numerical error by using precision computers and software, reducing the complexity by enhancing the model design, and preventing the human error using self and external checking.

Aleatory uncertainty implies the inherent fluctuation in the physical system, and can be dealt with using the probability distribution (Koutsoyiannis, 2010; Li et al., 2012; Beven, 2016). **Interaction uncertainty** that results from unexpected interactions between many events, can be handled using accurate simulation and optimization techniques, and simplify complexity between the components (Oberkampf et al., 2001; Thunnissen, 2003).

Obviously, there is a wide range of methods for dealing with uncertainty including different levels of mathematical complexity and data requirements. The selected method to use depends on the nature of the problem at hand including the availability of information, model complexity, source of uncertainty, type and desired accuracy of the results, and skills and experience of the modeller. It is worth noting that different methods of uncertainty analysis have their limitations and specific, valid and realistic assumptions.

2.2.4 Uncertainty Analysis Techniques in Water Resources

The great efforts in uncertainty analysis of hydrological models produced several sophisticated methods for addressing the sources of uncertainty. Selecting the method is based on the level of model complexity, the efficiency of the method to cover all faces of uncertainty, and the choice of the modeller. These methods were categorized into six main classes; approximation methods, analytical methods, sampling based methods, Bayesian methods, methods based on the analysis of model errors, and Fuzzy theory based methods (Shrestha and Solomatine, 2008). The following section explains some widely used and common methods for addressing uncertainty in hydrological models.

Monte Carlo Technique

Monte Carlo (MC) is a computational technique that dates back to the early 1970s. It is a stochastic technique for probabilistic representation of uncertainty based on model simulations results using random samples of input variables. The idea of this technique is to generate a huge number of model parameters sets repeatedly according to probability distributions and uncertainty limits for every parameter. Drawbacks of this method are applying professional judgment to come up with the probability distribution and uncertainty limits. In addition, it requires increasing the sample size to minimize the error and this leads to increase in computational time (Khu and Werner, 2003; Shapiro, 2003; Feil et al., 2009). Recently, techniques have emerged for variance reduction for obtaining high accuracy MC results without increasing the sample size, such as generalized likelihood uncertainty estimation (GLUE), Latin hypercube sampling (LHS), and Monte Carlo Markov chain MCMC.

Markov Chain Monte Carlo

This is a category of formal Bayesian approaches for evaluating parameter uncertainty in hydrological modelling. Markov Chain Monte Carlo (MCMC) techniques have helped solve some of the computational challenges. MCMC aims to explore the posterior distribution by generating a random process where the stationary distribution is the posterior distribution of the parameters (Kuczera and Parent, 1998; Bates and Campbell, 2001; Marshall et al., 2004). The efficiency of a MCMC algorithm depends on the number and type of random parameters in the analysis, location of non-random parameters in the model, and which criteria to stop the Markov Chain (Zheng and Han, 2016). Criteria to stop the Markov Chain algorithms after assessing the convergence of the algorithms is the most difficult challenge in this technique, where sufficient evidence should be indicated to the produced sample from algorithms representing the posterior distribution (Sinharay, 2004).

Parameter Solution (PARASOL)

The Parameter Solution (ParaSol) is a method developed by van Griensven and Meixner (2006) to perform optimization and uncertainty analysis for complex models based on the shuffled complex evolution method (SCE-UA) (Duan et al., 1992; Wu et al., 2013; Abbaspour, 2015). The idea of ParaSol is using the simulations produced during optimization to extract prediction uncertainty. ParaSol divides the outputs of SCE-UA optimization method into ‘behavioural’ simulations and ‘non-behavioural’ simulations and weight the prediction uncertainty by all ‘‘behavioural’’ simulations equally. ParaSol aims to aggregate objective functions into a global optimization criterion, minimizes these objective functions or a global optimization criterion by using Shuffled complex evolution (SCE-UA), and conduct uncertainty analysis. The method has been widely used in calibration of watershed model and other hydrological fields (van Griensven and Meixner, 2006; Wu et al., 2013; Abbaspour, 2015; Khoi and Thom, 2015). ParaSol’s disadvantages do not take into account the uncertainty of the model's structure, measured input and output, which leads to an underestimation of the prediction uncertainty (Yang et al., 2008).

Generalized Likelihood Uncertainty Estimation (GLUE)

The Generalized Likelihood Uncertainty Estimation (GLUE) technique is developed by Beven and Binley (1992) as stochastic procedure for model calibration and uncertainty estimation in complex models. At the time being, GLUE is the most widely used method for hydrological calibration and uncertainty estimation in the water resources and complex environmental systems modelling fields (Stedinger et al., 2008; Viola et al., 2009; Jin et al., 2010; Ng et al., 2010; Gong et al., 2011; Shen et al., 2012; Alazzy et al., 2015; Quan et al., 2015; Sun et al., 2016).

GLUE is an innovative method for uncertainty estimation based on running a large number of model simulations with different parameter sets to obtain the samples from prior distributions, and extracting the outputs and parameters (posterior) distributions based on the set of simulations showing the closest match to the observation according to the specified threshold of the object function. In GLUE, parameter uncertainty is defined as a set of distinct ‘‘behavioural’’ parameter sets with corresponding ‘‘likelihood weights’’. The advantage of GLUE is the parameter uncertainty accounts for all sources of uncertainty such as input uncertainty, model structural uncertainty, parameters uncertainty, and output uncertainty, because the likelihood measure value is correlated with a parameter set and reflects all these sources of error (Beven and Freer, 2001; Abbaspour, 2015). In addition, the theoretical simplicity and easiness of implementation make GLUE the most widely used in the water resources field. The goodness of calibration and prediction uncertainty is judged on the basis of Nash Sutcliffe Efficiency

(NSE), percent bias (PBIAS), Root mean square error (RMSE), p-factor (the closeness to 100%), and r-factor (less than 1) (Abbaspour, 2015).

The main drawbacks of GLUE is that it requires a huge number of model simulations. The effect of subjective decisions on outputs, such as selecting the threshold of objective function to distinguish behavioural from non-behavioural parameter sets, is also potentially problematic (Montanari, 2005). Selecting the efficient model with effective parameters may alleviate these drawbacks and reduce the computational time.

Sequential Uncertainty Fitting Algorithm (SUFI-2)

Sequential Uncertainty Fitting (SUFI-2) is a stochastic procedure developed by Abbaspour et al. (2004) to perform hydrological model calibration and uncertainty analysis. It determines uncertainties through the sequential and fitting process in which iteration and unknown parameter estimates are achieved before the final estimates. Parameter uncertainty is expressed as ranges and the Latin hypercube sampling procedure is used to draw independent parameter sets. the output uncertainty is quantified by the 95% prediction uncertainty band (95PPU) calculated at the 2.5% and 97.5% levels of the cumulative distribution function of the output variables (Abbaspour, 2015).

Similarly to GLUE, SUFI-2 represents uncertainties of all sources through parameter uncertainty in the hydrological model, including uncertainty in model input, model structure, model parameters, and observed data. In addition, the goodness of calibration and prediction uncertainty is judged by the same factors (Nash Sutcliffe Efficiency (NSE), percent bias (PBIAS), Root mean square error (RMSE), p-factor (the closeness to 100%), and r-factor (less than 1). According to the literature, the SUFI-2 method has been widely used in uncertainty analysis in hydrological models and performs better than other methods due to the high accuracy of results and lower computational time (Yang et al., 2008; Jajarmizadeh et al., 2012; Wu et al., 2013; Khoi and Thom, 2015; Taghvaye et al., 2016; Mehan et al., 2017). Although the SUFI-2 technique is able to provide more accurate and reasonable predictive results, one of its drawbacks is difficulty of implementation. Furthermore, it is currently only validated for use with the SWAT model, due to its programing limitations.

The above techniques are used in hydrological modelling for dealing with prediction uncertainty. They differ in their philosophies and give the modeller some flexibility for subjective decisions such as formulating the objective function, generalized likelihood measure, likelihood function, or calibration assessment metrics. Hence, the selection of an appropriate method is subject to some extent, to the modeller’s skills and experience.

2.2.5 Scenarios Analysis Approach

The future is uncertain, and a scenarios analysis approach is a method of dealing with the future uncertainties and aims to assess the potential impacts (Carter et al., 2007; Khosravi and Jha-Thakur, 2019). The three major drivers in any future water system are future demand, future supply, and future water shortage. A scenarios analysis approach is usually used to address uncertainty in future factors that affect water demand and supply such as future climate condition, population and water usage rates among others (Singh et al., 2010).

Scenario analysis is the most diverse of approaches to frame uncertainties and a model-assisted scenario analysis is useful for Identifying and addressing uncertainties, which may mitigate the vulnerability of long-term strategies (Sato and Altamirano, 2019). Scenarios analysis may apply to one uncertain factor to identify the uncertainty range in its impact on the water system, or frame the future of water demand and supply in the whole system based on a set of likelihood assumptions. A scenarios analysis approach is based on developing multiple scenarios with different drivers to cover all assumptions for underling variables in water demand and supply and use them to identify uncertainty in future estimates (Singh et al., 2010). Scenarios analysis has been widely used in water resources for a long time, and is a powerful tool that can be used by strategic planners for dealing with uncertainties in the future (Middelkoop et al., 2004; Pallottino et al., 2005; Means et al., 2005; Groves, 2005; Manca et al., 2006; Dessai and Hulme, 2007; Scott et al., 2012; Mukheibir and Mitchell, 2014; Safavi et al., 2016).

Scenario analysis is a procedure for developing responses to different future events based on various combinations of drivers with the aim of minimizing uncertainty and enhancing the chances of achieving desired results and finding the optimal solution. From the water management point of view, scenarios are created to help planners and decision-makers evaluate the effects of multiple management options.

2.2.6 Expert’s Assessment Approach

The expert’s assessment approach for dealing with uncertainties implies identifying and evaluating uncertainties using expert judgment elicitation (Aspinall and Cooke, 2013). Expert judgement has always played a large role in uncertainty and complexity issues. Expert judgement has been used in dealing with uncertainties in different fields for many years (Webler et al., 1991; Goossens and Cooke, 2001; O'Hagan et al., 2006; Aspinall and Cooke, 2013; Morgan, 2014; Babuscia and Cheung, 2014; Oppenheimer et al., 2016; Colson and Cooke, 2018; Bamber et al., 2019). This approach is based on formal procedures for gathering and obtaining expert opinions by any surveying means to evaluate and avoid uncertainties. It refers to participation of experts and stakeholders in the process of uncertainty addressing. In this approach, experts assess a set of target and calibration questions in a field of experts who have observed true values (Colson and Cooke, 2018).

The efficient and effective role of expert and stakeholders in managing the uncertainties in water resources is evident, particularly in water management. Scientists resort to this procedure for assessing uncertainties in the absence of sufficient relevant analytical and experimental data, or where available data and models cannot provide the required information, where expert knowledge is essentially the only source of accurate information (O'Hagan et al., 2006; Colson and Cooke, 2018). In this approach, experts and stakeholders are asked to carefully evaluate the uncertainties through questionnaires based on specified criteria (Wardekker et al., 2010). For example, in water management this may require respondents to evaluate adaptation policies, and management measures and optimal strategies that could bridge a water gap considering the uncertainties around these policies and measures. However, expert opinion elicitation is not an easy task, and practitioners should be aware of studies that guide accurate and reliable elicitation methods (O'Hagan et al., 2006). In addition, validating experts' judgments is also a difficult challenge because we resort to this method when other data is not available and subsequently evaluating accuracy is difficult (Colson and Cooke, 2018).

2.2.7 Hydrological Models

Although hydrological models are considered a source of uncertainty, they are important tools for explaining how complex systems work and provide valuable insights, as long as their structures and limitations are understood and interpreted explicitly. To reduce the uncertainty and simplify the complexity in hydrological systems, scientists use sophisticated models to simplify the complexity and simulate the complicated interactions between variables in the system to close the gap between simulated and observed data. According to Shrestha (2009), uncertainty sources differ with model complexity. The model complexity refers to numbers of parameters and required input data to run the model. With increasing model complexity, the uncertainty of model structure falls due to detailed simulation of the physical system. At the same time, if the hydrological model is not selected properly based on the parameters and required input data, uncertainty associated with the parameters and the input data will increase (Figure 2.1). Therefore, using the proper model to simulate the system, develop scenarios, and water management can help reduce the uncertainty.

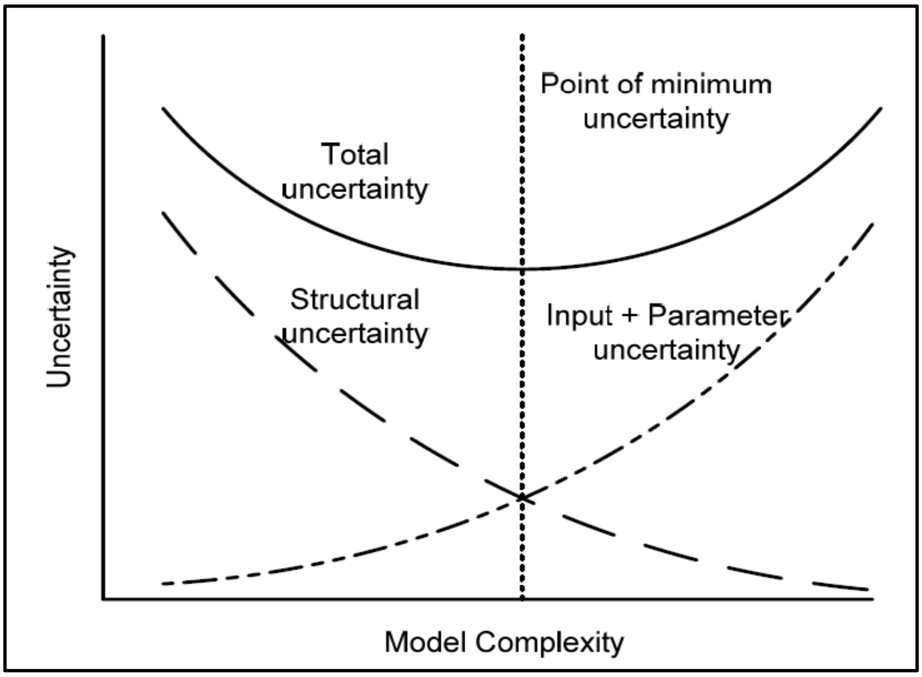


Figure 2.1 Relationship between model complexity, uncertainty and sources of model uncertainty (Shrestha, 2009).

2.3 Uncertainty and Complexity in Water Demand and Supply in Egypt

At a global scale, pressure on water resources is increasing with the rise of population and economic growth around the world speeding higher water demands for domestic, agricultural and industrial water purposes (Postel, 2000; Alcamo et al., 2007; Jury and Vaux, 2007; Shen et al., 2008; Shen et al., 2014). Potential changes in water resources are one of the greatest concerns regarding climate change and socio-economic developments (Shen et al., 2008). Uncertainty and complexity in the global water supply and demand issue are represented in the impact of climate change, population growth, water consumption in different sectors, transboundary problems in rivers basins, and water management policies among others. By focusing on the issue of supply and demand for water in Egypt, the situation becomes worse as a result of Egypt's location in an arid area, that the majority of its freshwater comes from outside its borders, its huge and continuous increase in population, human interventions in hydrological system, and the problems associated with development in the upstream countries.

Egypt as a developing country faces great challenges and an expected water crisis due to its limited water supply and increase in demand (Hamza and Mason, 2004; Elkassar, 2008; Fernando et al., 2012; Karajeh et al., 2013). According to the ministry of water resources and irrigation in Egypt, the annual water demand reached 80.25 BCM, while the available fresh water is 59.25 BCM in the year 2017. This means that the water shortage is estimated at 21 BCM. Egypt bridges this gap by unconventional resources such as water reuse, desalination, and shallow ground water. In fact, this is a wide gap between demand and supply but there is however uncertainty and complexity around this gap. For example, Egypt does not consider the shallow groundwater a conventional resource but deal with it as an unconventional resource into the water balance and considers the amount of rainfall as a 1.3 BCM/year, an unvarying constant used for long decades (Abu-Zeid, 1991; MWRI, 1997; MWRI, 2005; MWRI, 2010; MWRI, 2014; MWRI, 2018).

Elsaeed (2012) highlighted that Egypt is in a situation where it must plan for several different negative future scenarios as climate change may lead to increased temperatures and reduced rainfall rates. Even without any negative impact of climate change, Egypt is facing rapid growth in population, accelerated urbanization, and upstream countries with their own ambitions to protect future water needs. All of these challenges increase the uncertainty and complexity and will force Egypt to consider water resource management as a top priority for national security. In the next section, I focus on the sources of uncertainty and complexity in water demand and supply for Egypt.

2.3.1 Uncertainty and Complexity in Understanding the System

The Egyptian water system is uncertain and complex presenting difficulties to understand and represent the system. Firstly, Egypt has a dry climate with desert occupying most of the land, and rainfed water supply is uncertain (Allam and Allam, 2007). In addition, Egypt depends on water coming from the upstream Nile with storage in the High Aswan Dam (HAD) reservoir and outflow through the dam to meet the demand downstream. According to Abbaspour (2015) without knowledge of the operating rules of the High Dam, it would not be possible to simulate and model downstream processes; such rules are however extremely complicated due to the restrictions of Egypt's commitment to its share of Nile water. Moreover, the outflow through the HAD is subject to water levels in Nasser Lake, the size of the annual flood, and the needs downstream. The growing water gap from limited supply and increasing demand forced Egypt to develop non-conventional resources including seawater desalination, water reuse, and shallow groundwater, to supplement Nile River inflow, deep groundwater, and rainfall (MWRI, 2014; Djuma et al., 2016).

Egypt also experiences complexity in demand distribution, where the population is concentrated around and dependent on the Nile, while the population in the desert, on the Northern and Eastern Coasts, and Sinai rely on rainwater, groundwater, and seawater desalination. Moreover, agricultural lands are divided into old lands and newly cultivated lands in the desert; the old lands use Nile water only, while newly cultivated lands rely on the rainwater, groundwater, and Nile water (MWRI, 2010). Simulating and representing these variables and interrelationships makes the Egyptian water resources system more complex and uncertain.

2.3.2 Uncertainty and Complexity of Data

The water supply / hydrological data is uncertain and extremely complex. For example, the Nile inflows into the HAD reservoir include the Blue Nile, Atbara River in Ethiopia, and the White Nile in Sudan. The Blue Nile contributes 59%, Atbara River 13%, and the White Nile 28% (Swain, 2011). These multiple sources lead to a large variation, uncertainty, and complexity in the annual flow data due to the variability of rainfall in the contributing climatic regions; inflow to Egypt at Dongola station varied from 42.12 BCM to 105.13 BMC over the period 1965 – 2010 according the MWRI data. Dongola station had been built in 1964 for measuring the inflow data to the Nasser Lake. Discharge at Dongola is equal to the Nasser Lake interflow after deducting the proportion of 0.03%, which is equal to the losses for the distance between Dongola and

Nasser Lake inlet (Hassan and Willems, 2005; Abdel-Latif and Yacoub, 2011) (Figure 2.2).

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2.2 Locations of Dongola gauge station on Nile River, Nasser Lake, High Aswan Dam, and Egypt. Figure modified from Di Baldassarre et al. (2011).

For the outflow data through the HAD downstream, all research and Ministry of Water report this to be a constant 55.5 BCM/year as per the trans-boundary agreement between Egypt and Sudan (Abu-Zeid, 1991; Abdin and Gaafar, 2009; MWRI, 2010; MWRI, 2014). In practice the outflow from the HAD differs from year to year and is subject to the coming flood, amount of stored water in the reservoir, the dam's operational rules, and downstream needs. Data from MWRI show outflow is often above the agreed rate, varying between 52.1 BCM in 1988 and 67.2 BCM in 1999 over the period 1968 - 2015 (PJTCNW, 1968 -> 2015).

For rainfall over Egypt, the MWRI assumes 1.3 BCM/year and has done so for decades (Abu-Zeid et al., 1992; MWRI, 1997; Abdel-Shafy and Aly, 2002;

MWRI, 2010; MWRI, 2014). Unfortunately, there are no studies to confirm this estimate. Likewise, seawater desalination data is constant at 0.1 BCM/year, also without change for several decades; moreover, it is used in the coastal tourism sector only (MWRI, 2014). In addition, data on groundwater withdrawal may be uncertain as wells are not always registered and are dug without official permission.

For water demand data, the demand in domestic, irrigation, and industrial sectors is assessed using data on permanent and non-permanent population, irrigated areas, and number of large industrial units (Rayan and Djebedjian, 2000). As a result of population growth, agricultural expansion, industrial development, and an increase in living standards, water demand has multiplied (Allam and Allam, 2007). Population data affect the certainty of model estimates, as the population who work abroad for short periods are taken into account within the water demand process. In 2017, the number of Egyptians working abroad reached 10 million (CAPMAS, 2017a). For irrigated area data, the agricultural area divides into old lands and new cultivated lands; the old lands area decreases continuously due to urbanization whilst the new cultivated lands data is complex and misleading. Although data refers to an increase in new cultivated lands area, several projects were stopped due to the dry climate, water problems, and resettlement difficulties. Including the large Toshka new valley project in southern Egypt. The government claims that reclamation of huge areas in the deserts is still taking place with these projects irrigated by deep groundwater. This discrepancy may lead to uncertain data. As for water demand of industrial units' data, there is inaccurate information about the number of industrial units. This inaccuracy occurs as many industrial units are not registered in either ministry of water or trade, and operate in secret.

All these challenges and discrepancies in data lead to uncertain water demand and supply and thus represent a great challenge in simulating Egypt's water gap.

2.3.3 Uncertainty of Climate Change over Egypt

According to Faramarzi et al. (2013) study on the impacts of climate change on water supply in Africa, dry regions face higher uncertainties than wet regions, representing a further challenge to water supply in dry regions. Egypt is an arid country, very sensitive to water deficit due to climate change impacts. The uncertainty and complexity linked to climate change impacts on

Egyptian water resources involve two elements: uncertainty of climate change impact on the Egyptian inlands and uncertainty of climate variability on the upstream Nile on Egypt, where the majority of fresh water to Egypt comes from outside its borders, this increases the complexity in dealing with uncertainty.

Assessing the impact of climate change on water resources is essential in establishing measures for mitigation and adaptation to climate change. However, the wide range of uncertainty resulting from a long chain of modelling activities often clouds this process. In spite of the progress in improving climate models and projections, downscaling procedures, and hydrological models, there will remain uncertainties (Elshamy et al., 2013). Obviously, most studies that discuss the impact of climate change on water resources of Egypt were applied to the Nile upstream and ignored the climate impact on the Egyptian interior hydrological system. This oversight of climate impact on the Egyptian interior hydrological system is due to scarce rainfall over Egypt and reliance on water from outside Egypt’s borders. Therefore, the current and future impacts of climate over Egypt on the hydrological system is uncertain due to lack of analysis. On the other hand, many studies assess the impacts of climate change in Egypt on specific areas, including on agriculture, sea level rise, tourism, and the economy (e.g. Eid and Saleh, 1992; Strzepek et al., 1994; Yates and Strzepek, 1998a; Agrawala et al., 2004; Eid et al., 2007; Elsaeed, 2012; Nasef, 2012). Some climate change impacts in Egypt on specific area are discussed next.

Abdel-Shafy et al. (2010) tried to calculate the amount of rainwater over Egypt, and reported total rainwater of 1.8 BCM/year. This study used a simple method that calculated average rainfall from rainfall at five locations in Egypt only, and for just 16 months. Gado and El-Agha (2019) evaluated the feasibility of rainwater harvesting in urban areas only, over 22 cities in Egypt, and concluded that harvested annual rainwater can reach 142.5 MCM in the selected cities. Rainfall harvesting has highest potential for cities on the North Coast. For example, harvested rainwater could provide Alexandria with 12% of its future domestic water needs. This means that rainwater over Egypt, despite its scarcity, can play an important role in the hydrological system and add it to the water balance to overcome the water gap.

Strzepek et al. (1994) reported that climate change will likely affect water supply, crop yields and water consumption, but did not identify the percentage of impact or the used model for projections. Eid and Saleh (1992) stated that there is an increase in temperature will lead to increased evapotranspiration by crops increasing crop water requirements. Agrawala et al. (2004) compared between 17 GCMs developed since 1995 based on their predictive error for annual precipitation levels. The models that have error scores closest to zero are optimal. A combination of the eight best SCENGEN models (CSI2TR96, CSM_TR98, ECH3TR95, ECH4TR98, GISSTR95, HAD2TR95, HAD3TR00, PCM_TR00) was used to estimate the future changes of temperature and precipitation over Egypt for 2030, 2050, and 2100. The results have shown that the inter-model variation was so high that it was uncertain to predict whether annual average precipitation will increase or decrease. The models referred to an increase in temperature mean by 1.0°C, 1.4°C, and 2.4°C for 2030, 2050, and 2100 respectively. For precipitation change, the models reported a significant decrease by -5.2%, -7.6%, and -13.2% for 2030, 2050, and 2100 respectively. In addition, Nasef (2012) detected temperature change in Egypt through the period 1960-2000 that showed an upward trend in mean and minimum temperature and downward trend for maximum temperature. There was disparity between the means of decades, with the first decade the coolest and the fourth the warmest for all temperature variables. The southern part has a clear upward trend for all temperature variables.

There is no certainty about whether the climate variables over Egyptian inlands may decrease or increase and no one identify which the appropriate recent climatic models to use their data in Egypt’s climate projections so far. More studies are needed for assessing the potential climate impact on the future of water demand and in Egypt.

2.3.4 Uncertainty of Climate Variability over the Nile’s Upstream

Since the mid-1990s, the Egyptian Ministry of Water has depended on predictions of the Nile Forecasting System (NFS) as a hydrological model for the whole Nile Basin. The NFS uses by the Nile Forecasting Centre (NFC) in Egypt, which includes a gridded distributed hydrological model based on rainfall estimation from the Meteosat Second Generation (MSG) satellites to supervise, simulate and predict the whole Nile Basin, to identify flows especially at Dongola station, and to the HAD reservoir (Elshamy, 2008; Bellerby, 2009; Barnes, 2016; Nassar, 2017). The primary advantage of the NFS is that it covers the entire Nile basin system including soil moisture, slope and river routing, lakes, wetlands, and reservoirs in the basin (Elshamy, 2008). The key disadvantages of this system are its reliance on rainfall data obtained from the Meteosat Second Generation (MSG) satellite and not observed ground data, given that the rainfall data estimated from satellites is uncertain and inaccurate.

In addition, the NFS streamflow prediction technique employs past year observations as indicators of potential future rainfall to predict up to three months only for hydrological forecasts in order to organize the yearly water resources in Egypt; therefore, this system is not valid for the prediction of a long period. Although the MWRI confirmed that the NFS providing forecasts of satisfactory accuracy for Nile flows, Elshamy (2008) reported that the performance was only satisfactory for the Blue Nile and Atbara and was unsatisfactory for the other areas due to the quality of rainfall data and the discrepancies between basin areas. This inconsistency may be attributed to Elshamy’s dependence on the long-term simulation in comparison while the NFS which is applied for short period forecasts only.

A number of scientists who work on climate variability have taken the Nile Basin as a central point for their studies (e.g. Gleick, 1991; Conway, 1996; Yates and Strzepek, 1998b; Conway, 2005; Elshamy et al., 2009a; Elshamy et al., 2009b; Kingston and Taylor, 2010; SNCR, 2010; Di Baldassarre et al., 2011; El Ganzori, 2012). It can be shown that there is a significant fluctuation in rainfall and flows in the Nile basin leading to much uncertainty in the future. For instance, Gleick (1991) recorded a 50% decrease in runoff in the Blue Nile catchment due to a 20% reduction in rainfall. While Strzepek et al. (1994) summarized the impacts of climate change on the Nile's flow at Aswan. The UK Meteorological Office (UKMO) scenario recorded a 12% decrease in the Nile's flow, the Goddard Institute for Space Studies (GISS) and Low-end scenarios referred to 18% and 14% increases in the flow respectively, and the Geophysical Fluid Dynamics Laboratory (GFDL) results presented a dramatic decrease about 77% of the Nile flow at Aswan.

Conway (1996) verified a shift of –9% to +12% in mean annual Nile flows for 2025. In contrast, Yates and Strzepek (1998b) reported that five of six climate models showed an increase in Nile flows and only one presenting a slight decrease. In addition Conway (2005) stated that the average of Nile flow to Egypt was 76.5 BCM over the period 1981 – 1990 compared to 84 BCM for the period 1900 – 1959. Conway indicates this decline in Nile flow due to the climate variability in the Nile basin. Conway also mentioned that the variability in the White and Blue Nile flows influences the Main Nile flow. Another contribution to Elshamy et al. (2009b) used 17 GCMs to predict an average 15% decrease in flow of the Blue Nile by 2100, where the change varies from a reduction of 60% to a rise of 45%. Actually, this range appears unreasonable due to the considerable uncertainty in long-term future predictions. Moreover, The SNCR (2010) assessed the sensitivity of Nile river flows to climate change and concluded that the Atbara and the Blue Nile are highly sensitive to rainfall changes, while the Equatorial Nile flow reported low sensitivity and the White Nile has a moderate sensitivity to rainfall variability. The SNCR (2010) confirmed that a 10% reduction in rainfall over the Nile upstream could cause 31% decrease in Nile flow at Khartoum, while 10% rise in rainfall will lead to 36% increase in Nile flow at the same place. It is noted that this study depended on assumed scenarios, not time series analysis. Furthermore, El Ganzori (2012) refer to an increase in the Nile flow at Dongola over the period 2020 – 2049 using the period 1970 – 1999 as baseline. This increase is estimated by +0.5% to + 36.2% depending on the projections of PRECIS and HadCM3 models. In spite of the expected increase in Nile flow at Dongola, the Blue Nile flow change will likely range from -6% to 29% and the White Nile flow change may vary between -12% to +10%.

It can be seen that there is a huge uncertainty range of increase and decrease in Nile flow and rainfall; this may be due to the uncertainty in the projections of used climate models. According to climate variability research, scientists define the likelihood of an increasing or decreasing trend as ‘uncertainty’. Overall, it can be noted from these studies that there is a massive uncertainty about the climate variability in the Nile basin; many studies approved a decrease in Nile flows and rainfall and other studies reported an increase; this discrepancy due to the disagreement between used climate models and the applied methodology. Although, these previous studies discussed the uncertainty in climate variability over the Nile basin, no study has yet addressed the impact of this uncertainty on Egypt’s water demand and supply system.

2.3.5 Uncertainty of Population Growth

Egypt faces significant growing water demands, from a rapidly growing population, accelerated urbanization, higher living standards, and an agricultural policy that emphasizes expanding production to meet the needs of the population (Moghazy et al., 2013). The total water demand recorded was 80.25 BCM in 2017; the water demand in the domestic sector was 10.7 BCM in 2017; and the total water shortage in Egypt was 21BCM in the same year, a shortage expected to increase continuously due to population growth (MWRI, 2018). The availability of freshwater in Egypt is a significant challenge because the average population density has doubled in just 30 years (Hamza and Mason, 2004).

In 2013, Egypt’s population growth rate was 2.5%, according to the Central Agency for Public Mobilisation and Statistics (CAPMAS), and 2% in 2015, representing a net additional million Egyptian that year against a base population of 92 million people (CAPMAS, 2018; see Figure 2.3). In 2017, Egypt’s population was 95 million people resident in Egypt (plus a further 9 million expat Egyptians) (CAPMAS, 2018) against a 2005 projection for 2017 of 89 million people (CAPMAS, 2005). CAPMAS (2006) had projected the population to be 92.6 Million people by 2020 but now report this at 100 Million (CAPMAS, 2020). United Nations projections forecast Egypt’s population will rise from 62.3 million people in 1995 to 95.6 million people by 2025, and may reach 114.8 million people before 2065. It is noticeable that these projections were characterized by imprecision in forecasting, where population projections are tending to underestimate population growth. This may be attributed to the used model in prediction or ignoring important criteria when predicting the population, such as the migration factor. Longer-term projections (MWRI, 2014) conclude that strong growth will continue for decades with population in the range 120-150 million by 2050.

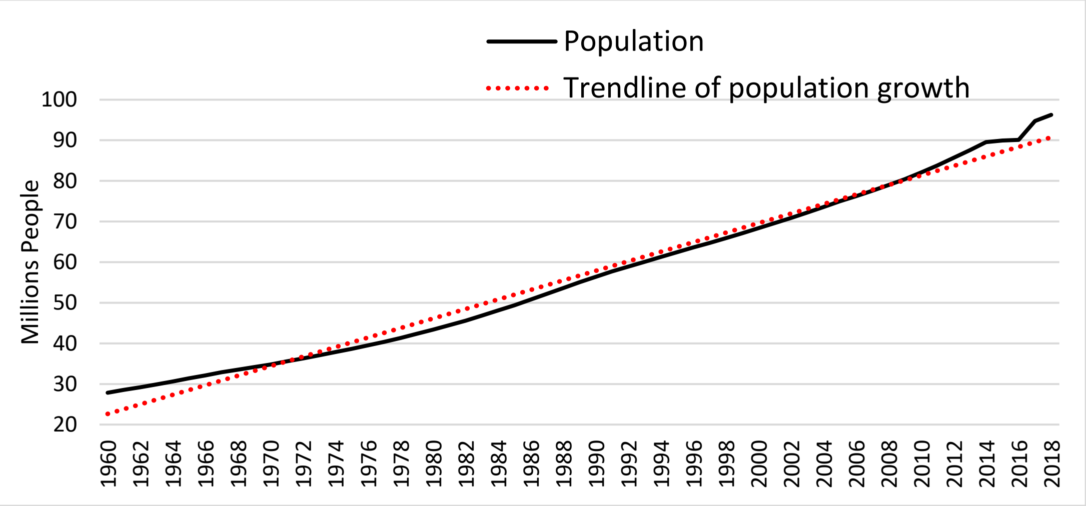


Figure 2.3 Trend of population growth in Egypt over the period (1960 - 2015) (CAPMAS, 2018).

This high population growth rates will exacerbate the water security problems. MWRI estimated that water needs are expected to rise 20% (15 BCM/yr) by the year 2020. However, future population growth is clearly uncertain and Egypt needs to develop different scenarios to deal with demand uncertainty arising from population uncertainty so as to manage the water demand and supply effectively.

The major challenge faced by the Egyptian government is the limited annual freshwater quota from the Nile of 55.5 km^3 year as written in the agreement between Egypt and Sudan in 1959. Population growth has led to reduction in the freshwater availability per capita (Table 2.1). MWRI (2018) reported that freshwater availability reached 570 m^3 per capita in 2017, and this is expected to drop dramatically to 324 m^3 by 2050 (MWRI, 2005).

Table 2.1 Decreasing fresh water availability per capita in Egypt (MWRI 2005).

Year	**Population million people**	**Nile water availability m^3/capita/year**
1960	25	2200
2000	62	887
2010	80	688
2015	90	611
2037	140	392
2050	170	324

Another uncertain and complex factor facing water in Egypt is the population's water consumption behaviour. Although water is a vital component of development in Egypt, the limited water resources are not treated as a scarce resource. Conversely, its use is supported by the Egyptian government, which unintendedly boosts wasteful activities and irrational use of resources (Ahmad, 2000). These wasteful activities can be noticed in flood-irrigation system in old lands and tradition of sprinkling water in the streets to beat the heat in the summer. Abdin and Gaafar (2009) confirmed that water stress conditions are poorly associated with water aware behaviour of the consumer, due to educational level, knowledge of scarcity, and cultural trends. In addition, the rapid population growth increases the extent of the water network, this may increase water losses, where distribution losses in the drinking water network reached 29% in 2015 (MWRI, 2017).

It is clear that population growth and its projection is uncertain but will push up water demand. Egypt is increasingly becoming a water-scarce country due to its population growth. In addition, the water consumption per capita is uncertain in the future due to accelerated lifestyle change, population behaviour that hinders the rational use of resources and water policies change to counter the irrational behaviour of the individual by increasing the price of water. Egypt's water consumption per capita was recorded 110 m3/capita/year in 2001 and 87.6 m3/capita/year in 2015 (Figure 2.4) (CAPMAS, 2001-> 2015). All these challenges are uncertainty sources need to be handled to imagine the future of water demand and supply in Egypt.

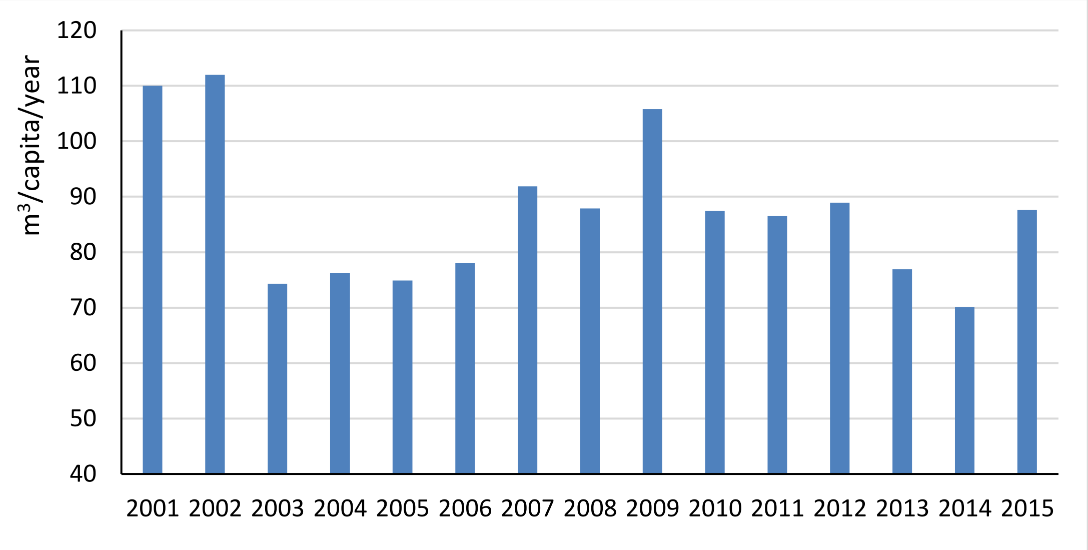


Figure 2.4 Change of water consumption per capita in Egypt 2001- 2015 (CAPMAS, 2001-> 2015).

2.3.6 Uncertainty of Agricultural and Industrial Expansion.

Due to accelerated development of the industrial sector and land reclamation projects to meet the population's needs from food and housing, a considerable increase in water demand is expected in the agricultural and industrial sectors. According to the MWRI (2018), water demand in the agricultural and industrial sectors reached 61.65 BCM and 5.4 BCM in 2017 respectively, and it is expected to increase continuously due to ongoing development. In fact, the government feels obliged to develop in this way to provide food for the increased population given the continuous decrease in per capita crop area and per capita crop production (MWRI, 2005).

For decades, Egypt has tried to increase its agricultural area through reclamation of desert land. In 2005, Egypt’s agricultural lands approached 8.22 million feddans (Hereher, 2009). According to the Ministry of Agriculture and Land Reclamation, the agricultural area recorded 9.096 million feddans in 2015. There was a proposal in the national plans to add 3.4 million feddans of desert land to the cultivated land area. In the beginning of 2016, the government announced the start of a project to reclaim 1.5 million feddans in the desert. This land expansion would place a tremendous stress on water supply. However, many reclamation projects have been proposed and announced, but have failed due to lack of water, a harsh climatic location, or lack of government support to provide services. Therefore, the agricultural and industrial policy in Egypt is in practice unclear. Figure 2.5 shows past and planned development areas for agriculture, residential cities, and industrial areas.

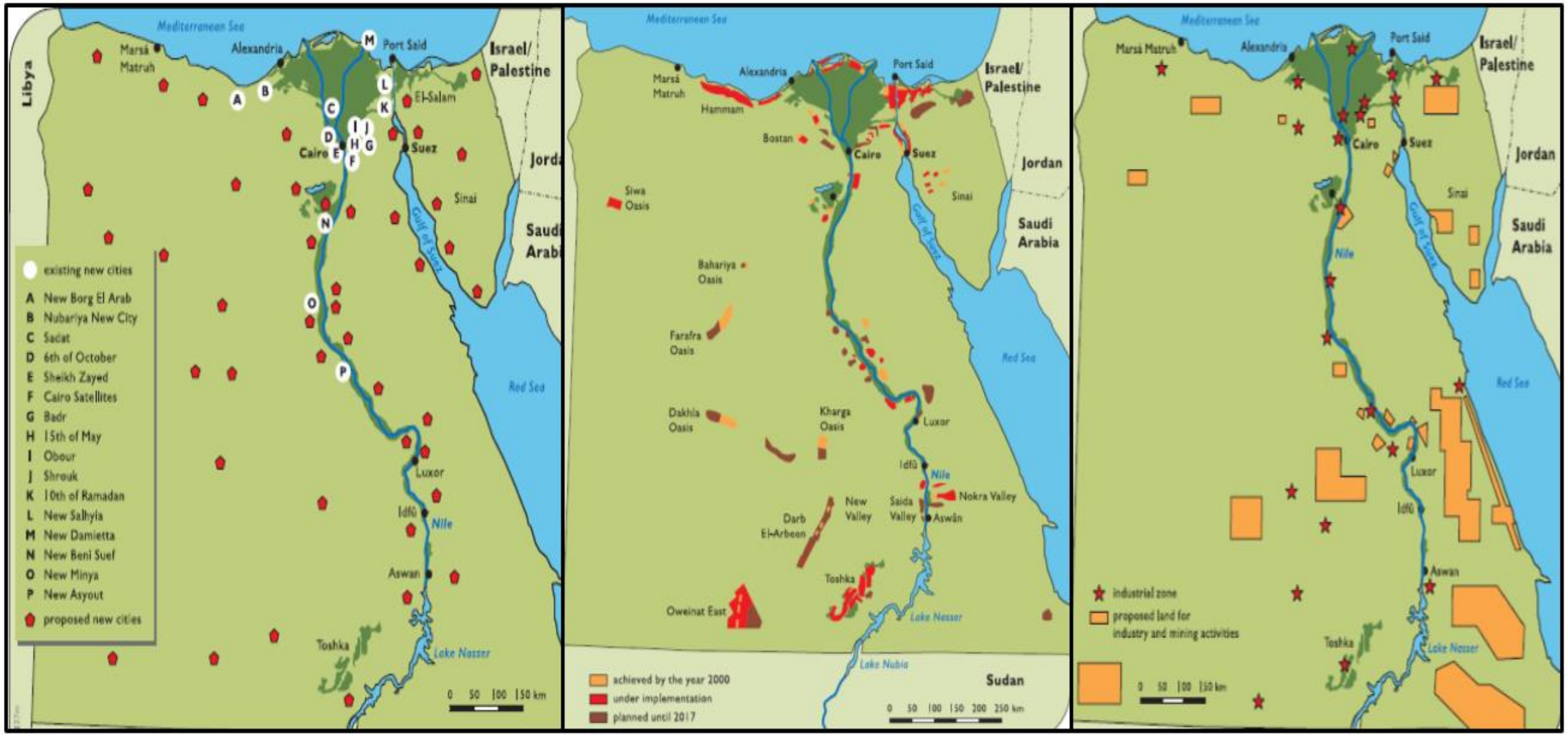


Figure 2.5 Land expansion (new cities, new industrial areas and cultivated lands (past and planned) (MWRI, 2005).

Besides the uncertain future of agricultural and industrial development, there are many challenges and uncertain factors associated with both sectors such as seepage losses from canals and drains, evaporation loss from water surfaces, water consumption per feddan and per industrial unit, and the accuracy of water distribution operation. It is worth noting that the losses in agricultural and industrial sectors reached 37% and 77% in 2015 (MWRI, 2017). The high apparent losses in industrial sectors is due to many industrial units not being registered; many units withdraw much water, use little, and discharge the wasted/unused water to the canals for recycling.

2.3.7 Uncertainty and Complexity of Riparian Countries' Developmental Plans.

Egypt’s last severe drought occurred in the mid-1980s but it is expected that future droughts would become more extreme, not only due to climate change but also due to development in riparian countries (Wolters et al., 2016). This includes uncertainties associated with the impact of climate change and development activities on droughts. Elsaeed (2012) recommended that Egypt should take into consideration the negative impacts of developmental plans in riparian countries on its water resources for securing future water needs. The developmental plans in the upstream countries related to the Nile River include the dams’ constructions for electricity purposes and water usages purposes.

The Nile Basin is an extremely complicated hydrologic system occupying an area of about 3 million km^2. There are six major reservoir dams within the Basin: High Aswan Dam 1970 (on the Main Nile), Merowe 2009 (Main Nile), Rosaries 1966 (Blue Nile), Khashm ElGirba 1964 (Atbara River), Sennar 1925 (Blue Nile) and Jebel Aulia 1937 (White Nile) as shown in Figure 2.6. These dams have limited storage capacities and are able to store only seasonally (Whittington et al., 2014). Therefore, these dams have not a significant effect on the water supply to Egypt because they have not year-round storage, unlike the HAD in Egypt. On the contrary, the main obstacle confronting Egypt today is the Grand Ethiopian Renaissance Dam (GERD), constructed on the Blue Nile at the Ethiopian border with Sudan. The GERD will be the second dam on the Nile system able to provide annual storage with a total storage capacity of 74 BCM, an active storage volume 59.2 BCM, and with dead storage volume 14.79 BCM (IPoE, 2013). The dam is built on the Blue Nile, which contributes about 59% of the annual inflow to Egypt. Therefore, there is uncertainty around the negative impacts of the GERD on the water supply to Egypt as a downstream country.

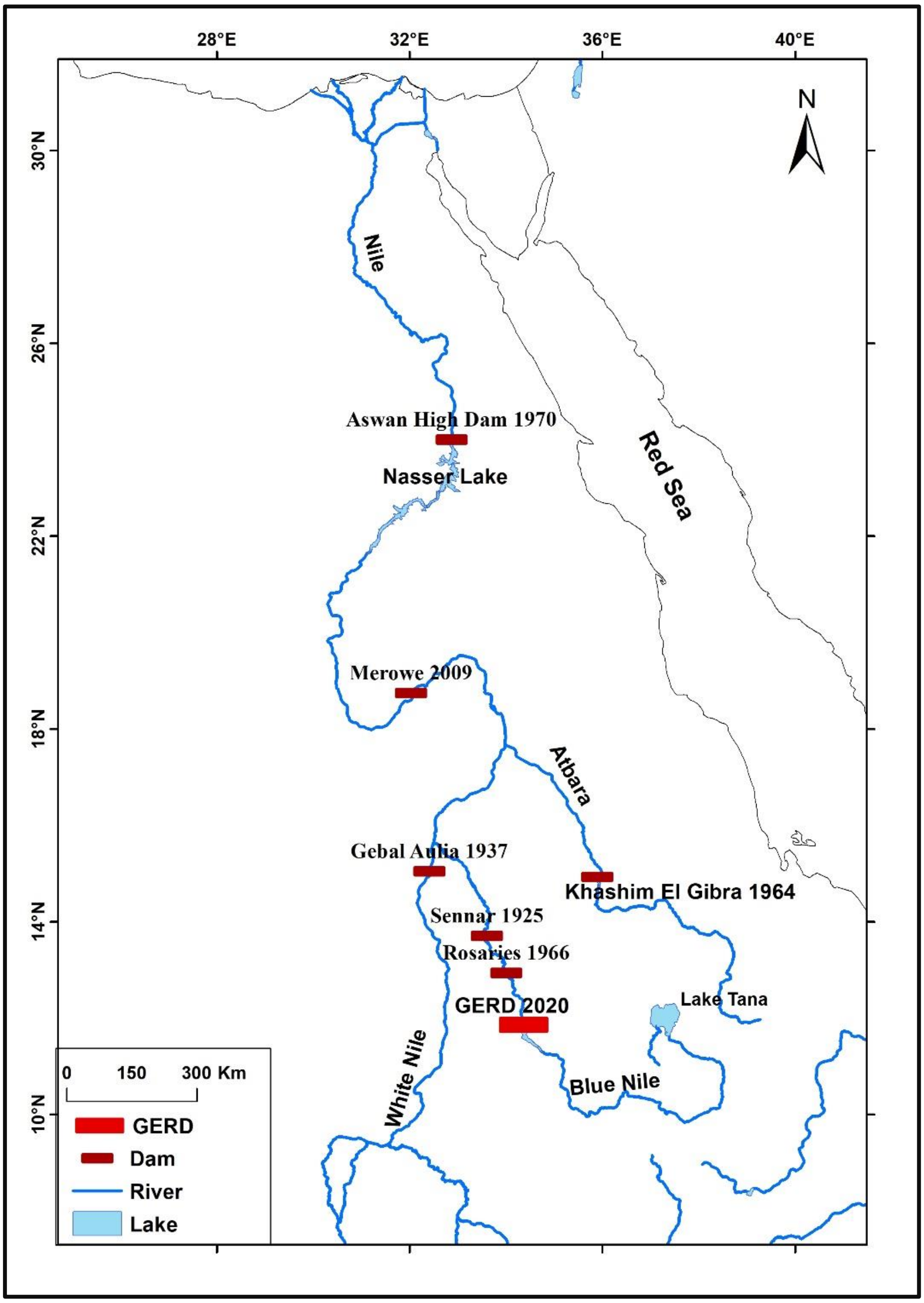


Figure 2.6 Nile River Basin dams, figure modified from Wheeler et al. (2016).

Several studies discuss the potential impacts of the GERD on Egypt. According to the final report of the International Panel of Experts (2013), if the dam's lake filling occurs during wet or normal years, Egypt will not be impacted but the power supply from the HAD will reduce by about 6% due to the lower water levels in Nasser Lake. If the filling of the dam's lake occurs during dry years, water supply to Egypt will be significantly impacted and will cause the loss of power supply at HAD over prolonged periods. It is worth noting that the panel recommended a more detailed assessment of effects on water resources in Sudan and Egypt. In fact, there are some gaps in this report; for example, the experts did not determine how many years are sufficient for filling without any impacts on the downstream countries. In addition, they defined the impacts with linguistic terms without giving any numbers to identify the sizes of impacts. Furthermore, the model used in the reported hydrological simulation is unknown. Further, terms of average, wet and dry periods are used in the analysis without identifying amounts and defining terms sufficiently, which is potentially misleading.

Ramadan et al. (2013) used the MODSIM model to simulate the impacts of the GERD on Egypt's water supply based on 2, 3, and 6 years as filling periods. The results found that filling of the GERD at normal flow over 2, 3, and 6 years will decrease active storage in Nasser Lake by 37.2, 25.4, 13.2 BCM respectively during each year. Filling at the minimum of average flow through 2, 3, 6 years decreases active storage in Nasser Lake by 25.9, 37.8, 45.1 BCM each year. The situation will be more dramatic in case of the filling at minimum flow where active storage in Nasser Lake will reduce by 44.3, 54.4, and 55.1 BCM during each year. It can be noted in this scenario, that the proposed filling year impacts are very close. Mulat and Moges (2014) depended used the MIKE simulation model to determine the impacts of the GERD on the HAD. This study used only a 6 year simulation filling period and at normal flow. They confirmed that the annual GERD outflows during the filling stage would never be less than 28.9 BCM per year, and concluded the proposed 6 years filling period is adequate to fill the reservoir with little effect on the irrigation water demands in Egypt. Abdelhaleem and Helal (2015) assessed the potential effects on Egypt's water supply deficit using the SOBEK model for implementing multiple scenarios. The results indicated that the decrease in Egypt's water share would not be more than 5 - 15% (equal to 52.7 – 47.2 BCM).

El Bastawesy et al. (2015) discussed uncertainty in predicting the expected shortage of net inflow to downstream due to the yearly variability upstream, and lack of data and models used to predict the Nile's flow patterns over coming years. Abdel-Satar et al. (2017) supported this, stating that the situation will be worse with reduced flow to the Egyptian Nile due to the GERD. The GERD also raises uncertainty as the dam body may not able to bear the volume of silt and huge water expected to be retained Behind the dam, whilst the dam's geological breakdown within 25 years has been predicted, with potential adverse consequences on downstream locations including Khartoum, and possibly the Aswan High Dam (AHD) (Abbas, 2010; Abbas, 2011).

Conversely, Tesfa (2013) used the MIKE basin river basin simulation model to point out the benefits of the GERD such as removing up to 86% of silt and sedimentation from Nasser Lake, reducing evaporation losses, and regulating the Nile flow over the year. Mulat and Moges (2014) discussed GERD benefits of increasing hyrdro-electric energy production in Ethiopia and the eastern Nile region, although this could decrease energy production from the HAD; they also noted that the GERD may result in reduced evaporation losses in Nasser Lake, as given the bathymetry, a lower water level implies a small lake surface area. Recently, Elsayed et al. (2020) suggested that the GERD filling and operation would have an effect on the Water-Food-Energy nexus in Egypt, with a significant impact if the filling process took place over a dry period.

Overall, the impact of the GERD will remain uncertain in relation to the threat to Egypt’s water supply. Although studies have analysed various scenarios, these ignore very wet and very dry years and overlook the GERD policy scenarios after the filling period.

2.4 Water Demand and Supply Future is Uncertain

As a result of the complexity of water demand and supply variables, factors, and interrelationships, the future of water demand and supply in Egypt is uncertain. Several scenarios have been developed to predict the future of both demand and supply in Egypt. These scenarios use assumptions that range from optimism to pessimism based on triple prediction (low, medium, high) of the variables in the Egyptian water system. These scenario studies are reviewed in this section.

Many studies forecast that water demand will rise, by up to 87.9 BCM by 2017 (UN CCA, 2001; Gharib, 2004; Abdin and Gaafar, 2009), 81.9 BCM by 2020 (Darwish et al., 1998), 69 BCM by 2017 (UN CCA, 2005), and 92.2 BCM by 2017 (Adly and Ahmed, 2009). Water supply is estimated to be 70.3BCM by 2020 (Darwish et al., 1998), 79 BCM by 2017 (Adly and Ahmed, 2009), and Allam and Allam (2007) estimated that future water demand and supply will vary between 78.75 BCM – 85.2 BCM by 2020. Actual water demand recorded in 2017 was 80.25 BCM, and water supply was 80.25 BCM due to increasing use of non-conventional resources. These inaccurate estimations by scientists and organizations may attribute to ignorance of demand variables, underestimation or overestimation to uncertain factors, using extremely simple models, or using misleading data. Another reason is that decision makers respond to the signals these forecasts give (e.g. by developing unconventional resources).

In 1997, the MWRI developed three scenarios depending on the reclamation plan to project the water balance in 2017, the first scenario assumed reclaiming of 1.5 million feddans, the second of 2 million feddans, and the third of 3.2 million feddans. The study reported that Egypt needs extra water, of about 24 BCM, to achieve the three scenarios by 2017. The scenarios did not extent to increased water requirements from other demand sources.

Yakoub (1997) identified the future of water demand from the population based on a set of assumptions, and concluded that domestic demand would rise from 4.5 BCM in 1995 to 7.5 BCM by 2017 due to population growth, and industrial demand would increase from 7.5 BCM to 14.6 BCM over the same period. In fact, domestic demand and industrial demand reached 10.7 BCM and 5.4 BCM in 2017 respectively. There is misleading data in observations for the industrial sector leads to this forecasting result, where many industrial units work in secret without a license and are not registered in the database of the ministry of water or ministry of industry.

Darwish et al. (1998) used Ministry of Public Works and Water Resources data to predict water supply and demand 2005-2025 based on Nile projects (Jonglei Canal, Mashar, Baher El-Ghazal), and improving the irrigation systems. Changes in water supply were 67.2, 68.5, 69.5, 70.3, 70.8 BCM in 2005, 2010, 2015, 2020, 2025, respectively. The water demand will be 67.70, 72.50, 77.30, 81.98, 87.54 BCM in the same years, respectively. Therefore, the water shortage could be 5.80, 9.30, 13.10, 16.98, 22.04 BCM, also in the same years. While the water demand, supply, and water deficit reached 80.25, 59.25, 21.00 BCM in 2017 respectively.

Allam and Allam (2007) provided a vision of future water demand and supply in Egypt based on a perception of the status of the available water resources. Three future water scenarios for 2020 were presented, and all showed that Egypt will suffer a considerable water deficit in the near future. The analysis used population forecast now known to be underestimates (population of 91 – 94 million people for the three scenarios, while actual population is more than 100 million in 2020) and ignored the impacts of climate change in the scenarios.

MWRI (2010) proposed three scenarios for water demand and supply to 2050: critical scenario, balanced scenario, optimistic scenario. The critical scenario assumed the continuation of the current rate of population growth of 2%, which leads to slowing the rates of development and assumed that Upper Nile projects will not be implemented. The balanced scenario assumed 1.8% as a population growth rate and an increase in the river's revenues by 2 BCM by implementing some Upper Nile projects. The optimistic scenario assumed a decrease in the rate of population growth to 1.6% and an increase in the river's revenue rates by about 4 BCM (MWRI, 2010). In fact, the three scenarios tend to be optimistic and ambitious scenarios, where the MWRI did not take into consideration the climate change impacts or the expected problems with riparian countries, and there is overestimation in the efficiency of water networks in different sectors. However, the results found the water demand for the three scenarios could be 88.3 BCM, 86.7 BCM, and 86.7 BCM in 2050 for critical, balanced, and optimistic scenario respectively. While the water shortage estimated by 26.3 BCM, 22.2 BCM, and 19.7 BCM in 2050 for the three scenarios respectively.

All the studies above used simple mathematical calculations without simulation modelling, and did not include many drivers or make numerous assumptions.

Mohie El Din and Moussa (2016) assessed different scenarios for 2025 using the more complex Water Evaluation and Planning (WEAP) model. The findings indicated that water shortage in 2025 would be 26 BCM/yr in case of continuation of current policies. It is noted however that the assumptions of scenarios were still extremely simple and overlooked many drivers including climate change. Moreover, Mohie El Din used inaccurate data and underestimated and overestimated assumptions. For example, Egypt’s population is estimated to be 83 million people in 2016 and 95 million people by 2025, while Egypt’s population estimated by 95 million people inside Egypt in 2017. In addition, the estimation of agricultural area was 7.6 million feddans in 2016 and 8.1 million feddans by 2025, whilst the agricultural area is recorded as 9.09 million feddans in 2015. Further, Mohie El Din also overestimated the number of industrial units and water loss rate of industrial sectors.

Overall, the future of water demand and supply for Egypt is ambiguous and Egypt is facing water scarcity due to a complex set of uncertain factors such as climate change, overpopulation, industrialization, agricultural expansion, and the transboundary problems with riparian countries due to their own developmental plans. During the 1990s, different scenarios predicted water surpluses in 2017 and 2025 yet an increase in the water deficit occurred. Recently, some scenarios did predict water shortage, but the actual shortage experienced has been far greater. More reliable scenarios are evidently required to deal with uncertainty in Egypt's water resources system.

2.5 Uncertainty of Water Management Policies

The objective of Egypt's key water policy is to bridge the water gap and ensure water security for the next generation. From the management point of view, uncertainty is the lack of accurate knowledge, regardless of the reason for this deficiency (Refsgaard et al., 2007). Water demand is always uncertain and changing on a variety of time scales depending on a range of variables, so the wise policy should be prepared to face the consequences of these changes. In fact, the Ministry of Water Resources and Irrigation in Egypt has developed several policies to manage the water resources including different measures to bridge the water gap. These measures are the result of many joint projects with international organizations; some measures have been implemented and some cannot be implemented. However, these measures and policies are surrounded by uncertainty in their ability to bridge the water gap (and I note the water gap remains despite application of various policies and measures).

Historically, Egypt has two types of water policy; water development policies and water allocation policies. These policies and measures can be summarized as follows:

In 1975, the first Egyptian water policy was prepared. This policy was extremely simple and had two stages to achieve two goals; the objective of the first stage was providing 12.2 BCM from drainage water reuse and 0.5 BCM from groundwater in the delta. The objective of the second stage was implementing upper Nile projects for cultivating 1.5 million feddans.

In 1980, the Ministry of Water Resources and Irrigation (MWRI) estimated water demand and supply for every five years up to 2000. The policy focused on irrigation improvement projects to save 5 BCM in the long-run and give Jonglei canal benefits. This policy did not define 'the long run'. However, irrigation improvement projects still occur whilst the Jonglei canal project has ceased.

In 1986, The MWRI created a new policy, revising the previous water policy based on a set of assumptions such as the operation time of the Jonglei canal (extended to 1992/1993), expanding the drainage reuse programme, reclaiming 2.5 million feddans, and expanding the projects of groundwater utilization in Nile valley and Delta.

In 1990, the MWRI introduced a new policy based on the new agricultural expansion policy. This policy included many assumptions as follows: achieving the Jonglei Canal in 2000, increasing the drainage water reuse from 4.7 BCM to 7.5 BCM by 2000, increasing the extraction of deep groundwater from 0.5 BCM to 2.5 BCM and from shallow groundwater 2.6 BCM to 4.9 BCM, decreasing the outflow to the sea from 1.8 to 0.3 BCM by 2000, cultivating 1.6 million feddans, and increasing the efficiency of domestic use from 50% to 80%. It can be noted that this policy includes more measures than the other policies but still neglects many measures and aspects.

In 1993, a new water policy was created to include new strategies based on ensuring the satisfying of water demands and expanding the agricultural areas based on water demand and supply scenarios for 2017.

Water policy **1997-2017** followed a more integrated management approach through closer cooperation between government institutions and water users in water management and operation of the water allocation system. The goals of this policy are to develop new resources, making better use of existing resources, and improve water quality (Table 2.2), achieving these goals by demand and supply management, and pollution control. It is noted that this policy has launched in 2005. The policy includes all activities related to water and takes into account technical, managerial, socio-economic and institutional aspects. However, it neglects uncertainty and did not set any metrics to identify the ability of the proposed measures to manage water demand and supply, or even the feasibility and possibility of implementing these measures. In long-run national policy formulation, uncertainty must be expressly considered rather than simply ignored. Water shortage still exists and is increasing in spite of application of all measures in the water policy.

Egypt is currently preparing a new national water policy (2017 - 2037) and has declared that this policy will be based on four pillars of: (i) water quality, (ii) water conservation, (iii) water resources development, and (iv) raising awareness. It is important to indicate that these measures and policy are subject to rethinking, particularly after the emergence of the GERD predicament.

Table 2.2 Goals and measures of National water policy (1997-2017) (MWRI, 2005)

Goals	**Measures & Method**
Developing new water resources	• Increase the harvesting of rainfall along the northern coast • Increase the benefits and management of shallow groundwater • Continue the cooperation with the upstream countries • Negotiate larger share of Nile water • Complete the project of Jonglei Canal • Increase the harvesting of flash floods
Making better use of existing resources	• Development of horizontal expansion area depending on water availability. • Improvement of water efficiency • Improvement of irrigation system • Reuse of drainage water • Reuse treated wastewater • Improvement water allocation
Improvement of water quality	• Encourage use of environment friendly agricultural methods • Increase the treatment of wastewater • Initiate cost recovery • Enhance water quality monitoring

2.6 Research Gap

It is concluded from previous literature that Egypt is facing water scarcity due to the impact of several uncertain factors including population growth, industrialization and agricultural expansion, climate change, and hydro political problems on the upstream Nile, particularly the Grand Ethiopian Renaissance Dam. In addition, most water supply and demand scenarios in Egypt overlook many drivers and are based on simple mathematical calculations unable to address system complexity.

Egypt has a complex system of water demand and supply that includes multi variables and interrelationships for which there is significant lack of knowledge. In addition, used data used past modelling of water demand and supply is misleading and needs to be more reliable, with respect to, for example, inflow and outflow, rainfall, groundwater, and demand factors. Moreover, applied water policies and measures used for decades are clearly uncertain, as evidenced by their inefficiency to achieve their principal goal of bridging the water gap between supply and demand. Therefore, the current and future water demand, supply and shortage are ambiguous and uncertain and need to consider uncertainty and complexity. For the above reasons, this study planned to address the uncertainty and complexity in water demand and supply with a more capable, well-defined, calibrated, and verified modelling methodology.

There is a need to better understand the complexity of Egyptian water demand and supply and address uncertainties in the hydrological system, potential future water demand and supply, and water management. Consequently, we need a drastically different approach to those used before, going beyond conventional methods used to date, to address the uncertainty and complexity inherent in water demand and supply scenarios, hydrological modelling and management scenarios.

The present study will contribute to filling the gap of dealing with uncertainty and complexity in water demand and supply scenarios by quantifying the uncertainty in hydrological modelling, assessing the impacts of uncertain factors on water demand and supply, predicting the uncertain future of water demand and supply, and evaluating the uncertainty in water management to bridge Egypt’s water gap.

These knowledge gaps were converted into research questions and objectives outlined in Chapter 1. Question 1 and Objective 1 are investigated in Chapter 4 to deal with uncertainty and complexity in Egypt's water demand and supply system, data, and model to establish a primary understanding of the basin hydrology and use the calibrated hydrological model in the next chapters. Question 2 and Objective 2 are discussed in Chapter 5 to fill the gap related to assessing the impacts of future uncertainty factors on water demand and supply. Question 3 and Objective 3 are identified in Chapter 6 to fill the gap of the expected future water demand and supply in Egypt. Question 4 and Objective 4 are presented in Chapter 7 to evaluate the uncertainty in water policy and identify the optimal methods to bridge the future water gap. Having identified the research questions and objectives from the gaps in knowledge, I then chose the methods described in chapter 3 to answer the research questions and achieve the objectives of the thesis.

Chapter 3
Methodology

3.1 Introduction

The purpose of this chapter is to introduce the research methodology of this empirical study regarding how we can deal with uncertainty and complexity in water demand and supply in Egypt. Uncertainty exists in the modelling process, future projections, and management policy. The aim of this study is to handle the uncertainty and complexity associated with water security in terms of water demand and supply modelling, projection, and management. This methodology provides four approaches to deal with uncertainty at different levels. These are a predictive approach to deal with uncertainty in hydrological modelling; an exploratory approach to evaluate the uncertainty and risk associated with future influencing factors; a scenarios approach to assess uncertainty and imagine the future. Finally, a precautionary approach is used to deal with the uncertainty in management to bridge the water gap. The applicability of these four approaches for this study is discussed in-depth in this chapter.

These approaches are widely used in analysing uncertainty in hydrological modelling and are appropriate when a researcher seeks to understand uncertainty and complexity in the system and interrelationships between variables. The approaches are based on the rationale that the purpose for which the model is built will determine how to address uncertainty. For example, if the purpose of a model is prediction, dealing with uncertainty will be based on quantifying and reducing it to make the model predictable and accurate. These approaches are described as follows:

- The prediction approach is used to predict and reduce uncertainty in hydrological modelling. This approach depends on dealing with parameter uncertainty using sensitivity analysis and uncertainty algorithms to reduce the uncertainty in input data errors, model parameters and variables, and model structure. The objective of this approach is developing the hydrological model to represent the water demand and supply system accurately reducing uncertainty as much as I can.

- The exploratory approach is used to explore uncertainty and quantify the risk of factors affecting future water demand and supply. The approach is applied in the hydrological model using projections of factors such as climate and population growth.

- The scenarios approach is a technique for obtaining a close picture of the water demand and supply's future by running the model with a set of probabilities and assumptions. This technique draws upon inductive reasoning in modelling.

- The precautionary approach is used in managing water resources to overcome water shortage. This approach examines to what extent the measures are certain to bridge the water gap.

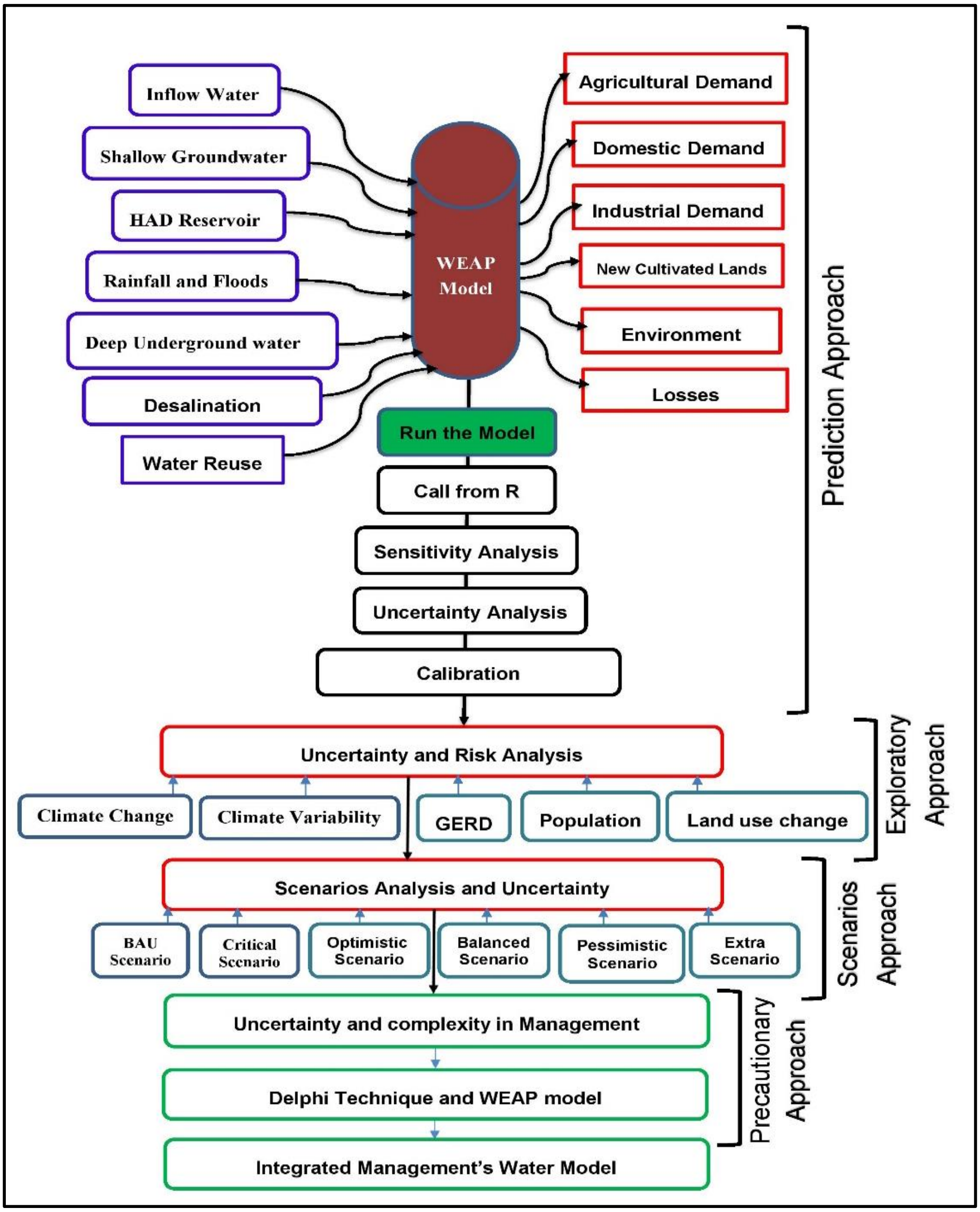


Figure 3.1 Research methodology.

The applied methodology is illustrated in Figure 3.1. To achieve this method, this work has passed through a set of stages, as follows:

3.2 Literature Review

This analysed, in chapter two, studies that investigated uncertainty and complexity in water systems. These studies varied from global, regional, to local studies. These studies are related to uncertainty analysis techniques in hydrological modelling, uncertainty sources, and advanced hydrological models. This stage helped design the methodology by identifying the methods of dealing with uncertainty and complexity and specifying the required data during the field work for modelling purpose.

3.3 Field Work

This study provides more than three months of field work to collect the required data, meeting stakeholders and implement questionnaires related to uncertainty and complexity in water demand and supply in Egypt. The design of research was influenced by dealing with required data, for example, some data was available in an annual, not monthly time-step such as demand data. This led to selecting a model that can run on an annual time-step. Another example is that there was some missing data in certain time periods such as the demand data, which was missed before 1990. This led to determine the study period to be from 1990 - 2015.

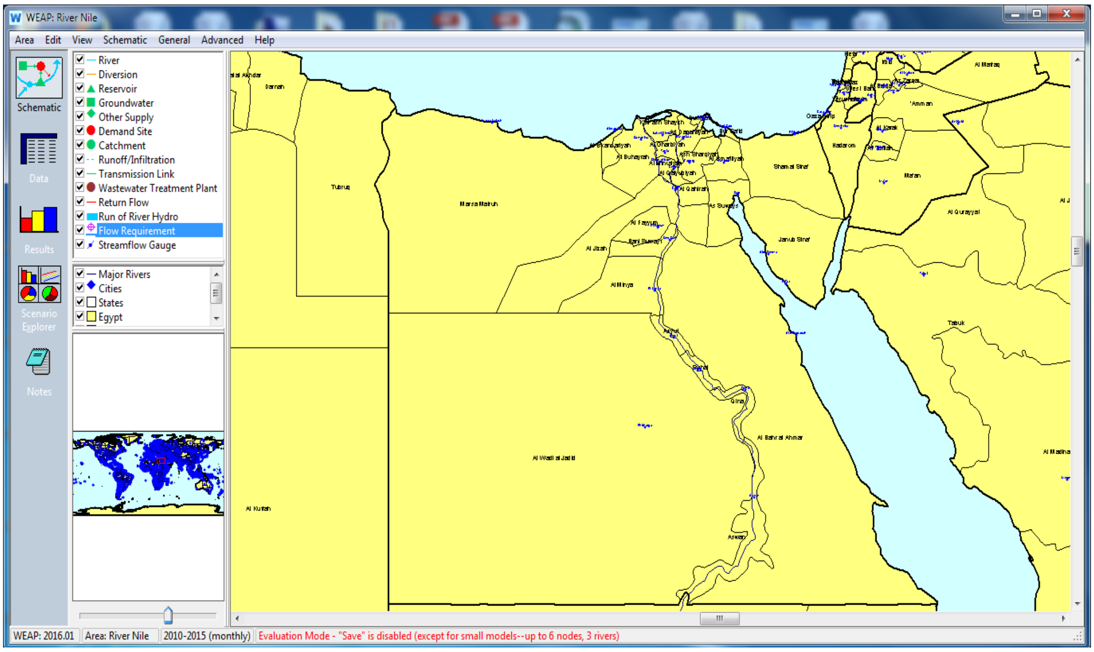
3.4 Hydrological Modelling

Hydrological modelling is necessary to simulate the water system to address the uncertainty and complexity in water demand and supply. A hydrological model is critical to the study, but many potentially suitable models exist. To select the appropriate model I create a set of criteria to support the decision process. These criteria are the model’s efficiency to represent the Egyptian water system, model flexibility for the required data, simplicity of model structure, parameters’ number, model efficiency in parameter estimation, possibility of linking with uncertainty's algorithms, model capability to develop future scenarios and integrated water management. According to these criteria, I evaluated many models (see Appendix 1). The Water Evaluation and Planning (WEAP) software is the most useful, simple and understandable model, and one that provides the needed or desired information with the desired accuracy. WEAP is thus selected for the present study.

3.4.1 WEAP Model

WEAP (Water Evaluation and Planning) is a user-friendly model that takes an integrated approach to water resources planning (WEAP, 2016). WEAP has been applied to water resources assessments and development in dozens of countries (e.g. Algeria, Jordon, South Africa, United States, India). It provides a comprehensive, flexible and user-friendly framework for policy analysis. It evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems (WEAP, 2012). WEAP was developed by the Centre of the Stockholm Environmental Institute for water resources planning (Sieber and Purkey, 2015). It uses an integrated approach to simulate water systems and policy options. As a database, WEAP provides a framework for storing water demand and supply information and features. As a forecasting tool, WEAP is enabled to simulate and deal with water demand and supply components such as streamflows, runoff, reservoirs, discharge, pollution generation, treatment and water quality, and discharge. As a policy analysis tool, WEAP can evaluate a wide range of water development and management strategies and takes into consideration various and competing usages of water systems. (Sieber and Purkey, 2015). The WEAP structure consists of five main views, as follows:

- The Schematic view contains GIS-based tools, in which objects of both demand and supply side can be created.
- The Data view is used to create variables and relationships, assumptions and projections using mathematical expressions.
- The Results view show all model outputs, in charts and tables, and on the Schematic.
- The Scenario Explorer is used to highlight key data.
- The Notes view provides a place to document any data and assumptions. Figure 3.2 shows the interface of the WEAP Model.



WEAP: 2016.01 | Area: River Nile | 2010-2015 (monthly) | Evaluation Mode - "Save" is disabled (except for small models--up to 6 nodes, 3 rivers)

Figure 3.2 the GIS interface of WEAP model

3.4.2 Why WEAP?

WEAP has been used since 1991, often for modelling large river basins, for example the Olifants River basin in South Africa (Levite et al., 2003), Lake Naivasha, Kenya (Alfarra, 2004), the Volta basin in Ghana (Condappa et al., 2008), Krishna River, India (Bharati et al., 2009), Merced river basins, USA (Kiparsky et al., 2014), Chifeng city, China (Hao et al., 2015), Nestos hydrosystem, Greece (Tsoukalas and Makropoulos, 2015a; Tsoukalas and Makropoulos, 2015b; Tsoukalas et al., 2016), Jareh Dam, Iran (Azari and Asadi, 2017), Yala catchment, Kenya (Okungu et al., 2017), and Indus river basin (Asghar et al., 2019). WEAP's popularity is due to its capability to simulate a wide range of hydrological, economic, and technical components, such as river streamflow, rainfall, groundwater flow, seawater desalination, water reuse, water losses, water demand by sector, and allocation priorities. Its superior use is also beneficial for the simplicity of structure, flexibility, and user-friendliness of the parameters used in uncertainty analysis, which makes its running and optimization easy. WEAP is employed in only a few studies in Egypt, and for management only (Mahmoud and Amer, 1998; Mohie El Din and Moussa, 2016; Ramadan et al., 2019). From the applications above, WEAP’s advantages are reported as follows:

For hydrological simulation, WEAP has the efficiency to represent any complex system using the nodes and links in the GIS interface by drag and drop. In addition, the principle of the model is investigating and presenting water demand and supply to compare between them and give the unmet demands in the results, then developing an exploratory analysis to identify the impacts on increasing or decreasing water demand and supply, and examining measures to select the optimal measures to overcome the deficit.

For the required data purpose, Although WEAP requires a large amount of data to run, it is more flexible in the required time period of data, where it can be run on a daily, monthly, or annual time-step. This gave the priority to selecting the WEAP model, where Egypt's demand data is available only on annual time-step and after 1990. The feasibility of WEAP model handled the restrictions of data in Egypt by running the model on annual time-step.

For the uncertainty analysis, WEAP presents the demand and supply sides and includes the Parameter Estimation tool (PEST) for parameters optimization. PEST (Parameter Estimation) is a free software package for Model-Independent Parameter Estimation and Uncertainty Analysis embedded in WEAP to allow the user to modify model parameters to increase the model's accuracy and automating the process of comparing WEAP outputs to historical observations (Sieber and Purkey, 2015). The PEST tool will reduce the run time for applying the uncertainty methods and help to reduce the complexity by determining the initial ranges of parameters before conducting the uncertainty analysis. The simplicity of the model and the ability to understand the model structure and modelling process may help in reduce the uncertainty and complexity. WEAP can be recalled from python and R to conduct the uncertainty analysis in R. In addition, usage of multiple simulations and full ranges of scenarios in WEAP are useful to deal with the uncertainty and complexity of water system by expecting the potential future and providing stakeholders with the best solution (Leong and Lai, 2017). WEAP has the capability to deal with all sorts of uncertainty and complexity. For example, uncertainty and complexity related to modelling of water demand and supply using simulation, optimization and calibration. Uncertainty and complexity related to future factors' impacts using scenarios. Uncertainty and complexity related to water management and policy using adaptation scenarios and examination the measures and options. Furthermore, it is effective in comparing demand and supply and extracting the water shortage in the results. Further, WEAP is accepted by most hydrologists and water resource planners as a powerful model.

For scenarios analysis, WEAP enables its users to study long-term impacts and create future scenarios efficiently. In addition, it is allows users to combine different variables and drivers such as climate, demographic, economic, environmental...etc., to create different scenarios simply. In many studies WEAP has demonstrated its performance in simulating and analysing scenarios for long-term development and management of water resources (e.g. Lévite et al., 2003; Abrishamchi et al., 2007; Mugatsia, 2010; Hamlat et al., 2013; Zerkaoui et al., 2018; Amin et al., 2018).

For integrated water resources management (IWRM), WEAP is used widely and successfully across the world. It is effective as a management modelling tool to examine and select the optimal measures to bridge water deficits. WEAP has high level planning at local and regional scales, and has proved to be a useful robust tool for decision support in the futuristic management of water resources (Droubi et al., 2008; Al-Omari et al., 2009; Le Page et al., 2012; Hadded et al., 2013; Li et al., 2015).

For the model structure, WEAP has a reasonable structure compared to the other more complex models, where WEAP includes eight calibration parameters only to specify the rainfall-runoff process in the catchment area compared to other models that have a large number of parameters. This advantage is key in this study because parameter uncertainties increase with model complexity (Shrestha, 2009). In addition, WEAP schematic is a GIS-based user-friendly interface with a variety of tools that allow representing the links between the variables of demand and supply effectively.

Therefore, the WEAP model is used in this study to conduct hydrological modelling, sensitivity analysis, uncertainty analysis, and calibration, for the period 1990 - 2015. The scenarios analysis and integrated water management modelling are then conducted for the period 2016 - 2050.

The prediction approach addresses uncertainty in hydrological modelling from uncertainty in model structure, input data, and model parameters, using the procedures set out next.

3.4.3 Sensitivity Analysis

Selecting the sensitive parameters and estimating their ranges is essential to reduce complexity and perform uncertainty analysis efficiently by saving the computational time. The initial sensitivity analysis using the PEST tool in WEAP is conducted as an initial estimation of parameters to determine the sensitive parameters and approximate ranges. After identifying the parameters, global sensitivity analysis is applied in R software to determine the most sensitive parameters and optimal range. The global sensitivity analysis is used because it considers the full domain of uncertainty of the uncertain model quantities (Saltelli et al., 2008). In addition, global sensitivity analysis allows the uncertain inputs and parameters to vary separately within their whole range of variation. Therefore, the integration of the local and global method proposed by Morris (1991) is conducted in R software.

3.4.4 Uncertainty Analysis Using GLUE

Most of the uncertainty analysis techniques used in hydrology usually lump all the errors into a single term and assign the uncertainty in the input-output representation of the model primarily to the parameters. These techniques are based on the optimization algorithm to search the parameter space. As discussed in the literature review, there are many algorithms used to estimate and apply the uncertainty analysis, but the GLUE and SUFI-2 algorithms are widely used due to their high efficiency. Although SUFI-2 performs better than GLUE and reduces analysis time, the SUFI-2 is not available in R software or supported by an open source code. Dr. Karim Abbaspour, the developer of SUFI-2, confirmed (*pers. comm.*) that this algorithm is developed for the SWAT model and it is embedded only in SWAT-CUP. Given this constraint, the GLUE method is implemented with WEAP for uncertainty analysis and calibration, addressing four-discharge gauge stations over the period 1990 – 2015 (Chapter 4). In this study, the calibration period is (1990-2006), and the validation period is (2007-2015). The p-factor and r-factor are used to evaluate the uncertainty analysis, and NSE, PBIAS, RMSE are used to evaluate the performance of the model. Finally, a novel classification of uncertainty and complexity is conducted depending on the present study's analyses and results.

3.5 Uncertainty in Future Water Demand and Supply

For a complex system, where it is difficult to identify probabilities of events or future outcomes, for whatever reason, an option is to create plausible scenarios of what could happen in the future that affect the performance of the system (WWAP, 2012). Uncertainty can be addressed by examining multiple projections or scenarios, or several runs of the same model (with different initial conditions or parameters), and comparing the results. While this will not decrease the uncertainty intrinsically, it provides insight into the range of uncertainty and the probability of different outcomes (Barnes, 2016).

The exploratory approach is used in this step to assess the uncertainty in the future. After optimizing the WEAP model and extracting the reference scenario in the previous step (Chapter 4), I input a set of variable projections in the model to evaluate their risk's uncertainty on water demand and supply (Chapter 5). WEAP was run with each variable individually to detect its impact on water demand and supply. The variables addressed are climate change over Egypt, climate variability over the Nile's upstream basin, population growth, land use change, and the Grand Ethiopian Renaissance Dam (GERD). These variables are selected based on previous studies and stakeholders' opinions during the questionnaire (see Section 3.6 below and Appendix 3).

Besides the exploratory approach, the scenarios approach is applied using a set of probabilities and assumptions for each scenario to imagine the future of water demand and supply (Chapter 6). These probabilities and assumptions are extracted from the historical data, projections data, ministries' plans for development and literature review. Six scenarios are employed to detect potential futures of water demand and supply in Egypt (Business as usual, Critical, Optimistic, Balanced, Pessimistic, and Hybrid). These scenarios are determined to cover all future possibilities. WEAP is run for each scenario to determine water demand, water supply, water deficit, and HADR volume. The uncertainty and risk for each scenario is quantified statistically by coefficient of variation.

It is worth noting that several studies adopt a methodology for addressing uncertainty using scenarios to determine possible future ranges of the identified uncertainties, allowing the modeller to avoid the idea of single uncertain future (Peterson et al., 2003; Kok and Van Delden, 2009; Kok et al., 2011; Jones, 2012; Gal et al., 2014; Bárcena et al., 2015; Lan et al., 2015; Beh et al., 2015; Maier et al., 2016). Although the probability of any generated scenario actually occurring is likely to be almost non-existent, having a set of potential scenarios can help decision-makers and operators learn how their system will likely work under possible futures. Usually, future scenarios will address both natural phenomena and human decisions.

3.6 Uncertainty in Water Management

After dealing with uncertainty and complexity in hydrological modelling (Chapter 4) and assessing the impacts of future uncertainty factors on water demand and supply (Chapter 5), then framing the potential future via scenarios (Chapter 6), I use the WEAP model as a management tool to deal with uncertainty in water management (Chapter 7). When uncertainty is high, the precautionary principal and adaptive management may be more appropriate to deal with uncertainty (Peterson et al., 2003; WWAP, 2012; Kundzewicz et al., 2018). The precautionary approach is used to evaluate measures to bridge the water deficit under the worst scenario. This study produces probabilistic measures to bridge the water gap in Egypt over the period 2016-2050. The selection of optimal measures depends mainly on experts' knowledge and arguments through questionnaire, which help illustrate the uncertainties associated with measures' efficiency, future water demand and supply.

Before applying the questionnaire, the explanation of the project was introduced for the participants individually, and ethical consent considerations were explained (e.g. right to withdraw, anonymity, confidentially, data security). My positionality as an assistant lecturer at Egyptian university provided me with access to the stakeholders in different organizations by letters from my university to the heads of organizations to help me to get the data and apply the questionnaire. It did not matter at all for the participants, as they dealt with me as just a PhD student who wants to apply questionnaire and complete the research project. In addition, my positionality as an Egyptian citizen studying issues of uncertainty and complexity in water demand and supply in Egypt remained at the forefront of my mind to rebuild the realities about water demand, supply, and deficit and find the optimal solution to bridge the water gap.

The questionnaires for gathering the stakeholders’ opinions and extracting the proposed measures and actions (Appendix 3) are moderated by the Delphi technique, a way to obtain a common view of issues where there is little or no certain evidence and where opinion is important (Desai, 2002; Thangaratinam and Redman, 2005; De Carvalho et al., 2017). The Delphi method is widely used in resolving complex water resources issues (e.g. Taylor and Ryder, 2003; Lahham et al., 2011; Mutikanga et al., 2011; Basco-Carrera et al., 2017; Ward et al., 2019). Nine key organizational stakeholders from different organizations and specialized researchers in water resources are identified carefully to conduct the questionnaires as follows:

- Ministry of Housing, Utilities and New Communities
- Ministry of Water Resources and Irrigation
- Ministry of Local Development
- Ministry of Health and Population

- Ministry of Industry
- Ministry of Agriculture and Land Reclamation
- Egyptian Environmental Affairs Agency
- National Water Research Centre
- University professors specialized in water resources

After analysing the questionnaires and obtaining the results and the proposed measures, the WEAP model is run with these measures to examine their efficiency to close the water gap between demand and supply. The selected measures, the uncertainties associated with water management, and questionnaires with stakeholders in Egypt will be discussed in detail in Chapter 7.

The conclusion, recommendations, limitations and future work of this study are discussed in Chapter 8.

The goal of this chapter was to outline the research method used to answer the research questions. A discussion of the procedure, data collection, used approaches, techniques, and analysis, and questionnaire outlined the specifics of how the study was conducted. The goal of next Chapters 4, 5, 6, and 7 is to provide the study results and demonstrate that the methodology described in Chapter 3 was followed.

Chapter 4

Uncertainty and Complexity in Egypt's Water Demand and Supply

4.1 Overview

This chapter investigates the complexity and uncertainty in water demand and supply in Egypt using the prediction approach to deal with both issues. The prediction approach using the GLUE method is applied with the WEAP model to reduce and quantify the uncertainties in model outputs. The parameter estimation tool (PEST) that is embedded in WEAP is used to help in estimating the parameters' ranges and reduce computational time. In addition, global sensitivity analysis is applied to identify the most sensitive parameters and decrease the number of parameters in the calibration procedure. The findings are also discussed in the light of the analysis and previous literature in order to identify the classification of uncertainty and complexity in water demand and supply modelling.

The main results show that the water demand and supply system in Egypt can be simulated, reducing the uncertainty and complexity associated with data and system, depending on the WEAP model and the GLUE method as effective and reliable tools in hydrological modelling. There is uncertainty over the water shortage in Egypt due to the fluctuation of water demand and supply from year to year. In addition, the extent of the uncertainty that can be reduced is subject to the source of the uncertainty, data reliability, system understanding, and analyst choices of tools for modelling and addressing uncertainty. Further, classification of uncertainties and measure of complexity in water demand and supply are proposed.

4.2 Introduction

Recently, uncertainty and complexity have become essential considerations in hydrological modelling. Uncertainty can result from incomplete knowledge of the system components, future factors, and the inner processes for simulating the system well. The complexity is appearing in the modelling procedures and contributes in the uncertainty degree and may exists in every step of modelling, for example, the complexity in collecting the required data, choosing the used model to predict, estimating the ranges of model parameters, and number of factors and interrelationships (Edmonds, 1999; Leonard, 2009). The basic intent of this chapter is to clarify how we can deal with complexity and uncertainty in the Egyptian water demand and supply system. As clarified in (Chapter 2) the Egyptian hydrological system is complicated and has several uncertain components and we need to discuss the uncertainty factors which affect demand and supply sides. Liu and Gupta (2007) reported that the best approach for addressing hydrologic uncertainty properly is to quantify, and reduce uncertainty implicated in hydrologic modelling in a systematic way. Uncertainty is manifested in input data or parameter values, model structure or process understanding, and modelling process. To reduce uncertainty, data collection, analytical capacity, and predictive ability are all required (WWAP, 2012). For more clarification, in order to reduce uncertainty in hydrological predictions, three procedures should be taken: (1) obtaining more accurate and precise hydrological data; (2) Using enhanced and reliable hydrologic models which have better representations of physical system and better mathematical techniques; and (3) Using powerful and effective techniques which can better extract and assimilate information depending on the available data, the hydrologic models and prediction processes (Beven and Young, 2003; Liu and Gupta, 2007). This chapter provides a coherent and integrated approach in dealing with different kinds of uncertainty and reducing the complexity in Egypt’s water system.

Hydrological models are not sufficient to provide this knowledge; the used model should combine the processes of demand and supply sides. In this study, I apply the WEAP model as a hydrological and management model using the Soil Moisture method to simulate streamflow and observed volume in the HADR reservoir. Egypt is the study area, where it has a complex system includes many variables, interrelationships, and specific operation rules that increase the complexity.

Dealing with uncertainty is often based on the purpose of model and study. This chapter is dealing with the complexity and uncertainty in modelling process using the prediction approach based on GLUE algorithm. During the hydrological modelling, the various causes of uncertainty affect the model outputs’ quality. The GLUE algorithm is used in hydrology for quantifying and estimating the uncertainty of model predictions that connect with model structure, measurement error, input data, and model parameters (Stedinger et al., 2008). Due to the uncertainty in input data, model structure and parameters, the uncertainty analysis based on the prediction approach aims to estimate the degree of confidence in the model outputs.

In the present chapter, handling complexity through reducing the reasons in the hydrological system relies on the modeller experience in choosing the appropriate model, estimating parameters ranges, variables, and understanding the interrelationships and interconnections in the system (Raccoon, 1995; Leonard, 2009). The most complex step in hydrological modelling is parameters range estimation, where this step increase the computational time of modelling and optimization process. The chapter presents a novel method to reduce the complexity in the model by reducing the number of parameters and its ranges before applying the GLUE method and sensitivity analysis. This method is depending on the PEST Parameters estimation tool that is embedded in WEAP model. PEST is used for adjusting the parameters range based on the increase/decrease of the Nash-Sutcliffe efficiency (NSE) value by checking how each adjustment affects the model outputs’ quality.

Although water supply and demand may not change, they can be better managed by understanding and simplifying the complexity and minimizing the uncertainty in the water system. This is an essential procedure to increase our knowledge about the hydrological system of Egypt by investigating Egypt's water demand and supply, and water gap over the period 1990 - 2015. In addition, a new classification for uncertainty and complexity is presented based on the findings of uncertainty and complexity analysis. This classification is used to discuss and investigate the types and sources of uncertainty and complexity in Egypt’s water demand and supply.

4.3 Materials and methods

4.3.1 Study Area

The study area for which modelling is performed in is the Nile catchment, in Egypt. The Egyptian Nile originates south of Egypt in the Blue Nile, Atbara river in Ethiopia, the White Nile in Sudan, and Lakes Victoria and Albert. The length of the river in Egypt is about 1520 km excluding tributaries within Egypt, equivalent to about 22.9% of its total length. The total area of the catchment is 242,526 km^2 which lies between latitude 31° 34′ 4″ E to 21° 22′ 5″ E and longitude 35° 74′ 5″ N to 29° 8′ 17″ N (Figure 4.1). The Egyptian Environmental Affairs Agency report that the Nile is the source of 95% of Egypt’s renewable freshwater and it is a vital element of sustainability of the country. Egypt has an arid desert climate with 20 - 200 mm of annual average rainfall along the narrow Mediterranean coast in the north. The average mean temperatures vary from 10 °C in winter to 32°C in summer.

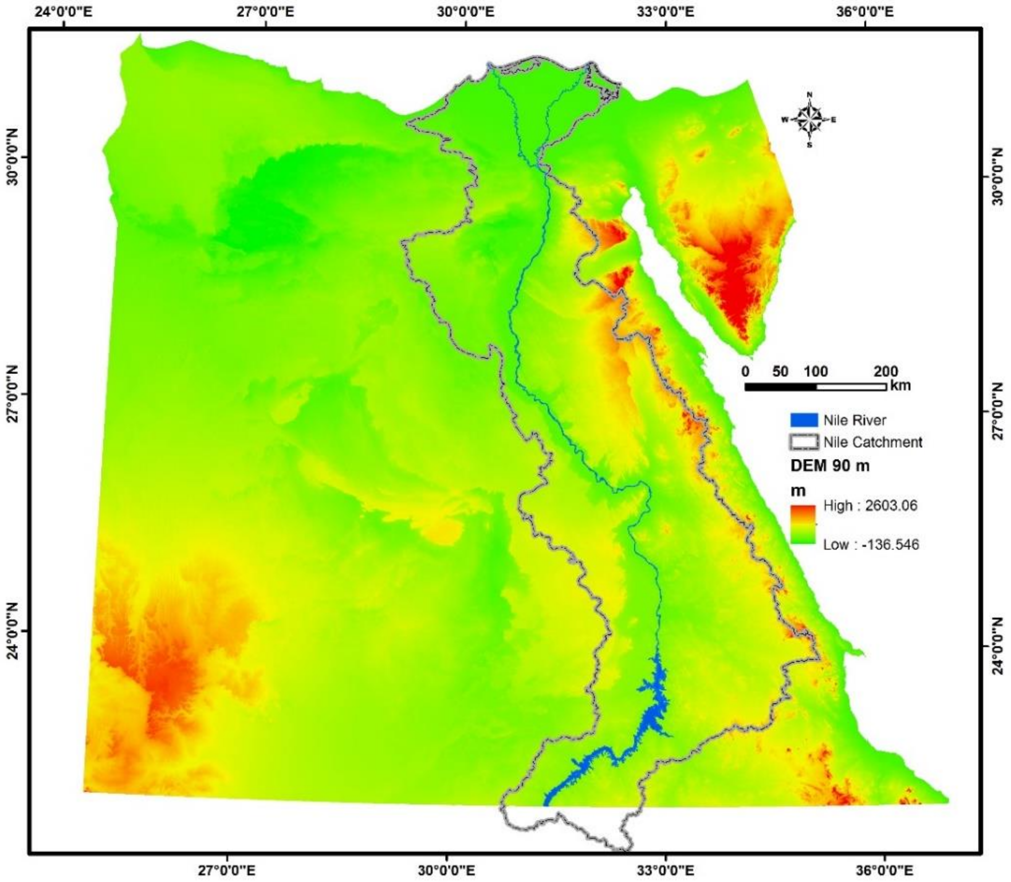


Figure 4.1 The study area showing the Egyptian Nile catchment.

4.3.2 WEAP Application

Selecting the appropriate model to simulate the catchment processes is the key step in the hydrological modelling and it has great impact on the uncertainty and complexity and the model outputs' quality. The applied model should fit the requirements of the area of study based on the nature of variables, the physical interaction in the study area, and the purpose of study. In this study, the WEAP model is applied as a hydrological model to simulate and represent demand and supply components and the catchment process in the study area. WEAP is used to develop the set of variables, parameters, and equations to adapt the analysis to constraints and conditions with possible data exchange with other software such as Excel and R. In addition, PEST for parameter estimation embedded in WEAP is applied to this study to support the calibration process. This tool makes the detection of parameter estimation easier, and helps accelerate the uncertainty analysis by reducing the complexity of the parameters numbers and investigated ranges.

4.3.3 WEAP Design and Approach

WEAP is developed as a multi-purpose, multi-reservoir simulation software to determine the optimal allocation of water for each time-step according to the priorities of demand and supply. It simulates water demand and supply, flows, storage, groundwater, pollution, treatment, discharge as a forecasting tool. The model provides a flexible and user-friendly interface for hydrological analysis as presented in Figure 4.2. The integrated approach to simulating both water demand, natural flows, and engineered features such as reservoir, groundwater extraction makes WEAP different and more accurate to present the conditions of the region especially, the arid downstream region like Egypt.

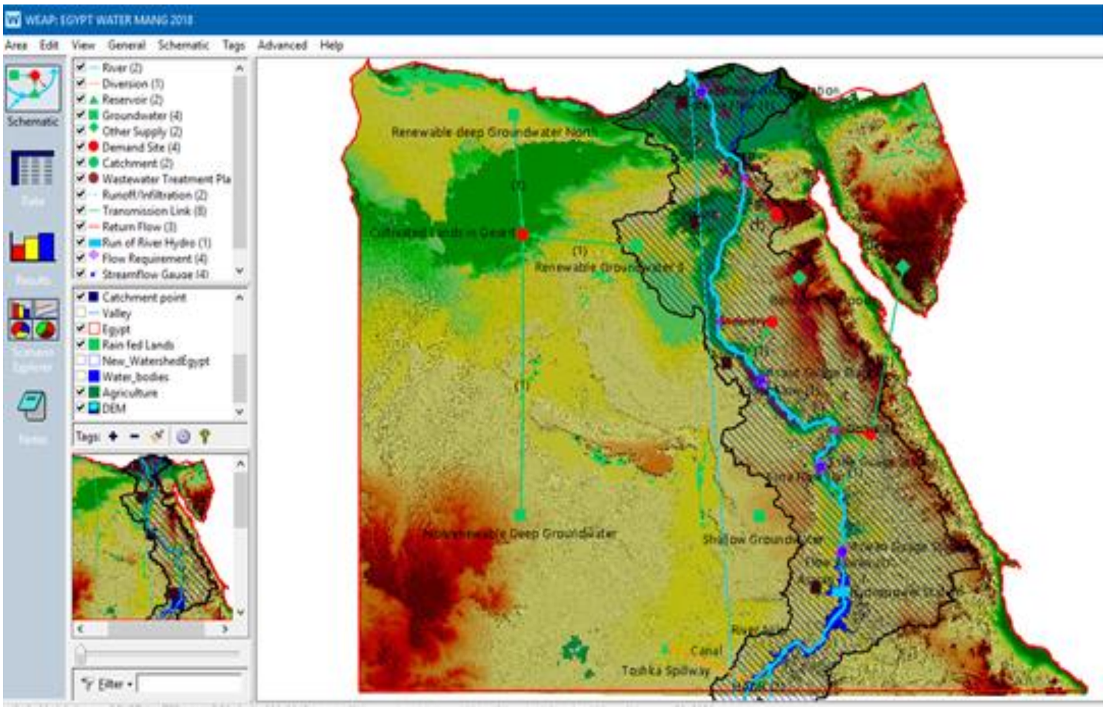


Figure 4.2 The schematic and structure of WEAP model.

WEAP is designed to provide a number of methodological consideration: an integrated planning framework, scenarios explorer to understand the impact of different development choice, demand management, and environmental assessment. WEAP objects and procedures help the planners to investigate a full range of issues and uncertainties related to climate, watershed nature and condition, projected demand, ecosystem needs, operational rules and infrastructure. WEAP represents the system in many elements such as water supply sources (river, creeks, groundwater, reservoir, and desalination plants), ecosystem requirements, water demands and water quality. The data structure and level of details can be customized based on the purpose of analysis (WEAP, 2016)

WEAP computes a water amount and contamination mass equalization for each node and link in the framework on a daily, monthly or yearly time step. Water is dispatched to meet the demand sites requirements depending on the demand priorities, supply preferences, and other constraints determined by the user. The principle of the model is investigating and presenting the water demand and supply to compare between them and giving the unmet demands in the results, then developing the exploratory analysis to identify the impacts on increasing or decreasing the water demand and supply. The hydrological modelling of a watershed using WEAP can be summarized in the following steps:

- Identifying the study area and time frame,
- Identify the required data for running the model,
- Determining the current account that indicate the period of study,
- Drawing the river from the upstream to the downstream,
- Building the schematic model by delineating the catchment area and preparing the data such as DEM, land cover, and climate data,
- Choosing the method to simulate the catchment processes on a daily, monthly, or yearly basis,
- Specifying the demand nodes, supply nodes, reservoirs, groundwater, and other supply,
- Forming the transmission links and outflow links,
- Projecting the streamflow gauge stations and climate stations,
- Inputting the required data for every feature carefully,
- Running the model to explore the error and missed data to fix it until accepted the results,
- Using the PEST parameters estimation tool to help in the calibration process, optimization and determine the parameters ranges to reduce the complexity before applying the UA,
- For this study, dealing with the uncertainty and complexity by applying the sensitivity and uncertainty analysis using GLUE algorithm in R software,
- Calculating the NSE, PBIAS, and RMSE to indicate the accurate model simulation,

- Depicting the water demand and supply, and determining the water shortage.

Based on these steps, WEAP is used to simulate both the hydrological behaviour and anthropogenic activities of water resources to analyse the water availability and unmet demand in the study area.

4.3.4 Algorithm Structure of WEAP Model

The model structure has an essential role in the model complexity, model performance, and modelling uncertainty (Butts et al., 2004). WEAP depends on a hierarchical structure to disaggregate water supply and demand data. It is simple to adapt this structure to the nature of the problem and data availability. WEAP model structure exist into two features: nodes and links represent the water demand and supply, links transfer water between nodes. The linear programing is applied at every node to evaluate the satisfaction of demand site and the analyst determines the instream flow needs based on a daily, monthly or yearly basis and the priority of the demand site that the user defines (Yang et al., 2018). WEAP calculates the water balance based on:

$$Q_{inflow} = Q_{outflow} + Q_{consumption} + Q_{storage} \qquad \text{(Equation 4.1)}$$

Where:

Q_{inflow} is total inflows at a node,
$Q_{outflow}$ is total outflows at a node,
$Q_{consumption}$ is water consumed at a node,
$Q_{storage}$ is net of any change in storage (reservoirs and aquifers).

In addition, WEAP has numerous equations to deal with the complexity of water demand and supply variables as shown in the following equations:

(a) The change in storage (ΔS) = Input (I) – Output (O) (Equation 4.2)
Where inputs may be precipitation, groundwater, and runoff while outputs may be domestic use, irrigation use, industrial use, losses from the system, and evaporation.

(b) The total of required water for the demand site (DS) is calculated as the sum of the consumptions for all the demand site's bottom-level branches (Br) as shown by:

Annual Demand DS = (Total Activity Level Br x Water consumption Rate Br)
(Equation 4.3)

A bottom-level branch is one that has no branches below it (disaggregated from the sectoral demands).

(c) Annual level of activity driving demand, such as agriculture area, population using water for domestic purpose, or industrial unit in the industrial sector, the total annual activity level is calculated by:

Total Activity Level Br = Activity Level Br x Activity Level Br' x Activity Level Br'' x... (Equation 4.4)

The annual level of activity variable depend on the data of population number, agriculture area, and the number of industrial units and may have impact on increasing the uncertainty value.

(d) The annual water consumption rate is derived from the amount of water consumption in the demand site divided by the annual activity level.

(e) The unmet demand is the water shortage and is derived from the difference between the demand and supply side.

The principle of hydrological models is based on gaining a better understanding of water movement and distribution to the demand sites in the basin. Basically, the hydrological models depend on the streamflow records as an indicator to simulate the catchment processes. The models simulate the distribution of streamflow in time and space and the impact of topography, land use, soil properties, irrigation practices, rainfall, demand and supply sides on streamflow. Drylands and irrigated areas focus on understanding the interaction of two natural resources; soil and water (Alhammadi and Al-Shrouf, 2013). The water system in Egypt is highly controlled and depends on the outflow from the HADR and a tenuous rainfall. The streamflow could be affected by discharge from the High dam, rainfall, surface irrigation, soil proprieties, and water usage. The uncertainty in these variables may contribute to uncertainty in the outputs and affect model quality. Previous research has reported the impact of irrigation practices on antecedent soil water, runoff, and streamflow pattern (Ozdogan et al., 2010; Rahbeh et al., 2013; Zeng and Cai, 2014; Essaid and Caldwell, 2017).

WEAP offers five methods for simulating catchment processes: (1) Irrigation demand only versions of the FAO crop requirements approach; (2) Rainfall Runoff simplified coefficient method; (3) Rainfall Runoff soil moisture method; (4) MABIA (FAO 56, dual KC, daily);(5) Plant growth (daily; CO_2, water and temperature stress effects) (WEAP, 2016). Every method depends on the required data and its availability, behaviour of the water supply and demand in the study area, and the purpose of research. Although the soil moisture method is the most complex, it is applied in this study because it depicts the actual water supply and demand condition in the catchment, and also allows for characterization of the impacts of land use and soil types on catchment processes (Ali Amin et al., 2018). It represents the catchment with two soil layers, upper and lower, to simulate evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow. Figure 4.3 illustrates the equations incorporated in the soil moisture method.

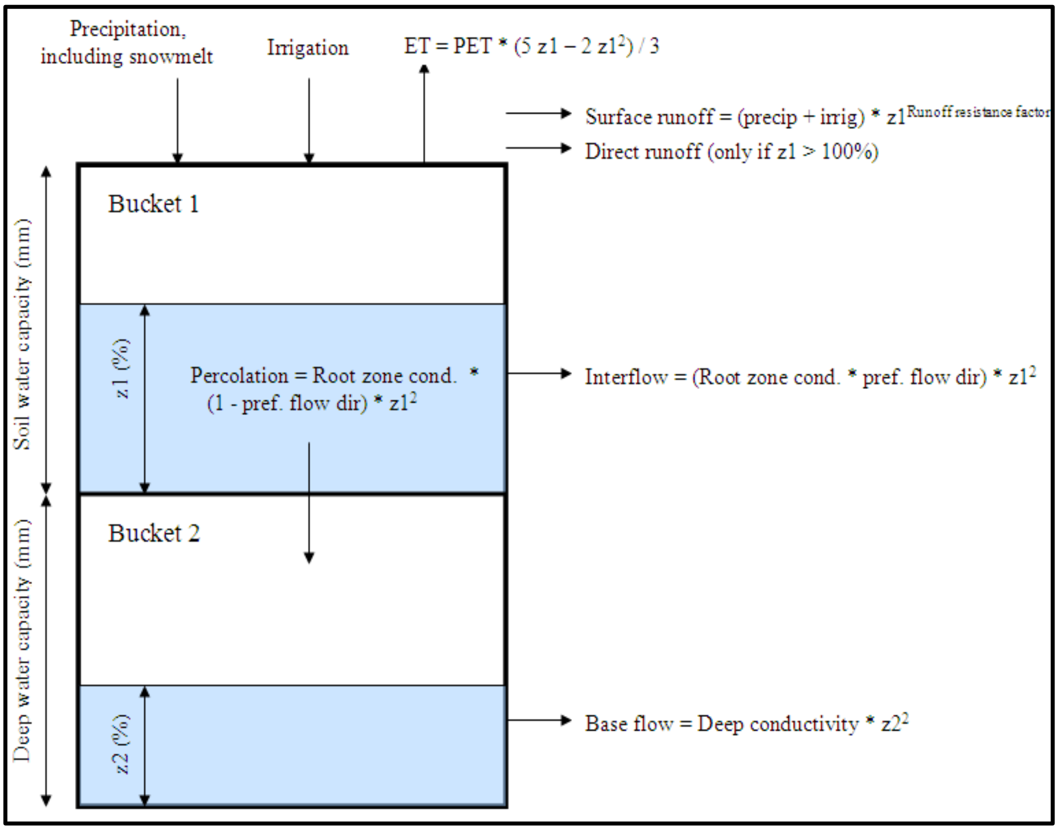


Figure 4.3 Conceptual diagram for soil moisture method (WEAP, 2016)

Agriculture is the greatest consumer of water in Egypt, accounting for about 85% of all demand. Surface irrigation is used for long periods; the soil becomes waterlogged and has unreasonably high water tables in different farming zones and changes to the irrigation method may reduce water demand. Systematically, the soil moisture method is suitable to simulate the catchment processes in the study area. WEAP uses the mathematical formula of the soil moisture method to calculate the water balance (Ahmadaali et al., 2018) as follows:

$$Rd_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{RRF_j} - f_j k_{s,j} z_{1,j}^2 - (1 - f_j)k_{s,j} z_{1,j}^2$$

(Equation 4.5)

Where:

$z_{1,j}$ = [1, 0] is the relative soil water storage, P_e is the effective precipitation (mm), PET(t) is the reference potential evapotranspiration, $k_{c,j}$ is the crop coefficient, and RRF_j is the Runoff Resistance Factor of the land cover (higher values of RRF_j lead to less surface runoff); $P_e(t)z_{1,j}^{RRFj}$ is the surface runoff, $f_j\ k_{s,j}\ z^2_{1,j}$ is the interflow from the first soil layer, f_j is the partition coefficient related to the land cover type, and $k_{s,j}$ is the saturated hydraulic conductivity of the root zone (mm/time).

With reference to WEAP, the Soil Moisture Method requires extensive input data and parameters to run the model including soil, climate, land use, elevation, and inflow and outflow data. These data requirements are discussed further below.

4.3.5 Model Setup for Egypt

WEAP is developed for Egypt by building a schematic model to represent the Egyptian water demand and supply system. The first stage is drawing the Nile in Egypt from the upstream to the downstream then delineating the catchment area of the Nile in Egypt. Using the catchment delineation mode in WEAP physical data is input, including elevation, land use, soil, climate data, climate stations in the catchment area, and discharge gauge stations on the river.

The second step is representing the water demand and supply system as a network of nodes and links along the Nile at their relative position. The demand nodes represent the demand sites divided into agriculture, domestic, and industrial, while the supply nodes represent Nasser Lake reservoir, groundwater, and HAD outflow.

The demand sites are distributed along the Nile in Egypt depending on the plan of the Egyptian water ministry for water distribution. The Nile in Egypt is a controlled system, where water is released from the High dam to meet the needs of downstream sites with distribution for each area via downstream barrages. These barrages, at Aswan, Esna, Nagaa Hammadi, Assiut, and Delta distribute water according to the demand for each sector, and the slope and location of lower canals (NAWQAM, 2008). Figure 4.4 illustrates the complicated system structure and water distribution in Egypt. This structure adds complexity in understanding and representing the system and simulating the catchment processes.

According to this structure and distribution plan, the catchment area is divided into four divisions: Aswan-Esna, Esna-Assuit, Assuit-Delta, and Delta. The ministry of water distributes the water from the High dam for division as 8.4%, 27.4%, 32.1%, and 32.1%, respectively. Each division has three demand sites (agriculture, domestic, industrial) and data for every site is extracted from the original data of the whole sector based on the percentage of water distribution in each division.

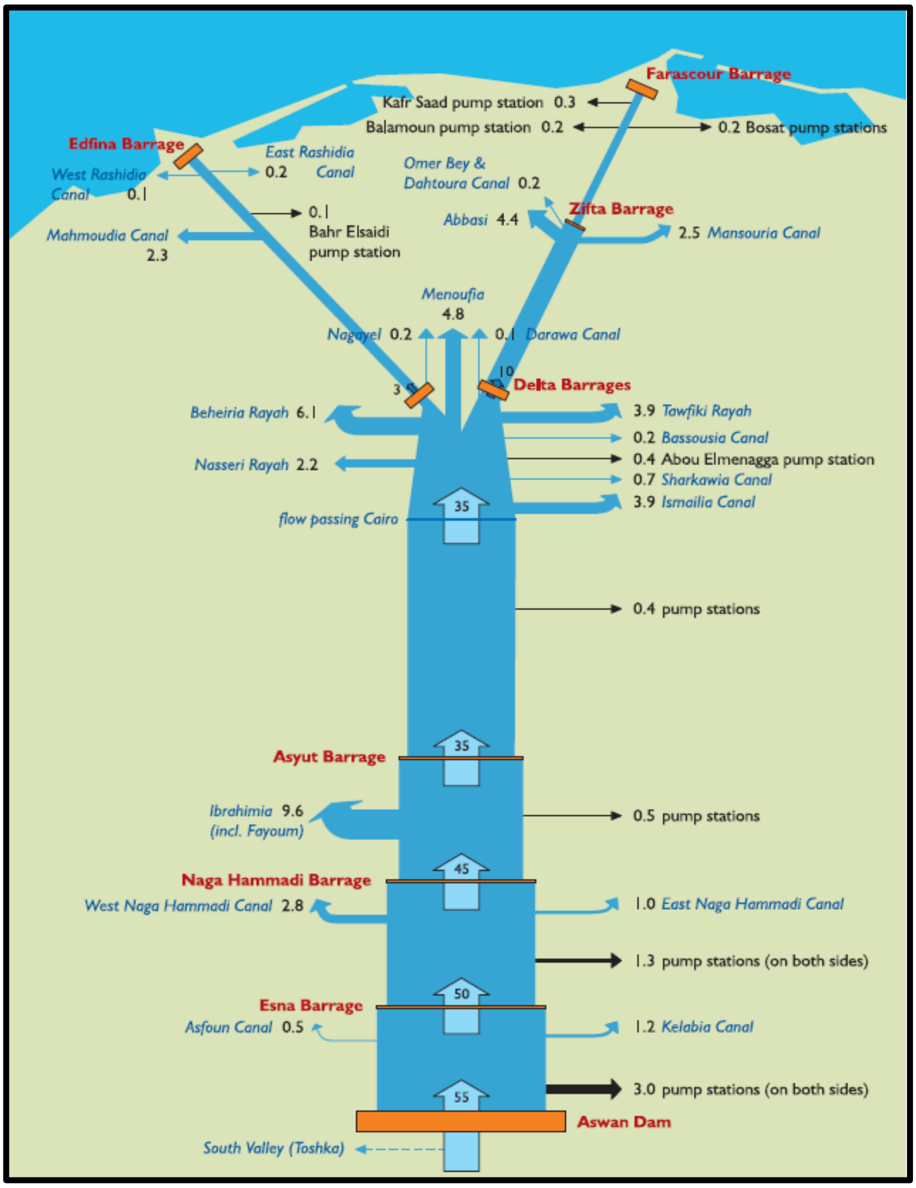


Figure 4.4 Water distribution in Egypt (NAWQAM, 2008)

Each node is then connected with the water supply sources via transmission links. Each node is given the rank of priority in demand and supply sides based on the historical water consumption data and observed values. According to these criteria, the demand priority is set as the same priority for all demand sites agriculture, domestic, and industrial use. Figure 4.5 shows the demand and supply system for Egypt in the WEAP schematic. Another important step is to run the model with available trial data to determine errors and determine the final required data to run the model, to be collected during fieldwork in Egypt.

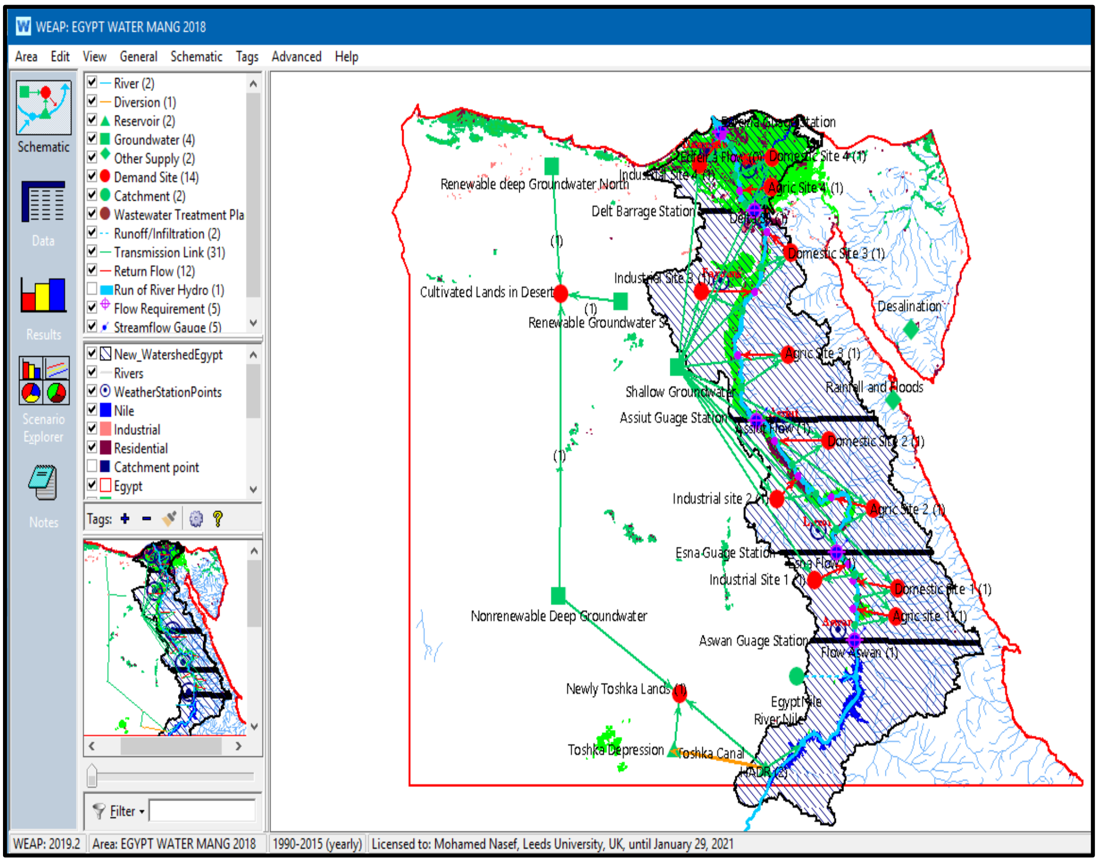


Figure 4.5 WEAP conceptual model of water demand and supply in Egypt.

4.3.6 Data Collection

The data used to run the model in this study falls into five categories (Table 4.1) and is further detailed below.

Table 4.1 The required data for WEAP model

Data	Description	Source
Remote sensing	Digital elevation model 30m for catchment delineation Land cover Soil data	NASA's Shuttle Radar Topography Mission European Space Agency's climate change initiative land cover database European Soil Data Centre
Hydrological and water supply	Inflow and outflow data (1965 – 2015), Reservoir operation rules, observed volume (1990 – 2015), Discharge gauge stations data (1990 – 2015), Groundwater data for shallow and deep aquifers (1990 – 2015).	Ministry of Water in Egypt
Climate (1990 – 2015)	Temperature and precipitation	Egyptian Meteorological Authority
Water demand (1990 – 2015)	Demand data in agriculture, domestic, industry, navigation, environmental usage, and evaporation.	Ministry of Water in Egypt
Socio-economic	Population Census (1950 – 2018) Agriculture area (old lands and new lands) (1960 – 2015) Industrial units in industry sector (1990 – 2015)	Central Agency for Public Mobilization and Statistics, Egypt (CAPMAS) Ministry of Agriculture and Land Reclamation, Egypt. Ministry of Trade and industry, Egypt.

4.3.6.1 Remote Sensing Data

Topographic Data

A digital elevation model (DEM) is digital data representing surface topography. Here I use the SRTM elevation data with resolution of 30m. The DEM is fundamental to delineate the catchment area and calculate the topographic parameters needed in catchment delineation including slope, stream length, and catchment boundary. Figure 4.6 shows the study area elevation, indicates the lowest point is -136m in the northern coast close to Alexandria and the highest point is about 2000m in the Sinai Peninsula.

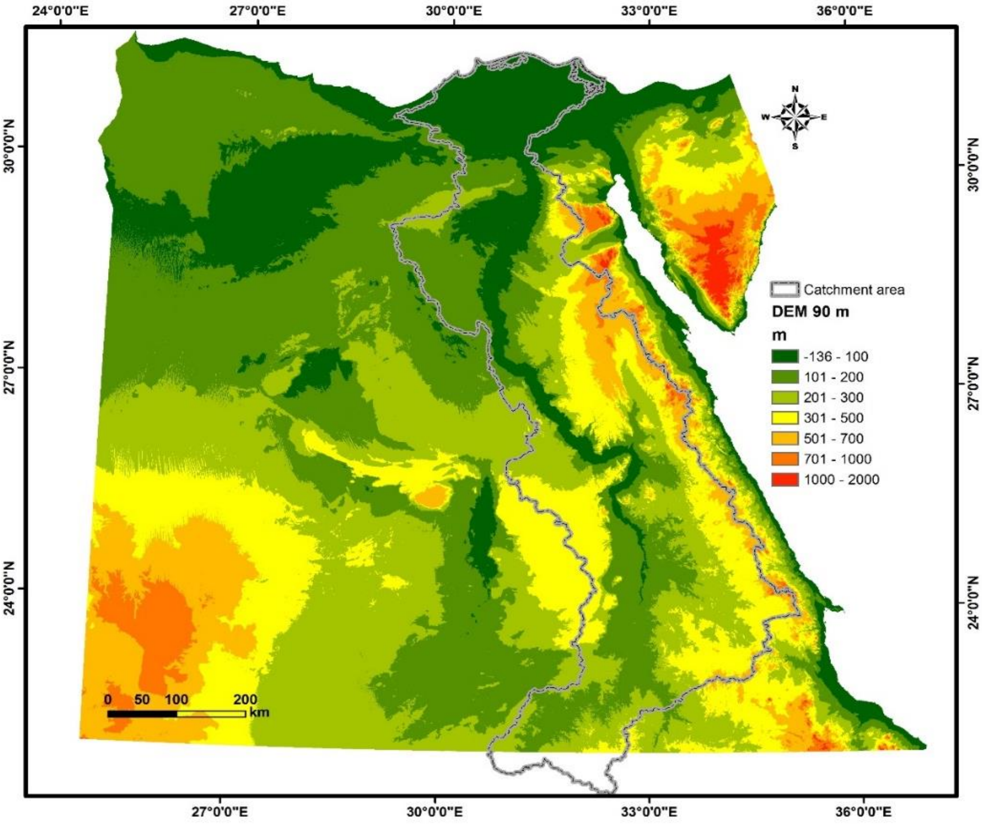


Figure 4.6 The digital elevation model for the study area (SRTM 30m).

Land Cover Data

WEAP depends on land cover to subdivide the catchment and calculate the area of every category as evapotranspiration, infiltration, and runoff vary with land cover. WEAP uses a built-in land cover database from the European Space Agency's Climate Change initiative (ESACCI) that includes 22 different classes, which can be modified, reclassified or renamed according to the study area, and modeller needs. The study area has six categories of land cover. The agricultural area is about 14.22% of the total catchment; the bare area, water bodies, spare vegetation, urban area, and brackish water cover 80.74%, 2.70%, 1.28%, 0.86%, and 0.18% respectively. Table 4.2 gives land cover statistics whilst Figure 4.7 maps land cover for the study area.

The agricultural land base consists of old lands in the Nile Valley and Delta, new lands reclaimed from the desert since 1952, rainfed areas, and several oases, where groundwater is used for irrigation. The total irrigated area amounts to about 9.096 million feddans in 2015 and the rainfed areas cover about 250,000 feddans in 2015. Rainfed agriculture exists in the Egyptian North coast, where North Sinai and Marsa Matrouh are located (Ouda and Zohry, 2016).

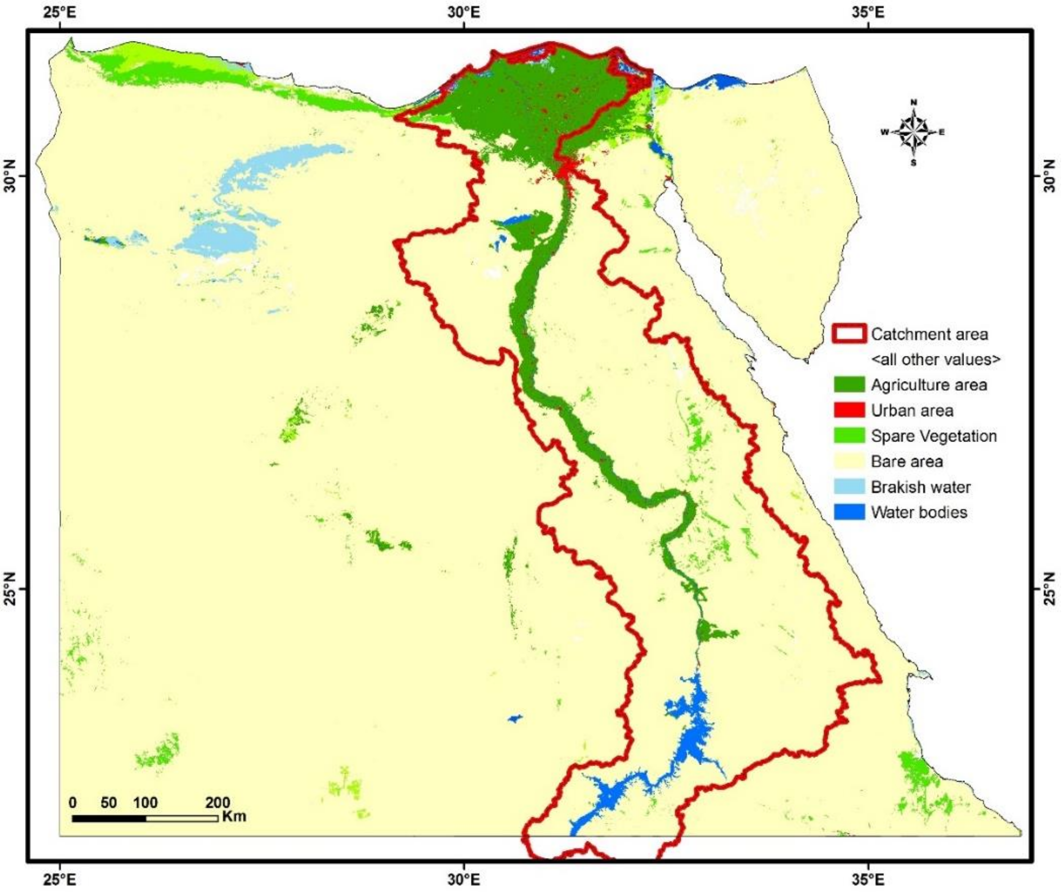


Figure 4.7 Land cover in the study area (ESACCI).

Table 4.2 Land cover statistics for the study catchment.

Category	Category name	Area Km^2	Total catchment area (%)
1	Agriculture area	34,501	14.22
2	Spare vegetation	3,106	1.28
3	Urban area	2,098	0.86
4	Water bodies	6,563	2.70
5	Bare area	195,817	80.74
6	Brackish water	441	0.18
	Total	242,526	100

Soil Data

Infiltration in the watershed depends on soil type, soil saturation, land cover, land slope, evaporation, evapotranspiration, and water usage. Soil types affect infiltration rates and influence water lost to evapotranspiration and runoff (Weeks and Stangland, 1971). The irrigated area around the Nile in Egypt is alluvial soil from clay texture along the Nile and in the Delta and is called the old land. According to the European Soil Data Centre (ESDAC) soil map, the catchment area has eight classes of major soil groups. The Leptosols (Lp) are in the dissected limestone plateau with lithosols and represent 47.15% of the catchment area. The Arenosols (AR) are loamy sand texture with depth of at least 100 cm from the soil surface and occupy 16% of the catchment area. The Fluvisols (FL) are alluvial soil from heavy clay, are waterlogged soil and make up 15.5% of the catchment total and are the most used in agriculture in Egypt. The Lithic calciorthids (CL) comprise 11.7% from the shallow and stoney loamy sand beside the sand dunes. The Regosols (RG) consists of very weakly mineral soil and form 5.3% of the catchment body. A slight percentage 1.5% from the salt affected soil in the lower Nile delta areas within 50 cm from the soil surface. In addition, 0.58% to Calcaric cambiso (CM) type is represented in fine-textured derived from rocks. Furthermore, 0.22% from the gypsic texture belongs to the category of Gypsisols (GY). Soil classes for Egypt and the catchment area are shown in Figure 4.8.

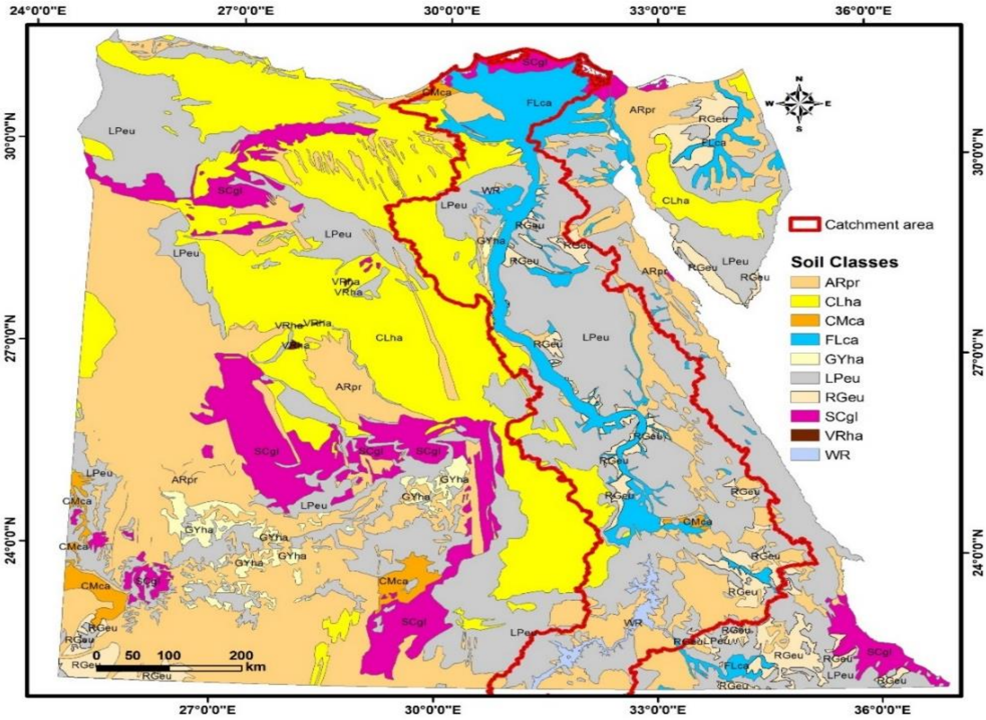


Figure 4.8 Soils distribution in the study area (ESDAC).

4.3.6.2 Climate Data

Climate parameters have an essential role in the hydrological cycle and modelling, where rainfall and temperature influence soil water content and groundwater recharge. An increase in temperature and evapotranspiration decreases soil water content, which leads to an increase in need for water through rainfall or irrigation (BIO Intelligence Service, 2014). Egypt is in an arid and semi-arid climate region where rainfall occurs only in winter and ranges from less than 25 mm in Upper Egypt to 200 mm along the Mediterranean coast (NWRP, 2005). WEAP includes automatic climate data from the Terrestrial hydrology group at Princeton University and can overlay gridded time-series climate data with elevation bands to specify the climate for each elevation band. In spite of WEAP's capabilities, using observed data is preferred to get results that are more accurate, thus, seven gauge stations have been used for the period 1990 to 2015, at Damnhour, Tanta, Cairo, Fayoum, Assiut, Luxor, and Aswan, and are distributed from the south to the north along the Nile (See Figure 4.9 and Table 4.3). Figure 4.10 details the relevant data, on annual rainfall, temperature, wind, and humidity over the period 1990 - 2015.

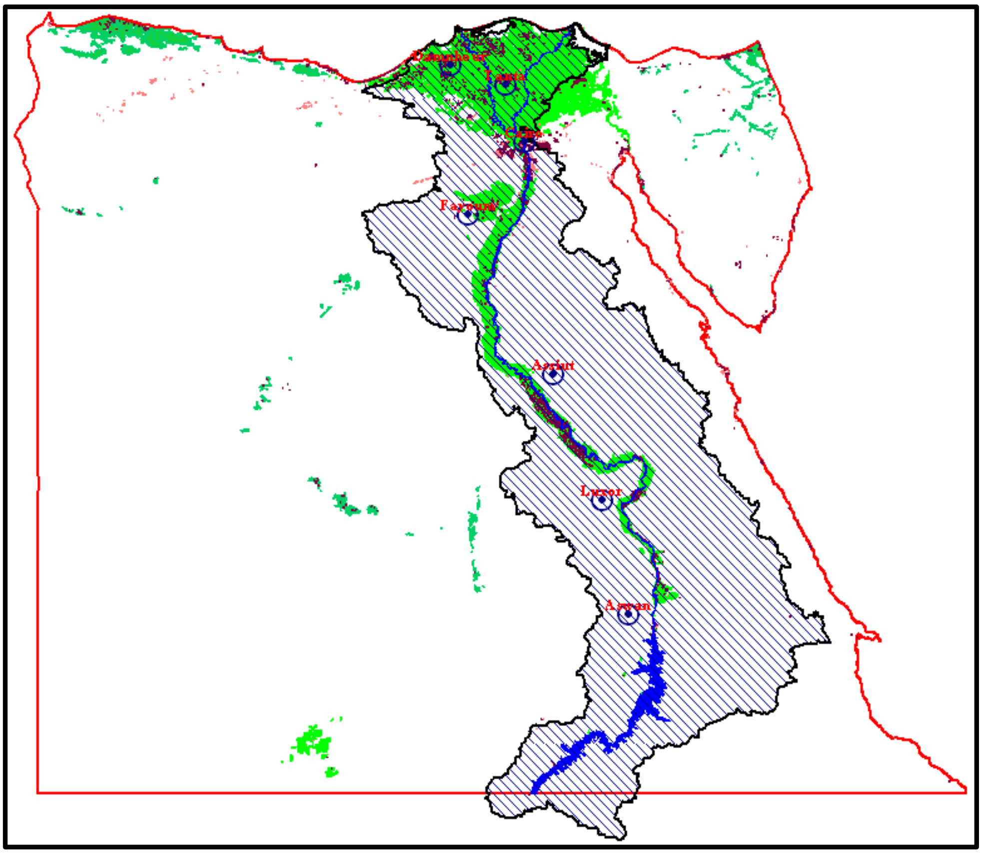


Figure 4.9 Climatic data gauge stations in the catchment area

Table 4.3 Climate stations in WEAP application

Station	**Lat.**	**Long.**	**Period**
Aswan	23° 58' 0.12''	32° 46' 59.16''	1990 - 2015
Luxor	25° 39' 14.13''	32° 13' 45.3''	1990 - 2015
Assiut	27° 12' 30.4''	31° 36' 33.2''	1990 - 2015
Fayoum	29° 12' 11.7''	30° 30' 46.7''	1990 - 2015
Cairo	30° 4' 53.6''	31° 14' 21.9''	1990 - 2015
Tanta	30° 47' 3.4''	30° 59' 29.7''	1990 - 2015
Damnhour	31° 1' 12.19''	30° 16' 47.2''	1990 - 2015

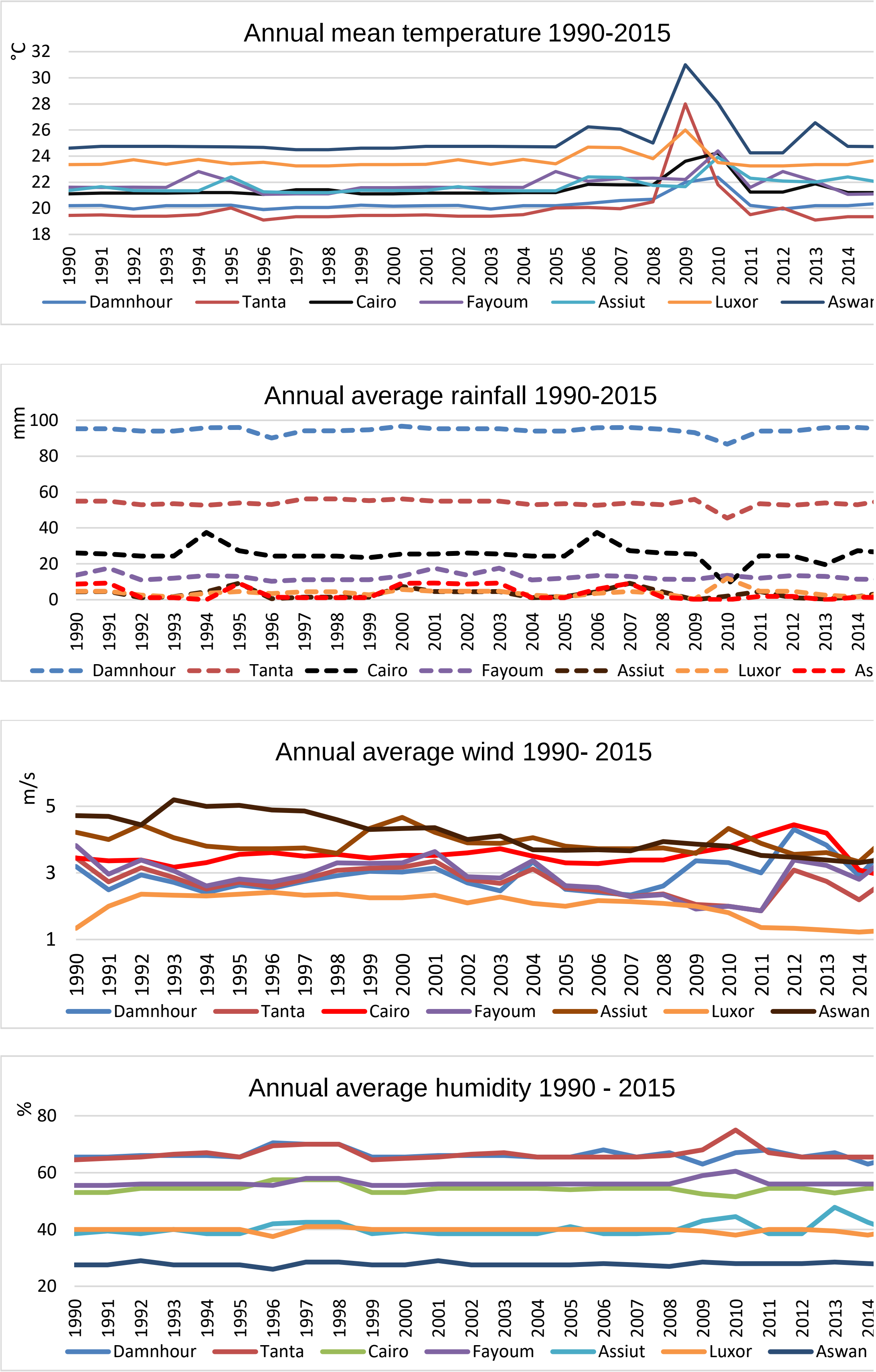


Figure 4.10 WEAP model climatic data for Egyptian gauge stations, 1990 - 2015. The annual time series of temperature and rainfall seem too flat due to the scale used for Y-axes.

4.3.6.3 Hydrological and Water Supply Data

The Egyptian water supply system is extremely complex, with most water coming from beyond the southern borders. A rare amount of winter rainfall occurs, estimated at around 20 - 200 mm. Desert, Nile and Delta's groundwater is an additional resource. Egypt depends on the Nile inflow by storage in the High Aswan Dam Reservoir (HADR) at the border with Sudan. The yearly inflow is shared with Sudan, with 55.5 BCM for Egypt and 18.5 BCM for Sudan (NWRP, 2005). Egypt then withdraws its water from the HADR to meet the demand at sites lower down the river.

Observed Inflow Data

Egypt depends on the Dongola gauge station in Sudan to monitor the inflow to the HADR. Dongola station was stablished in May 1962 at Dongola town, about 782 km from Aswan Dam and 430 km from Halfa (Abdel-Latif and Yacoub, 2011) (see Figure 2.2 in Chapter 2). The annual observed inflow data for the period (1965-2015) was collected as a PDF from the annual bulletin of irrigation and water resources statistics and converted to Excel for time series analysis. The period 1990-2015 is employed in WEAP for hydrological modelling due to the availability and suitability of demand data. The inflow average is estimated at 73 BCM over the period 1965-2015, while the inflow average in the agreement between Egypt and Sudan was 84 BCM over the period 1900-1959. Figure 4.11 presents the fluctuation in the inflow data and this may be attributed to climate variability in the Nile basin, where the quantities of flow depend on the variation in the rainfall in the Nile Basin every year. The changes of Nile flow and rainfall over the basin may be due to the number of El Nino and La Nina events (Siam and Eltahir, 2017).

According to the MWRI, Egypt faced a drought from 1980-1987 with a decrease of inflow below the average, between 69 – 42 BCM. During this period, the volume of HADR decreased from 133 BCM in 1979 to 37 BCM in 1988, while the dead storage is 31.6 BCM. Therefore, the uncertain future conditions due to climate change and variability in the Nile basin has an extreme impact on the water supply to Egypt.

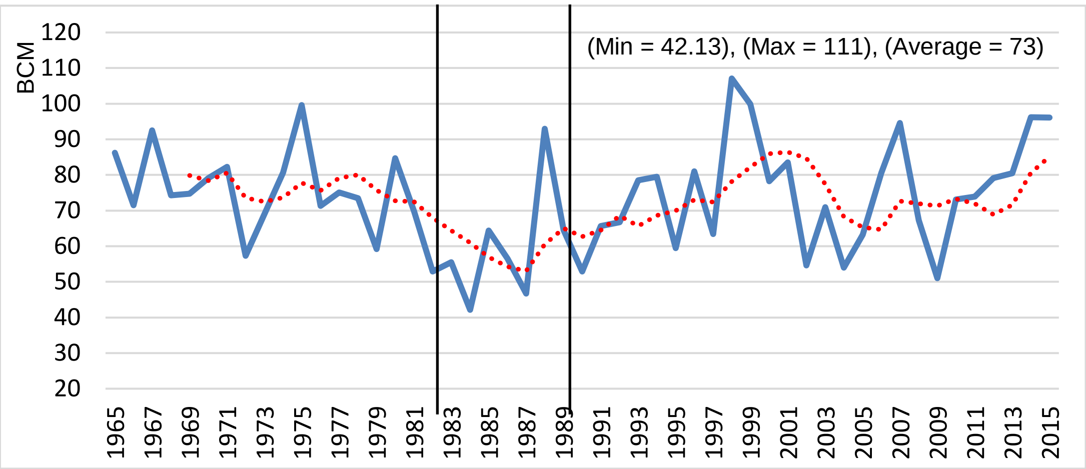


Figure 4.11 Annual observed inflow time series at Dongola gauge station. The red line show the moving 5-year average, and black lines the drought period.

Observed Outflow Data

The outflow from the HADR is released through the High dam to meet demand. The amount of outflow is not always 55.5 BCM/year, as the released amount depends on the needs of the demand sites, the high floods, and the water volume in HADR. Hence, the water system is becoming more complex. The annual observed outflow data over the period 1968-2015 was collected as a PDF from the annual bulletin of irrigation and water resources statistics and convert to Excel for time series analysis. The period of 1990-2015 is distinguished for running the WEAP model for the hydrological modelling due to the availability and suitability of demand data. According to the time series analysis, the outflow ranges between 52.15 - 67.25 BCM and the average is 57.73 BCM as represented in Figure 4.12. The significant variation in the outflow data after 1998 may belong to the surplus in the reservoir volume, where the significant inflow in the years of 1998, 1999, 2000, and 2001, where raised to 105, 99.8, 78.2, and 83.56 BCM, sequentially.

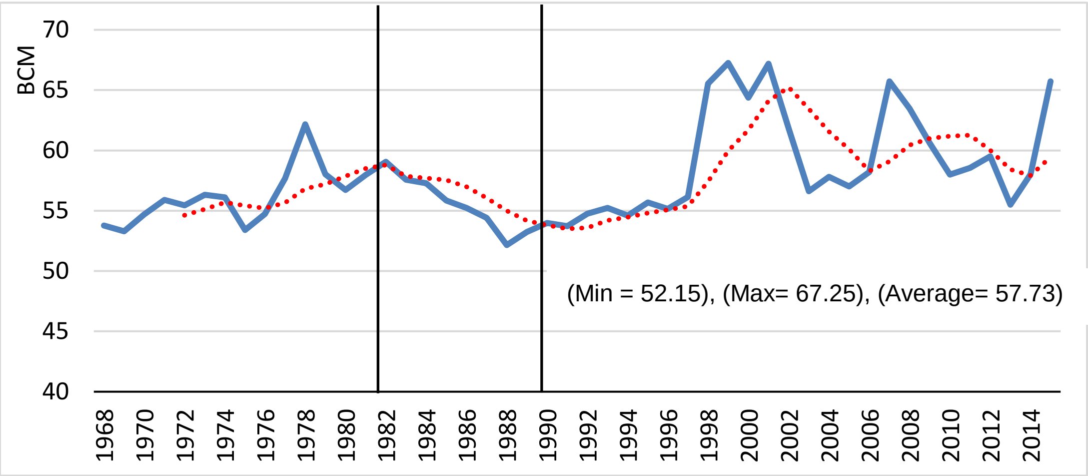


Figure 4.12 Annual observed outflow time series. The red line show the moving 5-year average, and black lines the drought period.

Discharge Gauge Stations Data

The hydrological models depend on the discharge records as an indicator to simulate catchment processes accurately. The study depends on four-discharge gauge stations records (1990-2015) for simulating, calibrating, validating the model and the uncertainty analysis. The observed data for these stations will be used to compare with the simulated data in the calibration process. The four-discharge gauge stations are Aswan, Esna, Assiut, and Delta as shown in Figure 4.13 and Table 4.4. These four stations are barrages to discharge and control the water distribution after the high dam.

Table 4.4 Discharge stations and observed period used for WEAP calibration and validation.

No.	Discharge station name	Latitude	Longitude	Period
1	Aswan	24° 4' 8.2"	32° 55' 24.9"	1990 - 2015
2	Esna	25° 21' 3.79"	32° 32' 45.2"	1990 - 2015
3	Assiut	27° 12' 16.77"	31° 10' 27.38"	1990 - 2015
5	Delta	30° 11' 35.3"	31° 7' 43.4"	1990 - 2015

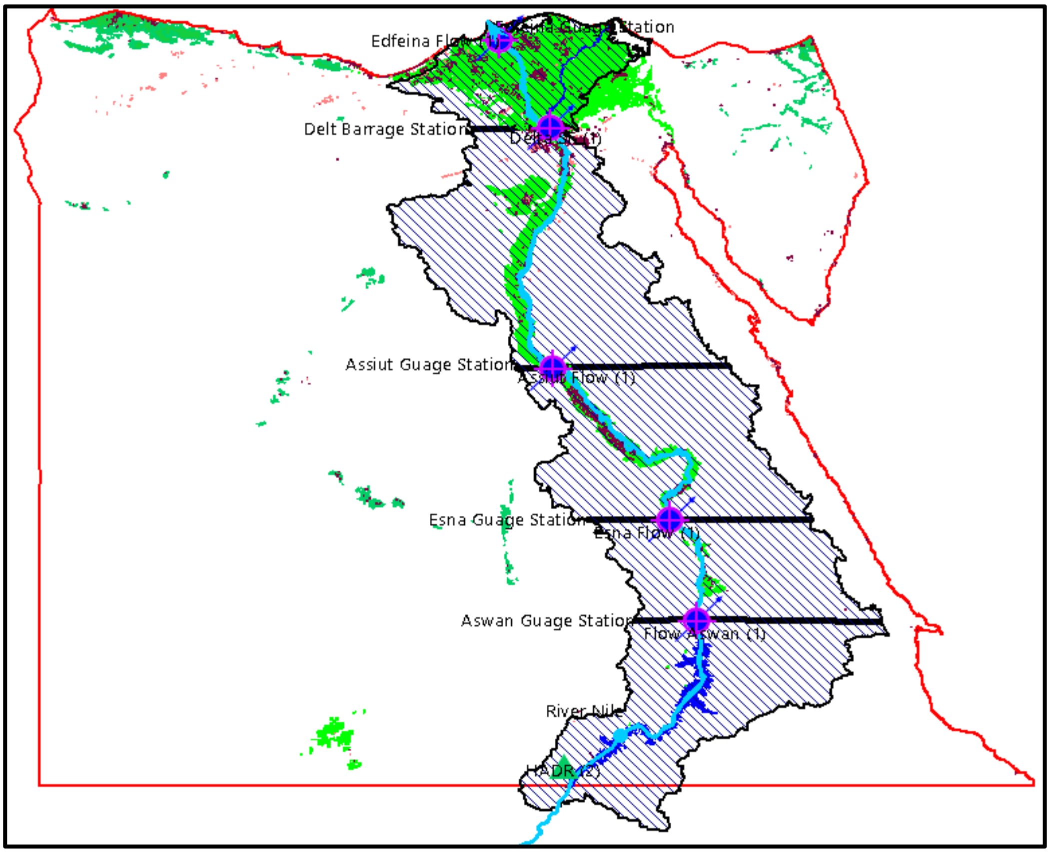


Figure 4.13 Locations of discharge stations on the Nile River in Egypt.

HADR Operation Rules

The High Aswan Dam Reservoir is the most influential component in the Egyptian water system. It receives inflow and regulates the outflow downstream through the High dam to meet the water needs of Egypt. In the WEAP model, the operation rules of reservoir must be represented. It is worth noting that without the knowledge of Aswan dam's operational rules, it is not possible to model and simulate downstream processes. The challenges of operating rules lead to more complexity due to the lack of understanding of reservoir rules and representing them in the model. The rules may be characterised as model constraints and can be summarized as:

- The HADR has max length about 500 km, max width 12 km, maximum depth 110 m, and the full capacity is 162 BCM (Muala et al., 2014),
- The storage capacity (162 BCM) is divided into 31.6 BCM dead storage between levels of 85-147 m, 90.7 BCM for live storage, and 39.7 BCM as flood control storage (Ahmed and Ismail, 2008),

- The HADR is in the midst of the desert with a large surface area, which causes high amounts of water evaporation, about 10 BCM/year (MWRI, 2005; Strzepek et al., 2008),
- Water above level 178 m must discharge to Toshka spillway to Toshka depression in the south of western desert to save the dam body. In addition, the maximum reservoir level on the 1st of August should not exceed 175 m above mean sea level. Any water that has to be released from the HAD to avoid higher water levels is not considered as part of Egypt's share of the Nile water (MWRI, 2005),
- Maximum release from the High Dam is 280 million m^3/day, while the minimum release is 60 million m^3/day for hydropower, navigation, and water quality (Soliman, 2010)
- According to the Agreement 1959, the released volume should not exceed 55.5 BCM, the share for Egypt.
- All these data are required to run the WEAP model beside the volume elevation curve as shown in Figure 4.14.
- The observed volume of HADR for the period 1990 – 2015 has been used for calibration and the reliability of the WEAP model. The model calculates the simulated volume in the reservoir depending on the equation: *Change in storage = (Inflow – Releases – Evaporation losses)* (Equation 4.6)

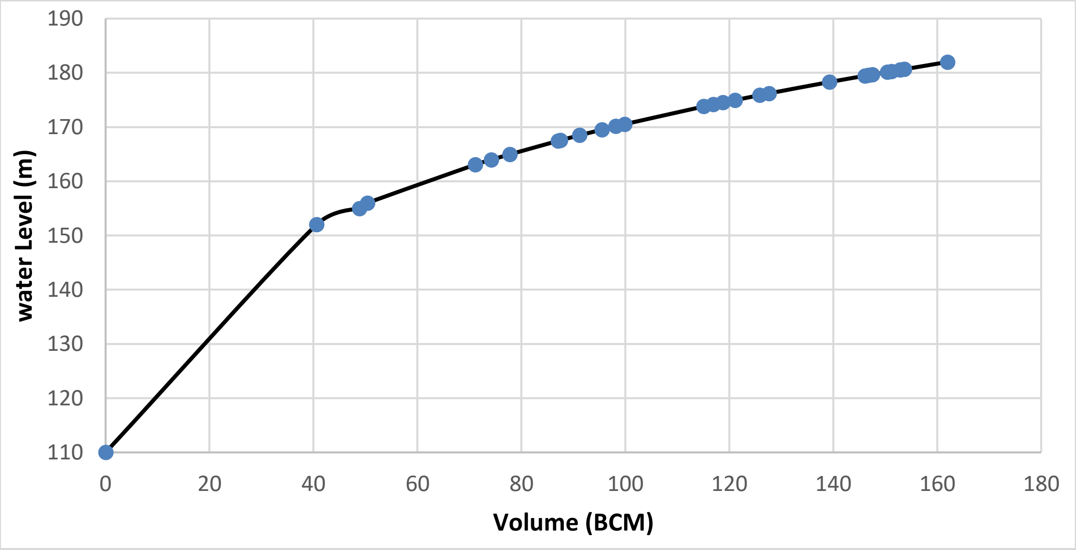


Figure 4.14 Volume elevation curve of HADR (MWRI, 2012).

Groundwater Data

Groundwater is the second resource of water in Egypt after the Nile River. There are three important groundwater aquifers; the shallow aquifer under Nile valley and delta, and deep aquifer in the Western desert and Sinai (Abdel-Shafy and Kamel, 2016). Egypt does not account for the shallow aquifer as a separated source because infiltration water from the Nile recharges it (NWRP, 2005). This study assumed the shallow aquifer as a source of water in Egypt as; it is renewable, recharged by the rainfall beside the Nile water, it has a huge storage capacity estimated at 500 BCM, and it is used by all sectors to meet demand. The deep groundwater aquifer in the desert is not renewable and total storage in the Western desert is estimated at 40,000 BCM (Zeid, 1992; MWRI, 2012; Abdel-Shafy, and Kamel, 2016; Attia, 2018). The groundwater abstractions data is collected from 1990-2015 to use in the WEAP model. According the data in Figure 4.15 and 4.16, groundwater abstractions in Delta and New Valley areas are about 6.9 BCM/yr in 2015, with 2.2 BCM/yr from the deep aquifer. Groundwater abstractions in Sinai and northern coast area are about 0.045, and 0.02 BCM/yr, respectively (MWRI, 2012).

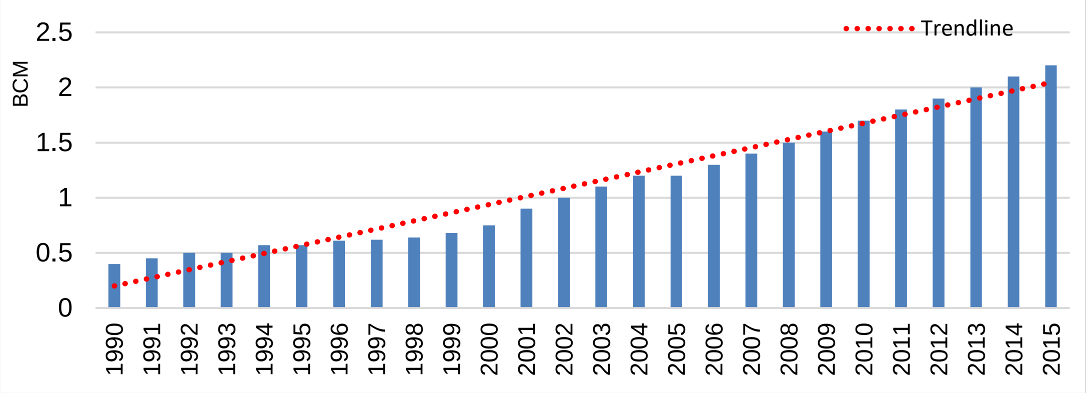


Figure 4.15 Non-renewable groundwater exploitation from deep aquifers.

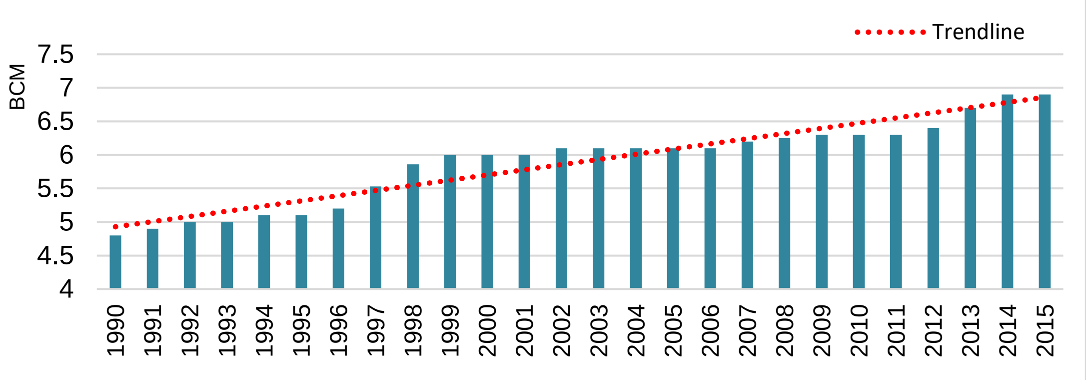


Figure 4.16 Underground water exploitation from in Shallow aquifer under Nile valley and Delta.

4.3.6.4 Water Demand Data

The demand data includes water consumption for agriculture, domestic, industry, and environment. This data is collected from the Ministry of Water for the period 1990-2015 as annual data. Unfortunately, monthly demand data is unavailable and annual data is available only for the years after 1990. This is because Egypt issues demand data for cities and villages on a monthly time step and for the whole country on an annual time step. This created restrictions on selecting the feasible model, where the model will be running at the annual time-step only. Figure 4.17 demonstrates the collected water demand data for different sectors in Egypt.

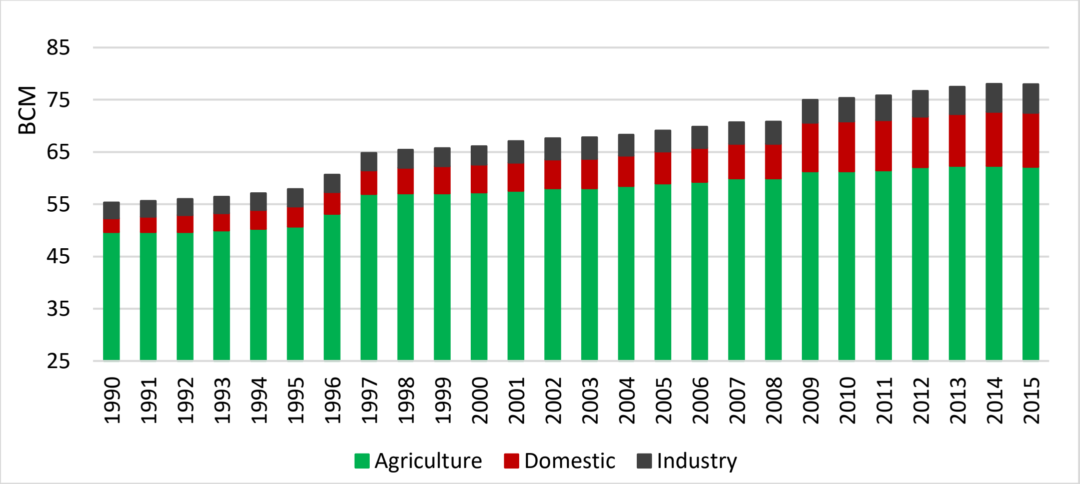


Figure 4.17 Water demand in different sectors in Egypt over the period 1990-2015.

4.3.6.5 Socio-economic Data

The WEAP model uses socio-economic data for calculating annual water consumption rate by dividing water demand by the total activity level of every demand site. The total activity level could be agricultural area, population number, or industrial units’ number. The socio-economic data (agricultural area, population number, or industrial units’ number) for the period 1990-2015 was collected from different sources and used to run the WEAP model. Figure 4.18 presents the collected socio-economic data.

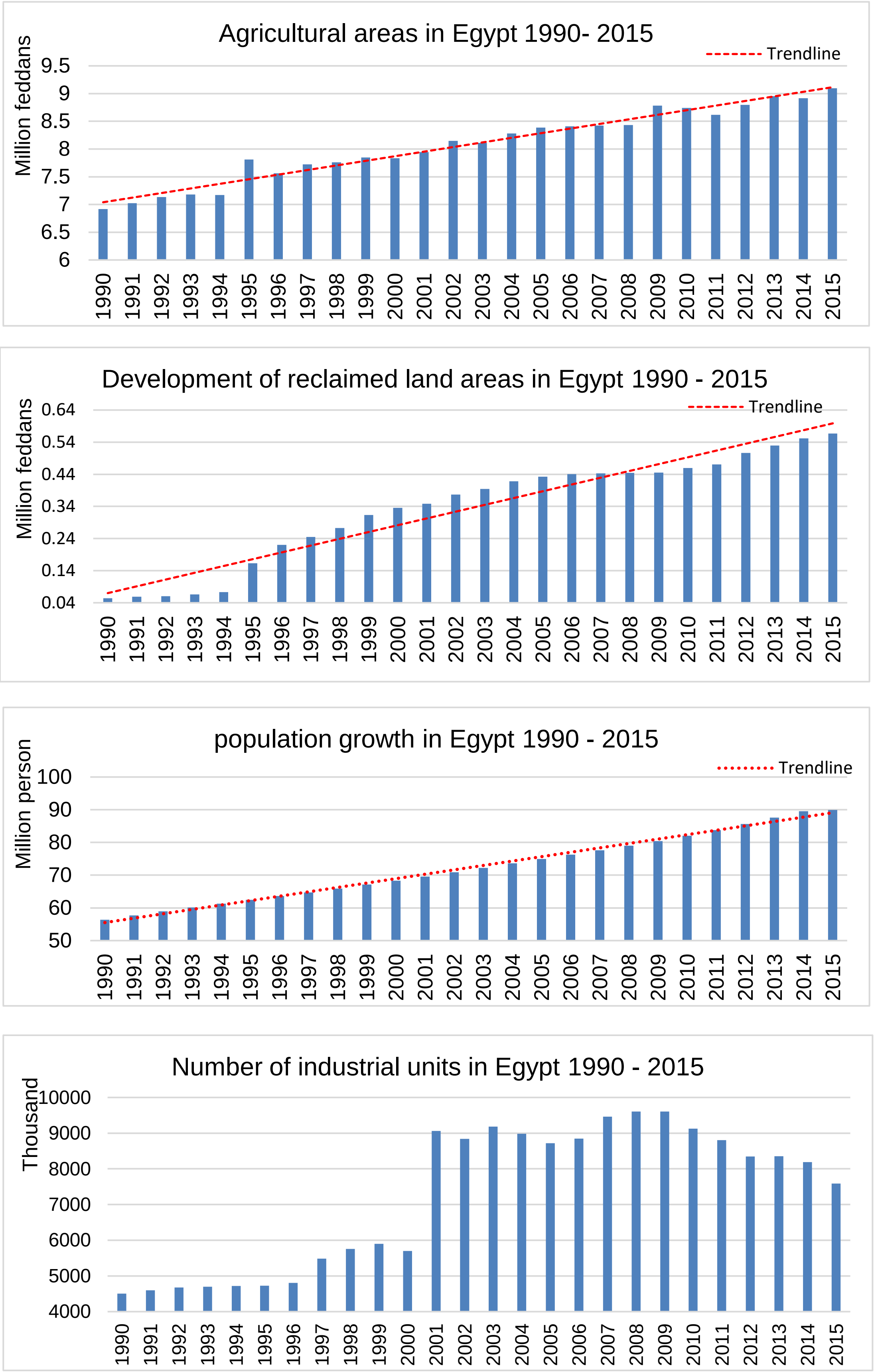


Figure 4.18 Socio-economic data for the period 1990-2015.

4.3.7 Methodology of Dealing with Uncertainty and Complexity.

After setting up the WEAP model, preparing the schematic for Egypt, and delineating the catchment area, the collected data is input to run the model initially. To deal with uncertainty in model structure, model parameters, and input water demand and supply data, the prediction approach was conducted using the GLUE method to predict uncertainty in the output. According to Shrestha (2009), model complexity is measured by its number of parameters and requirements of input data, where the input data and parameters numbers increase model complexity. In addition, if these complex models with several parameters and required input data are not appropriately parameterized or poor quality input data, the uncertainty associated with parameter estimation or input data is highly likely to increase. Therefore, the study deals with complexity in the parameters estimation using the PEST tool for estimating the initial parameters ranges before the uncertainty analysis.

4.3.7.1 Prediction Approach

As noted in the literature review, hydrological models driven by mathematical equations and assumptions are imprecise representations of hydrological processes in the real world. The imprecise representation of real hydrological processes leads to uncertainty in model outputs due error in measurement, model structure, and model parameter uncertainty (Benke et al., 2008; Shen et al., 2012; Pianosi, and Wagener, 2016). The prediction approach depends on analysis of uncertainties that are linked to input data, parameters, and model structure, by predicting and quantifying the uncertainty in the output model. Many algorithms are developed to can deal with the uncertainties in water demand and supply such as GLUE, SUFI2, PSO, ParaSol, and MCMC. The best performance is different for every method based on the computational time for optimization, implementation difficulties and ability to include all uncertainty sources.

4.3.7.2 Model Parameters’ Estimation and Complexity

All of the hydrological model parameters must be optimized. Technically, adjustment of parameter values indicates a high degree of uncertainty (Shen et al., 2011). Estimating parameters is complex in uncertainty analysis, as the increase in parameters’ number and range increases computational time for the optimization process. In addition, propagation of the uncertainties in the parameters leads to uncertainties in the model output variables (Abbaspour et al., 2011). For the parameters' number, selecting the model with as few parameters as possible can decrease complexity, and WEAP model meets this purpose.

Unfortunately, no suitable studies exist of Egypt to estimate parameter ranges. Therefore, the study uses the parameter estimation tool (PEST) embedded in WEAP. PEST implements the Gauss-Marquardt-Levenberg parameter estimation algorithm for nonlinear least squares curve-fitting problems by minimizing the sum of the squares of the errors between the data points (Wilson and Mantooth, 2013; Doherty et al., 2014). PEST allows the user to automate the process of comparing WEAP outputs to historical observations and modifying model parameters values to improve accuracy (Sieber and Purkey, 2016). The study depends on the increase/decrease of the Nash-Sutcliffe efficiency (NSE) (Equation given below) to evaluate the performance of each simulation by PEST in comparison to the observed values depending on the change in parameters values. The parameters estimating ranges obtained based on NSE greater than 0.5. This procedure is a manual sensitivity analysis, which could be defined as a trial and error analysis to adjust each parameter range and may help in reducing complexity and computational time. Eight parameters are linked to the soil moisture method in WEAP, and sensitive to streamflow, are used to investigate the initial ranges before applying the sensitivity analysis (SA) as shown in Table 4.5.

Table 4.5 Calibration parameter ranges used in the WEAP model.

Parameters	Discerption	Model Range	Default
SWC	Soil Water Capacity (Effective water holding capacity of upper soil layer)	0 and higher (mm)	1000
DWC	Deep Water Capacity (Effective water holding capacity of lower, deep soil layer)	0 and higher (mm)	1000
RZC	Root Zone Conductivity (mm)	0 and higher	20
DC	Deep Conductivity (mm) (Conductivity rate of the deep layer)	0.1 and higher	20
RRF	Runoff Resistance Factor	0 - 1000	2
PFD	Preferred Flow Direction	0 - 1	0.15
Z1	Relative storage in root zone soil water capacity (%)	0 – 100%	30%
Z2	Relative storage in lower soil bucket (%)	0 – 100%	30%

4.3.7.3 Global Sensitivity and Uncertainty Analysis

The basic methodology of the sensitivity analysis is to alter parameter values of the model and investigate changes in model output (Tomassini et al., 2007; Chu-Agor et al., 2011). Sensitivity analysis is essential as first; parameters represent processes that provide information on the most important process in the study. Second, sensitivity analysis helps decrease the number of parameters in the calibration procedure by eliminating non-sensitive parameters and determines the optimal value for parameter. In order to carry out the SA, calibration and uncertainty analysis of WEAP, python code was developed to automate the WEAP model and call it into R software for the sensitivity analysis and GLUE method application (see Appendix 2).

In this study, a parameter sensitivity analysis is applied prior to calibrating the model. The global sensitivity analysis method of Morris is implemented using the sensitivity package V1.18 in R software. The basic concept of this method is estimation of the change in output corresponding to a slight change in one factor (Morris, 1991; Zhang et al., 2019). The t-test is used to identify the relative significance of every parameter, where the larger the value of t-state, and the smaller the p-value, the more sensitive the parameter. Hence, the eight highest ranked parameters affecting streamflow will be selected for the subsequent GLUE uncertainty analysis.

In this chapter, uncertainty analysis refers to the propagation of all model input uncertainties to model output. Input uncertainties can result from physical input data such as land use, soil, climate or model parameters, and model structure. The interest in uncertainty analysis of hydrologic modelling generated many methods to deal with sources of uncertainty. Selecting the appropriate method is based on the level of model complexity, efficiency of the method to cover all faces of uncertainty, and choice of the modeller. The generalized likelihood uncertainty estimation (GLUE) is applied with WEAP using the GLUE package in R to quantify parameter uncertainty.

GLUE depicts parameter uncertainty and accounts for all sources of uncertainties including driving variables, model structure, parameters, and measured data (Beven and Binley, 1992; Yang et al., 2008; Vázquez et al., 2009; Abbaspour et al., 2011; Shen et al., 2012). It is important to note that the GLUE methodology determines the performance of the model focus on the parameter set, not on the individual parameters (Beven and Binley, 1992). GLUE uses Monte Carlo simulation to generate distributions of parameters that are conditioned on available data and associated uncertainty limits. The distributions of parameters are generated based on parameter sets that can produce appropriate model outputs compared to observed data (Jin et al., 2010; Jung et al., 2014). In this study, implementation of GLUE consists of the following steps:

- Generating random Samples of the parameter space. A large number of parameter sets is generated for Monte Carlo simulation.
- Specifying the likelihood function and the threshold value for behavioural parameter sets. Depending on the literature, the probability measure most commonly used for GLUE is the Nash-Sutcliffe coefficient NSE (Beven and Freer, 2001). The NSE is used as the likelihood function to evaluate performance of each simulation at each discharge station, by:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{obs,mean}\right)^2} \quad \text{(Equation 4.7)}$$

Where n is the number of the observed data points, Y^{obs} and Y^{sim} represent the observation and model simulation with parameter *i*, and $Y^{obs,\ mean}$ is the average of observation.

- The threshold value is set to be 0.50 as a reasonable value for WEAP simulation, where the simulation with NS value of more than 0.50 are considered to be behavioural, otherwise they are considered non-behavioural.
- Computing the likelihood values for the parameter sets and selecting the behavioural ones. The likelihood function quantifies the difference between the simulation and observation.
- Calculating the posterior likelihood distribution for behaviour parameter sets.
- Determining the uncertainty quantiles, where GLUE tries to capture most of the measured data within the 95% band of prediction uncertainty. The band of uncertainty is calculated at 2.5% and 97.5% of the cumulative distribution of output variable.
- Two measures are calculated using the “hydroGOF” package version 0.4 in R to assess the calibration and uncertainty performance, the P-factor and the R-factor.

The P-factor is the percentage of observations within the given uncertainty bounds, and the R-factor represents the average width of the given uncertainty bounds divided by the standard deviation of the observations

(Schuol et al., 2008; Abbaspour et al., 2009). The degree to which all uncertainties are accounted for is quantified by P-factor and R-factor, where *P-factor* equal to 1, and *R-factor* equal to zero indicate that all the simulated values matches with the observations perfectly. To assess the uncertainty, a value of P-factor > 0.5 and R-factor < 1 should be acceptable for this study, particularly considering the availability of data, system complexity, and the project scale. The used equations of P-factor and R-factor in this study are:

$$P\text{-}factor = NQ^{ob} / NQ^{ALL} * 100\% \qquad \text{(Equation 4.8)}$$

Where NQ^{ob} is the number of observations bracketed by the uncertainty bands, and NQ^{ALL} is the total number of observations.

$$R\text{-}factor = (Q^{UB} - Q^{LB}) / SD^{obs} \qquad \text{(Equation 4.9)}$$

Where Q^{UB} is the upper bound value, Q^{LB} is the lower bound value, and SD^{obs} is the standard deviation of the observed variable.

Finally, The Nash Sutcliffe Efficiency (NSE), percent bias (PBIAS) and root mean square error (RMSE) have been established to evaluate WEAP model performance and quality of calibration and validation for four stations discharge data. In this study, the calibration period is (1990-2006), and the validation period is (2007-2015). The developed classification of goodness of hydrological model by Moriasi et al. (2007) is used to judge model performance. NSE indicates the averaged measure of error and PBIAS measures the average tendency of the simulated values to be larger or smaller than their observed ones.

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{i=1}^{n} Y_i^{obs}} \qquad \text{(Equation 4.10)}$$

Where NSE >0.6 and PBIAS < ±10 indicate that the goodness of fit is very good. The optimal value for NSE=1 and PBIAS = 0.

4.4 Results and Discussion

In this chapter, the WEAP model represented the study area with 14 demand sites, four discharge stations, two groundwater aquifers, and a reservoir to simulate the hydrologic modelling using the soil moisture method. I used this method and the model parameters to calibrate the WEAP model for the period 1990-2015. I focused in this chapter on dealing with uncertainty and complexity in the water demand and supply system. The discharge data for four stations in the river basin in Egypt were used for calibration and analysing the uncertainty using the GLUE method. The results of this study are presented next.

4.4.1 Parameters Selection and Ranges Estimation

Determining model parameters and estimating their ranges to adjust the hydrology model are the most complex tasks in uncertainty analysis, as there are a large number of possibilities. Therefore, choosing the model with fewer parameters, and reducing their ranges can reduce complexity and decrease the number of model runs. The common approach is to adjust parameters that display the highest sensitivity. Table 4.6 reveals the result of parameters estimation using the above-described method. This method evaluates the effects of each input parameter to model outputs. It is apparent from the table that the most sensitive parameters are SWC, DWC, DC, RRF, and Z2 (defined in Table 4.5). This initial sensitivity is based on the significant variation in the NSE values between modelled and observed discharge station data (1990-2015). The green highlighted cells are the estimated ranges of those parameters when the parameters produced the best models. These narrower ranges will use in the global sensitivity and uncertainty analysis.

Table 4.6 Parameters estimation using PEST and Nash-Sutcliffe Efficiency (NSE).

Parameters		Value	NSE	Value	NSE	Value	NSE	Value	NSE	Value	NSE	Value	NSE
SWC	Barren	0	0.648	1	0.650	5	0.624	10	0.624	50	0.624	100	0.623
	Agric	0	0.648	1	0.650	5	0.618	10	0.618	50	0.618	100	0.618
	Spare	0	0.648	1	0.649	5	0.625	10	0.625	50	0.624	100	0.623
DWC		0	0.648	500	0.648	2000	0.651	5000	0.653	10000	0.654	20000	0.654
RZC		0	0.654	10	0.654	20	0.654	30	0.654	50	0.654	100	0.654
DC		0	0.648	10	0.653	20	0.654	30	0.654	50	0.648	100	0.605
RRF	Barren	0	-0.467	1	0.440	5	0.444	10	0.444	20	0.444	50	0.444
	Agric	0	-0.467	1	0.440	5	0.444	10	0.444	20	0.444	50	0.444
	Spare	0	-0.467	1	0.440	5	0.444	10	0.444	20	0.444	50	0.444
PFD		0	0.654	0.15	0.654	0.2	0.654	0.3	0.654	0.5	0.654	1	0.654
Z1		0	0.654	10	0.654	20	0.654	40	0.654	50	0.654	100	0.654
Z2		0	0.648	10	0.648	20	0.649	30	0.649	50	0.651	100	0.654

4.4.2 Sensitivity of the Model Parameters.

The global sensitivity analysis proposed by Morris (1991) was used to analyse parameters sensitivity to determine which parameters will be used for calibration and uncertainty analysis. The parameters ranges used for sensitivity analysis have been set based on the previous step using PEST and NSE. The t-test was used to identify the relative significance of every parameter, where the larger value of t-state, and the smaller p-value, the more sensitive the parameter. The input parameters as highlighted in Table 4.6 included SWC, Z2, DC, DWC, Z1, RRF, PFD, and RZC. The result of assessment of sensitivity analysis in the Table 4.7 shows that the soil water capacity (SWC) was evaluated to be the most sensitive parameters and the dominant factor in the hydrological model for the Nile river basin in Egypt. The outcome was observed that the first input parameter (SWC) should be adjusted using WEAP model calibration. The parameters of relative storage in the lower soil bucket (Z2) and deep conductivity (DC) presented higher sensitivity too. The other five parameters showed relatively less sensitivity. This means that the first three parameters (SWC, Z2, and DC) play a key role in simulation of streamflow and uncertainty in the study area, while the other five parameters (DWC, Z1, RRF, PFD, and RZC) have a lesser influence on the simulation results. Hence, the eight ranked parameters affecting streamflow will be selected for the following UA using GLUE method.

Table 4.7 Sensitivity analysis ranking of the input parameters and optimal values

Parameter	Rank	t-stat	P-value	Parameter range	Best-fit value
SWC	1	4.1066	0.0004	0 - 5	0.3
Z2	2	3.6952	0.00113	0 - 100	100
DC	3	2.1568	0.04124	10 - 30	20
DWC	4	1.8768	0.0727	10000 - 20000	19000
Z1	5	1.214	0.2363	0 - 100	30
RRF	6	0.9189	0.3672	0 - 5	1
PFD	7	0.6023	0.5525	0 - 1	0.15
RZC	8	0.3826	0.7053	0 - 100	20

4.4.3 Uncertainty Analysis

The uncertainty analysis was implemented in the calibration period (1990-2015) using GLUE in R software. GLUE is simple to use, and commonly in the field of hydrology. It is popular because it depends on a combination of parameters not just a single parameter, which makes the results truly meaningful. GLUE was applied in uncertainty analysis of the eight parameters in the WEAP model for the study area. The objective function NSE was set as 0.6 and Monte Carlo was used to randomly select groups of parameters. It was iterated three times; 2500 simulations were performed for each iteration within the parameter ranges as per Table 4.7. Then, all parameters above the proposed threshold value (0.6) were selected as behavioural parameters and sorted according to their likelihood values. The confidence level was set to 95%, and the uncertainty band of streamflow simulation value was calculated at 2.5% and 97.5% levels of the cumulative distribution of output variable. The P-factor and R-factor were calculated to assess the uncertainty, while the NSE, PBIAS and RMSE were used as benchmarking indices to evaluate goodness of fit, calibration and performance of the WEAP hydrological model. Calibration was done based on a comparison of the simulated discharges to their observed counterparts over the period 1990-2006 and the validation was done over the period (2007-2015).

For prediction uncertainty analysis, I found that GLUE was a powerful tool because of its relatively larger P-factor and reasonable R-factor (Table 4.8). In general, GLUE needs a huge number of sampling runs, about 10,000 to get an acceptable outputs particularly for a hydrologically complex simulation. In this study, GLUE needed only about 7500 runs to achieve a reasonable outputs as the PEST and NSE method above for estimating parameters and narrowing the ranges was used before applying the GLUE. According to the resulting P-factor and R-factor values, the GLUE method can be used for discharge simulation and uncertainty analysis of the Nile river basin in Egypt with the WEAP hydrological model. GLUE consider the error in the measured data, model parameters, and model structure, with results showing an acceptable uncertainty. It can be seen from Figure 4.19 that 100%, 88%, 56%, and 72% of the observations of Aswan, Esna, Assiut, and Delta respectively were bracketed by the 95% band of prediction uncertainty (2.5 - 97.5%) percentiles. The R-factor was <1 and equalled 0.65, 0.63, 0.45, and 0.47 in calibration, which means GLUE was able to capture the observations in calibration. For the validation, 100%, 78%, 56%, and 56% of the observations of Aswan, Esna, Assiut, and Delta respectively were bracketed by the 95%

band of prediction uncertainty (2.5 - 97.5%) percentiles. The R-factor was <1 and equalled 0.94, 1.0, 0.95, and 0.50.

Table 4.8 Results of uncertainty analysis, calibration and validation for hydrological modelling.

Station	calibration (1990 – 2006)					Performance Rating	Validation (2007 – 2015)				
	NSE	**PBIAS**	**RMSE**	**P-factor**	**R-factor**		**NSE**	**PBIAS**	**RMSE**	**P-factor**	**R-factor**
Aswan	0.96	+ 0.97	0.61	1	0.65	Very good	0.97	+0.86	0.51	1.00	0.94
Esna	0.74	- 1.20	2.30	0.88	0.63	Very good	0.55	+2.92	2.65	0.78	1.00
Assiut	0.78	+ 1.61	2.11	0.56	0.45	Very good	0.57	+5.35	2.46	0.56	0.95
Delta	0.76	- 3.06	1.03	0.72	0.47	Very good	0.53	-1.94	0.47	0.56	0.50
Number of runs						7500					
Source of parameter uncertainty (uncertainty described by parameter uncertainty).						All sources					
Conceptual basis of parameter uncertainty						- Normalization of generalized likelihood measure - Random sampling strategy					

The spatial variation of uncertainty is different in the Nile basin in Egypt, where the P-factor for the discharge stations are estimated 1, 0.88, 0.56, and 0.72 respectively (Table 4.8). These variations may be due to the stability of the natural and human sources of uncertainty from one area to another. For example, the model recorded a high certainty for the area around Aswan gauge station, which has less population, agricultural area, industrial units, and scarce rainfall. In contrast, a low certainty for the area around Assiut gauge station is attributed to an increase in the uncertainty factors and its anomalies from one year to another. These results represented an increased model uncertainty in the high rainfall and land use conditions.

From Figure 4.19, it is clear that most of the observations of discharge were bracketed by the 95% band of prediction uncertainty. However, several discharge observations were detected above the upper 97.5 % bound and below the lower 2.5 % bound. In addition, the simulated values were not completely in the range of confidence level 95%, indicating that the WEAP hydrology model performed well but could not fully simulate the discharge processes. This means that for a parameter, model structure and input data could cause uncertainty in the model simulation.

The WEAP model is calibrated at four-discharge gauge stations in the study area (Aswan, Esna, Assuit, and Delta). During discharge calibration from 1990-2006, the model performed better at the four stations according to the classification of Moriasi et al. (2007), where the results of NSE were greater than 0.6 and the PBIAS were less than ±10 as shown in Table 4.8 and Figure 4.19. It is observed that the NSE, PBIAS, and RMSE achieved the highest performance at Aswan gauge station (NSE= 0.96, PBIAS=+0.97, and RMSE=0.61) compared to the gauge stations of Esna, Assiut, and Delta. This is likely due to the difference in uncertainty associated with the simulated discharge for the four stations, 1990-2006. The GLUE method considers model structure as a source of uncertainty during the uncertainty analysis, but model structure uncertainty can also be assessed by comparing model results and real observations (Butts et al., 2004; Uusitalo et al., 2015). The comparison between model results and real observations using the NSE and PBIAS measures indicate a very good performance of the WEAP model in terms of the uncertainty of model structure. The NSE values are 0.96, 0.74, 0.78, and 0.76 at the four stations Aswan, Esna, Assiut, and Delta respectively. For the validation Period (2007-2015), the results indicated that NSE, PBIAS, and RMSE were 0.97, +0.86 and 0.51 respectively for Aswan station, 0.55, +2.92 and 2.65 for Esna station, 0.57, +5.35, and 2.46 for Assiut station, and 0.53, -1.94, and 0.47 for Delta station. The results of calibration, validation and uncertainty analysis were very good and indicated a very good performance of the WEAP model in terms of the uncertainty of model structure.

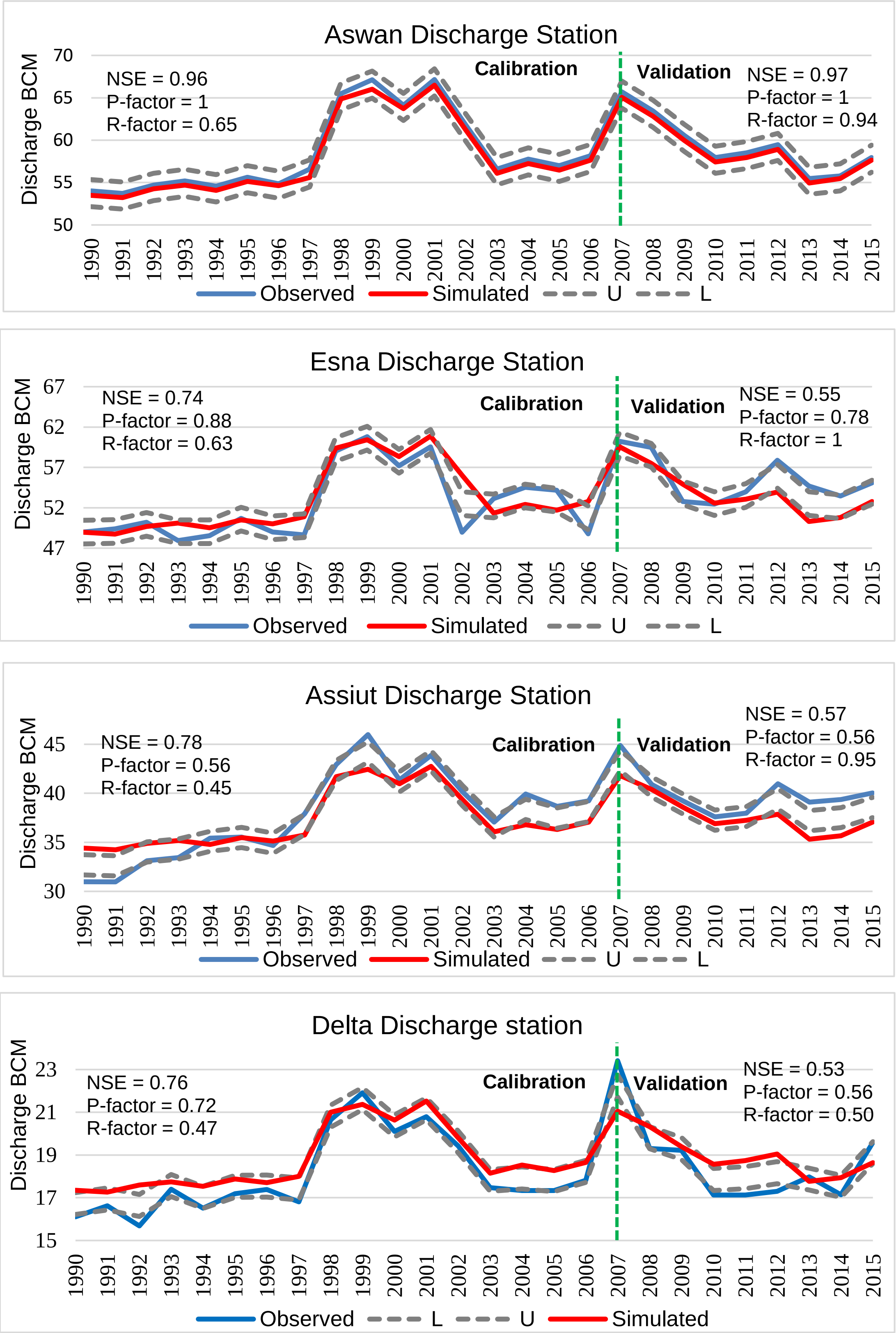


Figure 4.19 Simulated WEAP discharge compared to observed discharge for four gauge stations over the calibration period 1990-2006 and validation period 2007-2015. The uncertainty analysis results are represented in P-factor, R-factor, and highest NSE values. The gray dashed lines show the lower and upper uncertainty limits (L and U) on the calibration data using the GLUE method.

Using the WEAP hydrological model with fewer parameters and understandable structure made dealing with uncertainty in the hydrological modelling of the study area easier, reducing complexity, and achieving acceptable results. In addition, the experience of the modeller with the Egyptian hydrological system helped achieve a good system representation and played an important role in calibration and ensuring good model performance.

4.4.4 Model Results and Reliability

After calibrating the WEAP model and ensuring its accuracy, results can be applied to interpret the current status of the region. The results of implementing the model for water demand and supply in the study area are as follows.

Water demand and supply

The main water resources considered in this study are the Nile River, rainfall, shallow groundwater, deep groundwater, while the demand side is identified with 14 sites covering the demand from agriculture, domestic, and industry sectors. As Figure 4.20 shows, it is concluded that all demands for all sites are continuously increasing during the simulation period 1990-2015. The growing demand for water in Egypt is a response to an increasing agricultural area, population, and industrial production. The supply side fluctuates due to the variation of withdrawing from the reservoir, groundwater, and rainfall variability yearly. This leads to inconstant water shortage in the study area, depending on the annual supply. The Figures 4.20, 4.21, 4.22 show that in 2015, water demand was 80.2 BCM excluding environmental use and evaporation loss; water supply was 63.8 BCM considering the outflow from HAD was 55.5 BCM as reported by Ministry of Water. This difference between water demand and supply leads to water deficit (unmet demand), estimated at 16.4 BCM.

The results of the model show that distribution of demand varies spatially, according to variability in demand activity. The highest demand sites are in Assiut-Delta and Delta divisions, where demand is estimated at 31.87% for each division from the total demand in the whole basin. The water demand for the divisions of Esna-Assiut and Aswan-Esna is estimated at 27.3% and 8.9% respectively. In addition, the agricultural sector shows the highest demand in each area about 80% followed by domestic and industrial sectors about 13%

and 7% respectively. These percentages agree with the Ministry of Water report and previous research (NWRP, 2005; MWRI, 2012; Mohie and Moussa, 2016; Attia 2018).

Results illustrate that water supply in the study area is relatively different from one year to another according to the flooding year, rainfall variation, and groundwater exploitation. Figure 4.21 shows that in 2015, the Nile River provided 85.63% of the total supply reaching the study area, including rainfall. Groundwater provides 14.36% of supply (10.81% from shallow aquifers, 3.55% from deep aquifers). Desalination is insignificant at about 0.1 BCM in 2015. Note that groundwater exploitation is constantly increasing to bridge the gap between demand and supply. Differences in water demand and supply factors could contribute to model uncertainty due to errors in input data.

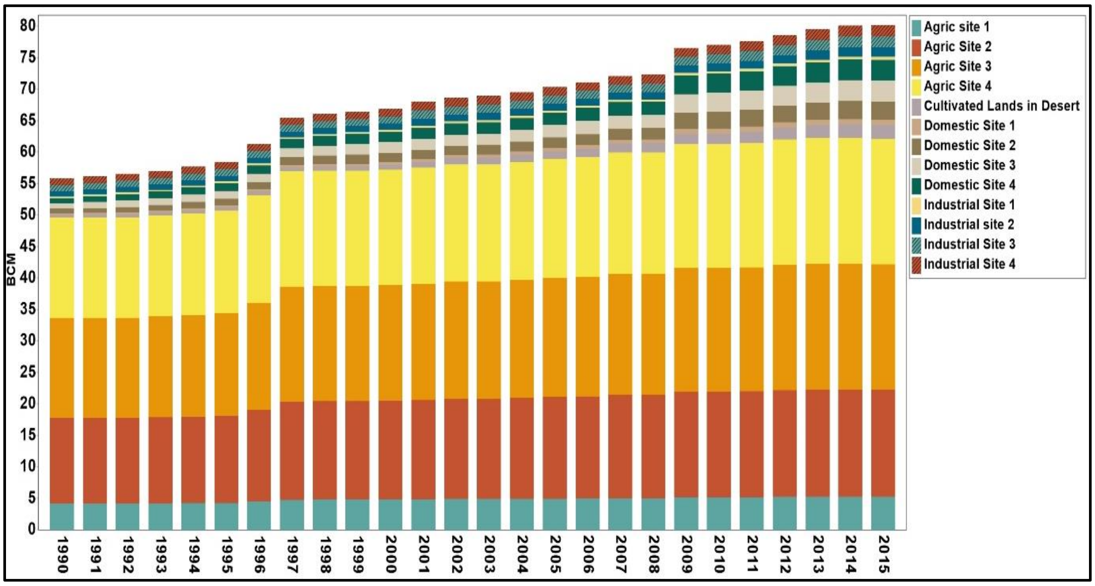


Figure 4.20 Water demand by sectors in the study area, 1990-2015.

Model results show Egypt faces severe water scarcity. The water deficit is rising and is unstable over the simulation period, estimated at 16.4 BCM in 2015 (Figure 4.22). It is noteworthy that the water deficit is different spatially from one area to another. For instance, the maximal water shortage is in Assiut-Delta and Delta divisions, where the shortfall is estimated to be 32.07% for each division. The water deficit for the divisions of Esna-Assiut and Aswan-Esna is estimated at 27.4% and 8.5% respectively. In addition, the water deficit varies by sector, where the agricultural sector has the highest scarcity demand at 79.75%, domestic sector at 13.3%, and industrial sector at 6.9%. A possible explanation for these results may be the different size of activities for each sector in each division, where the greater the size of the sector, the higher demand will be, which leads to a widening water deficit.

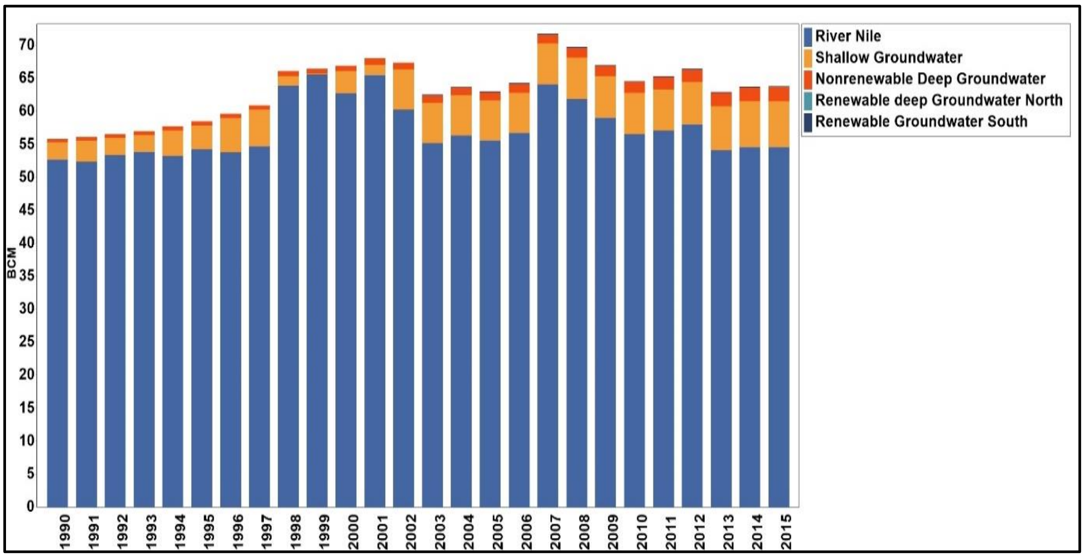


Figure 4.21 Water supply for all sources in Egypt, 1990-2015.

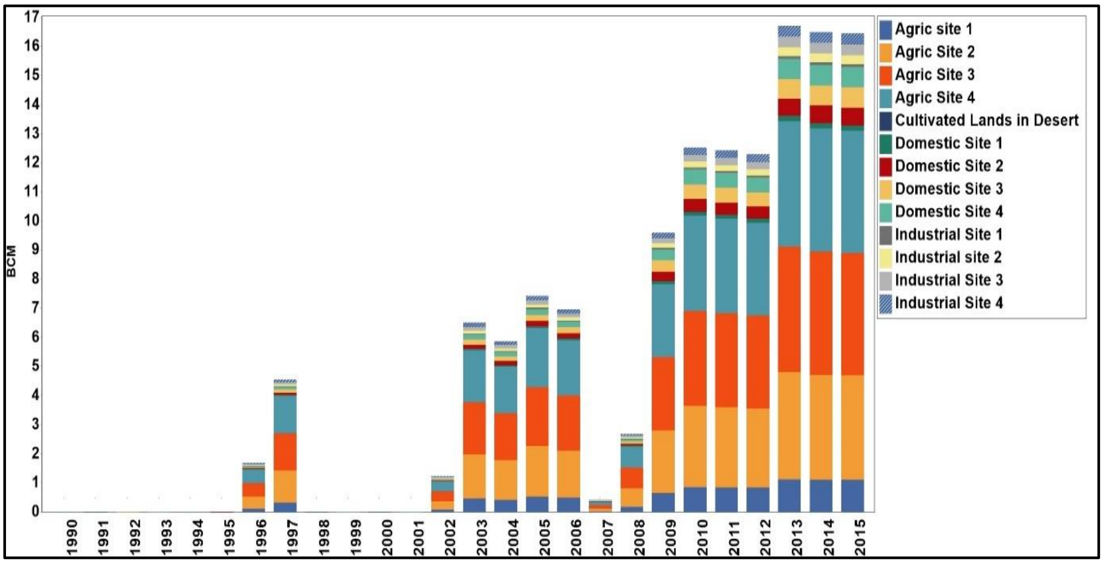


Figure 4.22 Water shortages by sector in Egypt, 1990-2015

Rainfall, Evapotranspiration, and Runoff

WEAP is a spatially continuous (lumped) model and represents the hydrologic basin with upper and lower layers of soil to simulate evapotranspiration, taking into account rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow. WEAP depends on land cover categories and soil types because these factors influence evapotranspiration and infiltration. In addition, climate has a key role in the hydrological cycle, where rainfall has a direct effect on evapotranspiration, runoff and soil moisture. The annual amount of rainfall, evapotranspiration, and runoff are estimated in WEAP depending on seven stations along the Nile river basin for 1990-2015. Figure 4.23 shows annual rainfall volume in the basin varies widely from one year to another, from 3.9 – 5.1 BCM. Egypt officially reported only 1.3 BCM as an estimated and approximate value (NWRP, 2005; MWRI, 2012). It is important to confirm that more detailed rainfall data and stations should be obtained for more accurate rainfall volume results.

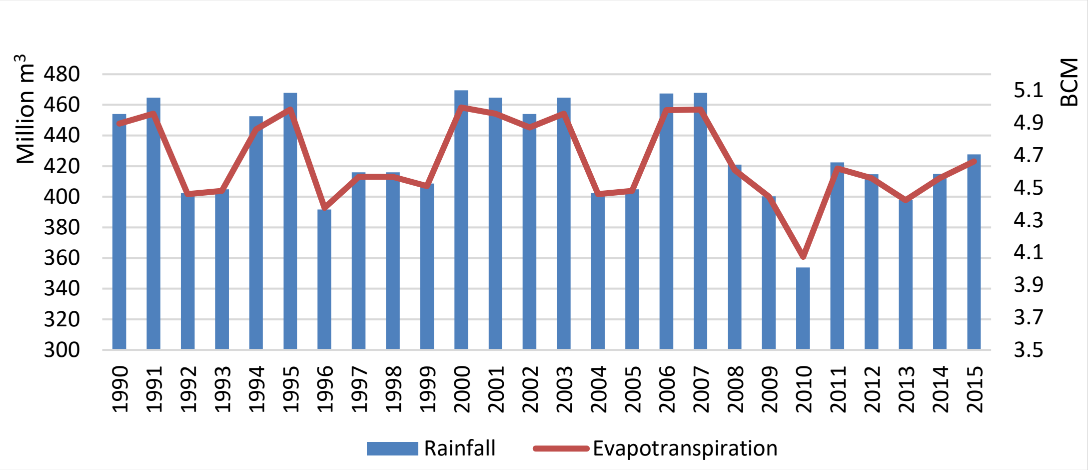


Figure 4.23 Annual rainfall volume and evapotranspiration in the catchment area, 1990 – 2015.

Evapotranspiration estimation using the Soil Moisture Method in WEAP is shown in Figure 4.23, and varied from 360 – 460 MCM. The change in annual evapotranspiration is unstable and in line with the variability in annual rainfall. The results of surface runoff present only the water that reaches the stream channel due to the rainfall. According to Figure 4.24, surface runoff ranges from 2 – 3.24 MCM and tends to decrease as a result of low rainfall in the catchment area. This means that the contribution of rainfall in the water supply system may lessen in the future.

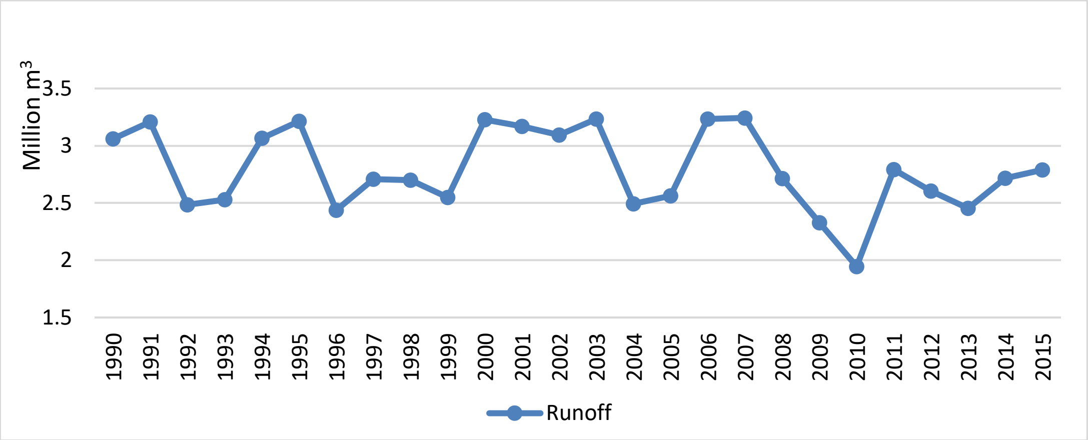


Figure 4.24 Annual surface runoff in the catchment area, 1990 – 2015.

4.4.4.1 Reliability of WEAP Modelling

WEAP model reliability is judged by comparison of simulated data with that reported by the Ministry of Water, and addresses water demand and supply, water deficit, HAD reservoir volume, and evaporation from the HADR. Figure 4.25 shows the modelled demand and supply over the simulation period 1990-2015 in comparison to the reported data. Modelled demand is very close to reported demand (80.14 BCM modelled in 2015 compared to reported 80.45 BCM). This result acceptable because the NSE = 0.92 and PBIAS = +2.33. In contrast, there is a significant difference between modelled and reported supply. This difference is due to Ministry of Water reporting withdrawal from HAD as 55.5 BCM, but this study depends on the actual outflow from HAD, which is different from year to year other according to the flooding and water level in the HADR.

In addition, Egypt does not consider abstraction from the shallow aquifer in the delta and valley as a water resource, as this is actually dissipated water from the Nile. Therefore, Egypt does not add this water to the supply side, but I add it because the model reflects what happens in practice. Furthermore, the disparity in estimating the amount of rainfall is clear, as Egypt estimates it at 1.3 BCM, while the model estimated it about 3.9 - 5.1 BCM based on the rainfall data of seven stations. These reasons are also behind the difference between the modelled and reported water gap as shown in Figure 4.26, where the modelled water gap is estimated at 16.4 BCM and Ministry of Water reported the gap to be 21.0 in 2015.

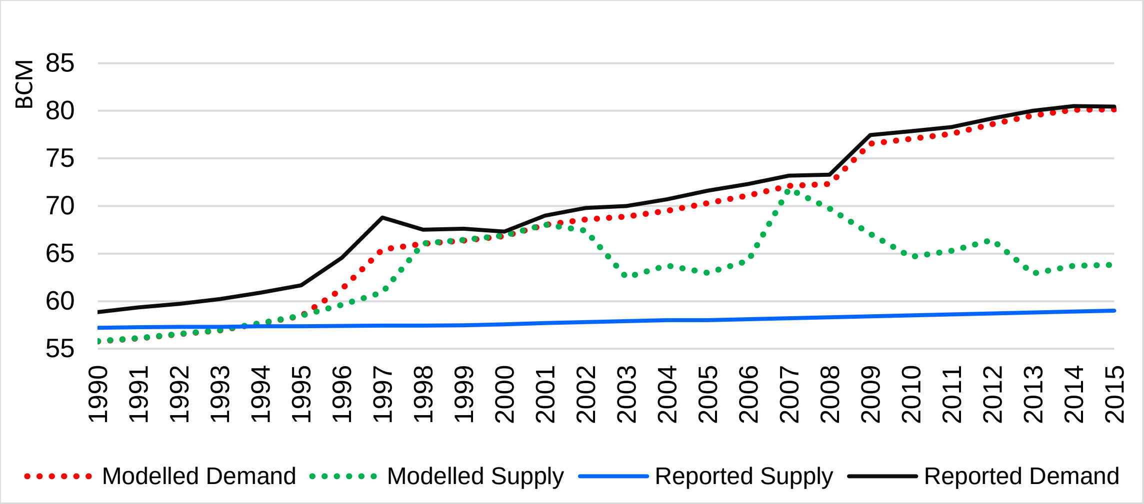


Figure 4.25 Water demand and supply in Egypt, 1990 – 2015.

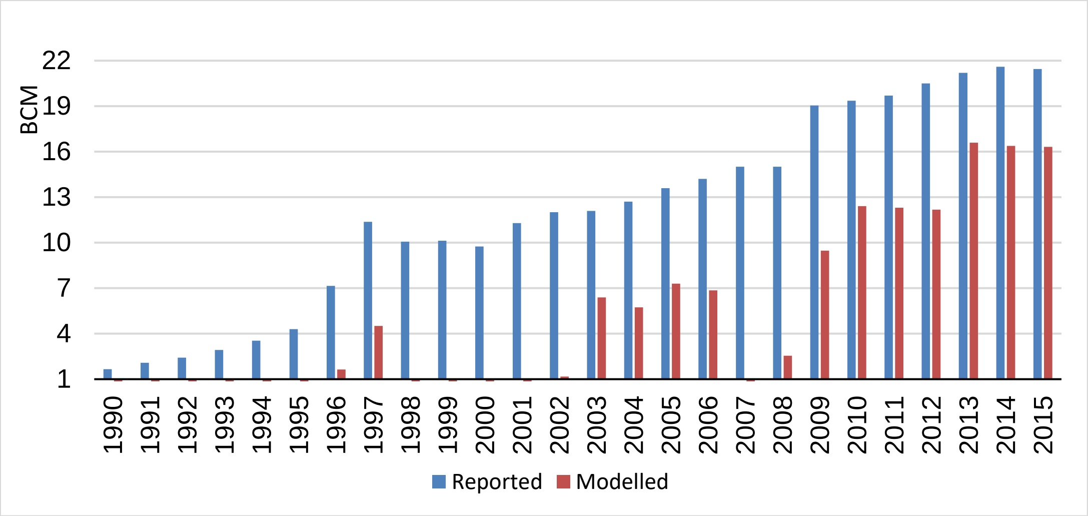


Figure 4.26 The evolution of the water gap in Egypt, 1990 – 2015.

For the reservoir storage volume, the WEAP model results are reasonable and accepted in comparison to the observed data, with NSE = 0.7 and PBIAS= -3. According to Figure 4.27, the slight difference may be due to measurement errors, evaporation quantities from the HADR, and unrecorded quantities of withdrawal from the HADR to Toshka lands. The Ministry of Water estimated the evaporation amount from the HADR at 10 BCM/yearly (MWRI, 2005). Figure 4.28 shows that the model result of evaporation from HADR is similar to the observed data. The small deviation may be explained by the fact that evaporation depends on the surface area of the reservoir lake, which increases and decreases according to the amount of water in the lake.

According to these results, it can be summarized that the WEAP model has a great ability to deal with and represent the complex system and it is more reliable than other methods applied in the literature.

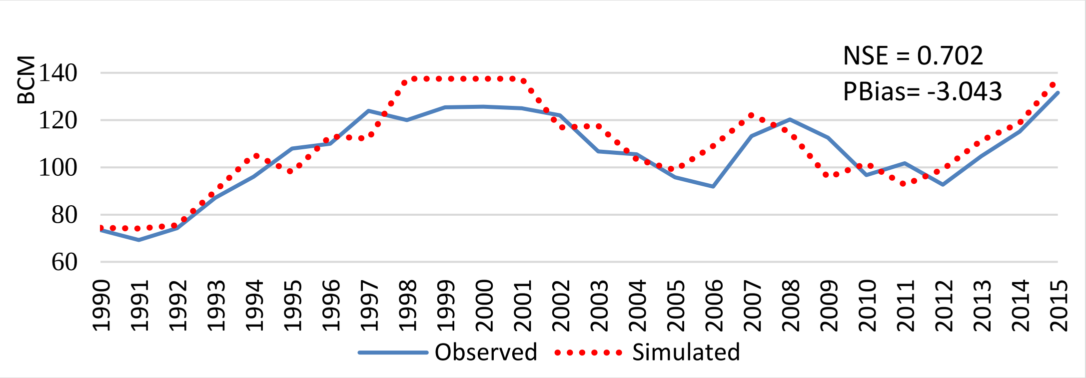


Figure 4.27 HAD reservoir observed and simulated volume, 1990 – 2015.

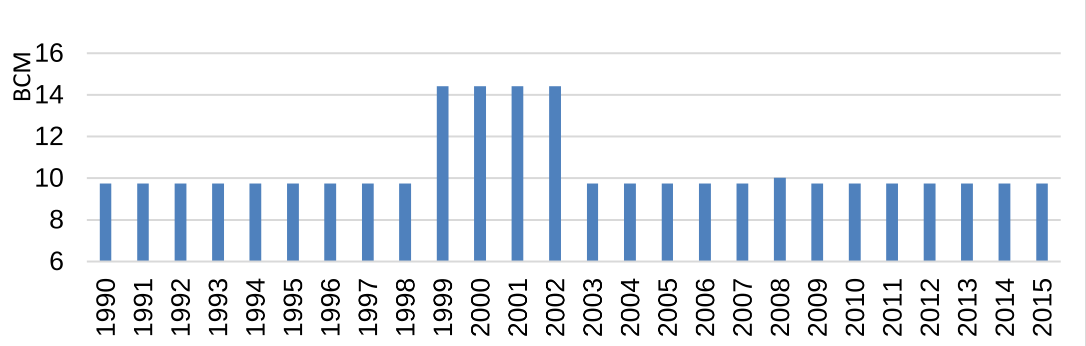


Figure 4.28 Yearly evaporation from HAD reservoir, 1990 – 2015.

4.4.5 Classification of Uncertainty and Complexity

The interaction and changes in the hydrological cycle, parameters, climate, population, land use, and human interventions create different classes of uncertainty associated with water demand and supply. According to the previous analyses and results, the uncertainties in water supply and demand can be categorized based on the different sources of uncertainty and activities. These uncertainties are summarized in Table 4.9 and discussed further below.

Hydrological Modelling uncertainty: This uncertainty results from errors in input data and variables, model structure and equation, and choosing inappropriate model parameters. The hydrological modelling uncertainty can be addressed and quantified using the sensitivity analysis and uncertainty analysis algorithms as discussed in Section 4.4.2 and 4.4.3 using sensitivity analysis and GLUE method. Additionally, the handling of model structure uncertainty can be addressed by comparison of simulated and observed values as discussed in Section 4.4.3 using the NSE and PBIAS to evaluate the WEAP model performance and quality of calibration.

Cognitive uncertainty: This uncertainty is related to the modeller's ability to understand the water system and be familiar with its components, as a lack of understanding of the system may lead to oversight of some of its elements. In addition, to the skills of modeller in performing the hydrological modelling process and model use. This type was addressed through this chapter based on the modeller's experience and study the system well, and investigating field visits. The result of the uncertainty analysis may indicate that the system was not properly represented due to poor modeller experience.

Table 4.9 Summary of uncertainty types, sources, predictability, and handling method in water demand and supply.

Type	Source	Predictability	Handling method
Hydrological modelling uncertainty	Input data, Model structure, Model parameters Modeller's experience	Predictable	Sensitivity and uncertainty analysis methods
Cognitive uncertainty	Modeller's experience and skills in modelling Lack of understanding the system	Predictable	Modeller's capabilities development Study the system well and investigating field visits

It is noted that this study involved a lot of complexity and challenges and needed to break down all sources of complexity in the modelling of water demand and supply. The complexities in the study appear as follows:

- Complexity of the required data to operate the model. Although adding more data may make models better, the large number of data required by the hydrological model could add more interrelation and it could increase the complexity of the conciliation processes. In addition, the large number or required data to run the model could increase the computational time to obtain the required accuracy. Furthermore, limitations of availability of the data required by the hydrological model could add more complexity to the modelling processes.

- Complexity of model structure. It refers to the large number of parameters, components of the model and interrelations between them. The study recommends that the modellers should select the model with simple structure but adequate complexity and appropriate parameters, where the sophisticated models with larger parameters, variables does not necessarily lead to improved performance of hydrological models (Perrin et al., 2001; Orth et al., 2015)
- Complexity of system representation and hydrological simulation. It refers to the challenge and intricacy state between system components, representations and understanding the hydrological system processes in the real world to be able to simulate the system.
- Complexity of model output. It refers to the number of outputs such as runoff, rainfall, evatranspiration, reservoir volume, demand and supply output. In addition, which one should the modeller focus on it? Is it in easy form to explain it and compare with the observed data?
- Complexity of computational time. It refers to the consumed time in optimization process to give the required results. This is subject to many elements such as the model structure, used algorithm in uncertainty analysis, PC specifications and performance, and scale of hydrological basin.
- Complexity of human interventions. It refers to the human interventions in the hydrological system that could add more complexity in representations and simulation such as barrages, canals, wells and people behaviours.

All these factors determine the level of system complexity and help in addressing the uncertainty in water demand and supply. Therefore, the study seeks to evaluate complexity against these complexity criteria, as illustrated in Table 4.10. These criteria are extracted by the study at hand and exist in every complex or simple hydrological system. Their evaluation is judged according to the expertise and capabilities of the modeller. Every criterion takes a score from one to four with the aggregate score determining the system complexity as follows:

- 0 – 6 Low complex. The system is simple, its components are easily represented and knowable, and prone to internal influences only,

- 7 – 12 Medium complex. The system is not simple, but its components are still clear and knowable, and is prone to internal influences only,

  - 13 – 18 High complex. The system is intricate and complicated, multi components, variables, but reasonably simulatable and predictable, and is prone to external and internal influences,

- 19 – 24 Very High complex. The system is chaotic, large number of components, required data, unknowable variables, neither simulatable nor predictable, and is open to multi external and internal influences.

Table 4.10 Criteria complexity in water demand and supply modelling.

Complexity Type	Complexity Degree				Score
	VH	**H**	**M**	**L**	
Complexity of the required data		3			3
Complexity of model structure			2		2
Complexity of model output			2		2
Complexity of system representation and hydrological simulation	4				4
Complexity of computational time			2		2
Complexity of human interventions		3			3
Total					16

By applying this scale to the case study, the degree of Egypt’s system complexity recorded a score of 16 and this refers to high complex, where the system is intricate and complicated, multi components, variables, but reasonably simulatable and predictable, and is prone to external and internal influences. These complexities dealt with in each criterion through this chapter by finding the optimal means for simplifying the process such as overcoming the limitations of data, selecting the appropriate model with few parameters, using PEST tool in initial sensitivity analysis to reduce the computational time, and understanding the system to represent it well as discussed in this study. Selecting the way of handling the complexity in the system, model or modelling is up to the modeller.

4.5 Conclusion

The uncertainty and complexity in water system simulation is a knotty problem that challenges researchers. It can be concluded that dealing with uncertainty and complexity of water demand and supply modelling is primarily subject to the modeller’s experience in selecting appropriate modelling tools including a suitable model, sensitive parameters, influential variables, and the designer's mastering of water system components. Uncertainty is inevitable and can be dealt with by its reduction in the model outputs through optimization algorithms, accurate input data and choosing models with fewer sensitive parameters. This is dependent on the subjective choice of the modeller based on the level of experience in modelling and understanding the complex hydrological system. Using the WEAP hydrological model with fewer parameters and understandable structure made dealing with uncertainty in the hydrological modelling of the study area easier, reduced the complexity, and acceptable results were achieved. The WEAP model is very reliable in estimating water demand and supply. In addition, GLUE is an appropriate algorithm to deal with uncertainty in water demand and supply system by quantifying the uncertainty in input data error and model structure based on the parameters uncertainty.

Uncertainty in the Egyptian water demand and supply system is associated with spatial variation of influential factors in the study area such as climate, agricultural area, population growth, industrial units, HAD outflow and human interventions, where the extreme annual change in these factors leads to a change of uncertainties in different basin areas. According to the results, the p-factor and the r-factor values were 1 and 0.65 in calibration period (1990-2006) for Aswan station, 0.88 and 0.63 for Esna station, 0.56 and 0.45 for Assiut station, 0.72 and 0.47 for Delta station. For the validation period (2007-2015), the p-factor and the r-factor values were 1 and 0.94 for Aswan station, 0.78 and 1 for Esna station, 0.56 and 0.95 for Assiut station, 0.56 and 0.50 for Delta station. In 2015, water demand was 80.2 BCM and water supply was 63.8 BCM. There is uncertainty in water deficit in Egypt due to the uncertain fluctuations in water demand and supply variables from one year to another. Water deficit in Egypt fluctuates and was estimated at 16.4 BCM in 2015. Moreover, it is mainly depends on the varied outflow from the HAD.

The uncertainties in water supply and demand can be classified based on the source of uncertainty and the method of dealing with it to hydrological modelling uncertainty and cognitive uncertainty. While the complexity is represented in Data limitations, selecting the model, model's structure, model's parameters, representing the system, explaining the outcomes, degree of uncertainty, computational time among others. It can be dealt with the complexity by finding the optimal mean for simplifying the process; the point, which is subject to the modeller’s decisions. Based on the results, there is a trade-off between model and system complexity, uncertainty, and predictive ability of water demand and supply, where representing the multi variables of the complex system and model’s parameters increases complexity and uncertainties. This may change the predictive ability based on the variables and factors involved in running the model. Overall, the rational selection of the model and modeller’s experience can minimize complexity, and an efficient and feasible uncertainty analysis algorithm can limit the uncertainty of simulation results.

This chapter involved many methodological decisions affected the results, for example, the choice of using the WEAP model in hydrological modelling, Using PEST tool for estimating the initial ranges of parameters, GLUE algorithm in uncertainty analysis and applying the validation test. The impact of these choices on results and conclusion are significant and efficient, where the using of WEAP model with its adequate parameters and structure led to simplifying the complexity of hydrological simulation although it required a large number of input data. In addition, the choice of reliance on the PEST tool embedded in the WEAP model assisted in estimating the initial ranges of model parameters and this reduced the computational time and the number of runs from 10000 to 7500 run. Furthermore, choosing GLUE method under the impact of choosing a cutoff threshold value 0.50 used to separate behavioural from non-behavioural parameters sets led to quantifying and addressing the uncertainty efficiently over the calibration and validation period, where the GLUE method accounts for all sources of uncertainties including driving variables, model structure, parameters, and measured data. Further, the choice of including the validation analysis and reliability of the WEAP model in the methodology led to ensure the reliance on the WEAP model in future prediction of the hydrological system. These methods and choices can be generalized broadly to other hydrological basins. The results are internally valid and can broadly generalize to other studies settings in the light of countries or regions have the same hydrological conditions particularly the downstream countries.

In accordance with the given analysis and results above, the WEAP model has the ability to represent different hydrologic situations. In a sense, this provides confidence that the impacts of uncertainty in future factors on water demand and supply can be accurately projected and assessed using the current calibrated WEAP model as discussed in Chapter 5.

Chapter 5
Assessment of the Future Impacts of Uncertainty in Factors Affecting Egypt's Water Demand and Supply

5.1 Overview

In the previous chapter, the uncertainty and complexity issue was addressed in hydrological modelling using WEAP model and GLUE method, the current status of water demand and supply was investigated, and the WEAP model was calibrated and ensured its accuracy. Chapter 5 now uses the optimized and calibrated WEAP model in in the previous step (Chapter 4) to explore and assess the impacts of future uncertainty factors on water demand and supply. In this chapter, the projections of future factors affecting Egypt's water demand and supply were input in the WEAP model to evaluate their risk’s uncertainty on water demand and supply. WEAP was run with each variable individually to detect its impact on water demand and supply and water gap.

Sources of future uncertainty in Egyptian water demand and supply are represented by climate change over Egypt, climate variability over the Nile’s upstream, population growth, land use change, and developmental plans in the riparian countries such as dam construction. The study aims at assessing the impacts of these uncertain factors on water demand and supply in Egypt using the exploratory approach, applied using the WEAP model to determine the impact of future uncertainty factors on water demand and supply to evaluate their likely threats in the future. The study depends on the projections of these factors to shape and quantify their impacts on the future water demand and supply; some projections are estimated from the models and historical data and others are assumed based on previous literature.

5.2 Introduction

Egypt faces risks of water shortages due to population growth and water consumption trends in different sectors. If this persists in the years to come, water available per capita will drop dramatically. To make matters worse, uncertainty associated with fluctuations in rainfall, development in Nile basin countries, and climate change may increase the water deficit in Egypt, driving policymakers to deal with unknown conditions by designing plans and policies that may not be appropriate. Uncertainty associated with these uncertain factors can be addressed by examining multiple projections or scenarios, or several runs of the same model (with different initial conditions or parameters), and comparing the results. While this will not decrease the uncertainty intrinsically, it provides insight into the range of uncertainty and the probability of different outputs (Barnes, 2016). Scientists indicate the probability of an increasing or decreasing tendency as uncertainty.

The purpose of this chapter is to assess the impacts of future, uncertain factors, on water demand and supply in Egypt using the exploratory approach based on projection of uncertainty factors. Future uncertainty factors to be addressed are climate change over Egypt, climate variability over the Nile’s upstream, Population growth, land use change, and the Grand Ethiopian Renaissance Dam (GERD). The exploratory approach is an essential procedure to increase our knowledge about the potential future of water demand and supply in Egypt. The exploratory approach is conducted by running the WEAP model with uncertain factors projections to assess their impacts on water demand and supply in the future over the period 2016 - 2050.

It is necessary for policymakers to understand the potential behaviour of uncertainty factors in the system for such a complex water system in Egypt. The present study quantifies the impact of uncertainty factors by adjusting their ranges outside the reference scenario value, thereby measuring the effects of more acute conditions. For example, the population growth rate of Egypt was changed in the range of 1.30 - 1.85% giving a population of 140 - 192 million people in 2050. The analysis was conducted by changing one model variable at a time while keeping the other variables unchanged to assess the impact of this variable on water demand and supply.

Uncertainty in climatic projections is likely to be irreducible due to the complex and chaotic nature of the climate system, and certain constraints on our ability to model complex systems (Harrison and Stainforth, 2009). Minimizing uncertainty in projections of climate change and their threats is one of the most important research needs, in order to inform stakeholders and assist communities to mitigate and adapt to changes. Crucial issues relate to data availability and understanding of processes in climate and hydrological models (Kundzewicz et al., 2018). To deal with this uncertainty we need to identify how the range of projections of future climate look and potential impacts on water demand and supply; the present methodology was designed to help in this point. In this study, climate change addresses how the rainfall, runoff, and evaporation over Egyptian lands will vary, while climate variability is the prediction of how much water Egypt will receive in the future, from the Nile at Dongola station, due to the rainfall variability over upstream lands.

One of the key uncertainties associated with identifying the impact of climate change on water resources is the used climatic models. Using projections of inaccurate climatic models leads to large uncertain outcomes. Recently, statistical and objective measures have been used for judging the efficiency of climate models to rate them and pick a set of high-performance models for analysis (Gleckler et al., 2008; Pierce et al., 2009; Santer et al., 2009; Holtanová et al., 2012; Perez et al., 2014). Dependency on a single metric of model performance may be misleading because it hides a more complicated picture of the relative features of different models (Gleckler et al., 2008). Therefore, using more quantitative metrics to assess model performance is necessary to facilitate the selection of the best performing model.

In many studies, population growth was determined as a major factor in uncertainty of water demand and supply. In Egypt, the average population density has doubled over the past 30 years (Hamza and Mason, 2004). The major challenge faced by the Egyptian government is increasing water demand due to population growth with limited water supply. In 2013, the population growth rate reached 2.5%, (CAPMAS, 2014). While the growth rate is recorded approximately 2% in 2015, which means an additional million Egyptian are born every year (CAPMAS, 2016). In the present study, United Nations and CAPMAS projections of Egypt’s population are used to assess the potential impacts of population growth on water demand and supply.

Land use change is identified as another source of future uncertainty that may affect future water demand and supply. As a result of the rapid increase in water demand in the agricultural and industrial sectors (Abu-Zeid, 1991), the study assesses the uncertainty of the impact of land-use change on water demand and supply in Egypt using projections data for both sectors. In this study, land-use change means the change in agricultural area, industrial units’ number, and population number. Increase in water demand in the agricultural and industrial sectors is due to the development of the manufacturing sector and land reclamation projects.

The rapid development in the Nile Basin countries as a serious challenge to water supplies in Egypt, as this development in riparian countries is linked to building dams to store the Nile's water and generate electricity. The last uncertain factor is discussed in this study is the predicament of the Grand Ethiopian Renaissance Dam. Recently, constructed on the Blue Nile at the

Ethiopian border with Sudan. The Blue Nile contributes to about 60% of the annual water supply of Egypt at Aswan. The present study discusses the potential threats of the GERD on water demand and supply in Egypt through reservoir filling scenarios and the policy after the filling period.

5.3 Data and Method

After using the WEAP model to quantify uncertainty in the hydrological modelling and calibration, the exploratory approach is used with WEAP to assess and explore the potential impacts of uncertain factors on water demand and supply. The exploratory approach deals with uncertainty in factors driving future water demand and supply and depends on incorporating uncertain projections of factors into the WEAP model, rather than addressing observed data to identify model uncertainty, as in Chapter 4. The period up to 2050 was used to run the model based on data availability and due to greater reliability of prediction for short to medium periods than long periods.

The factors addressed are based on literature review and stakeholder questionnaire during fieldwork (given explanation in section 3.6, Chapter 3 and section 7.2.1, Chapter 7) (Appendix 3). The factors are climate change, climate variability, population growth, land use change, and the Grand Ethiopian Renaissance Dam. The change in these factors could increase uncertainty in the future and pose a significant threat to water security. The exploratory approach does not eliminate these uncertainties, but can detect extreme behaviour patterns or dramatic changes on demand and supply due to the factors. The number of uncertainty factors, multiplicity of projections, and models used to produce these projections may increase the complexity and uncertainty.

The methodology applied in this chapter is:

1. Create the WEAP model schematic for current demand and supply by building the demand and supply nodes; links between them, and specify the priority for each node (Figure 5.1).

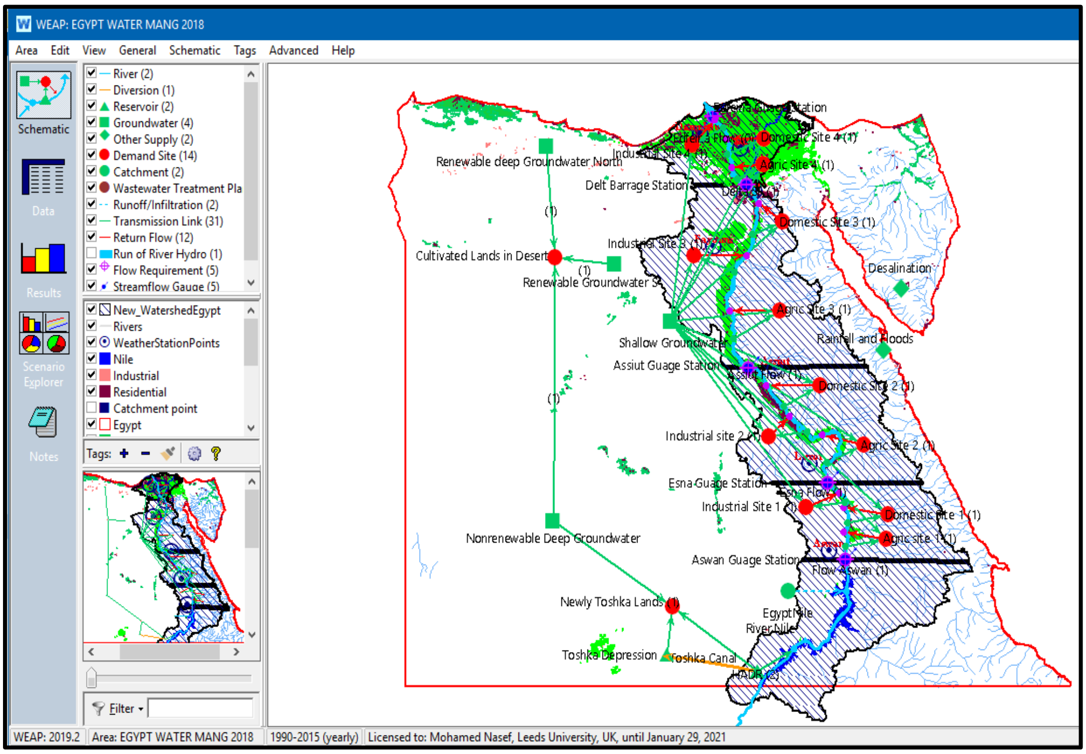


Figure 5.1 WEAP schematic for forecast to 2050.

1. The WEAP model is operated on annual time step (1990 – 2015) due to the availability of data and the current situation is set for (2015).

2. Apply the required data to simulate the evolution of the system under the different demands of domestic, agricultural, and industrial sectors.

3. Run the model to calibrate it with the current situation.

4. Determine the timeframe of the projections and future scenarios to 2050. The timeframe has critical importance when looking at uncertainty and complexity in the future. The study assumes that the medium-term period to 2050 is more feasible and authentic than longer-term periods, which may contain more sudden events, which lead to increased uncertainty and complexity. In addition, policy plans must be on a short-term period to facilitate their implementation and assess their outcomes.

5. Prepare the required data (2016 – 2050) for uncertainty factors (climate change, climate variability, population growth, land use change, and the GERD) and use in the WEAP model individually for addressing the uncertainty range and the risk in the future to each factor. The risk and uncertainty for these factors will be evaluated based on the change in demand, supply, and water deficit.

To achieve this data as shown in Table 5.1 is collected for the WEAP model application.

Table 5.1 Data used in Egypt water supply/demand forecasts to 2050

Data	Unit	Source
Agricultural area (1960 – 2015)	Million feddan	Ministry of Agriculture and Land Reclamation, Egypt.
Population census (1950 – 2018)	Million People	Central Agency for Public Mobilization and Statistics, Egypt.
Numbers of Industrial units (1990 – 2015)	Units	Ministry of Trade and industry, Egypt.
Environment demand	BCM	Ministry of Water in Egypt
Rainfall and Temperature data (1990 – 2015)	BCM	Egyptian Meteorological Authority
River supply at Dongola station (1965 – 2015)	BCM	Ministry of Water in Egypt
HAD Outflow (1965 – 2015)	BCM	Ministry of Water in Egypt
Shallow groundwater (1990 – 2015)	BCM	Ministry of Water in Egypt
Deep groundwater (1990 – 2015)	BCM	Ministry of Water in Egypt
Desalination (1990 – 2015)	BCM	Ministry of Water in Egypt
Reused Water from different sectors (1990 – 2015)	BCM	Ministry of Water in Egypt
Water loss from different sectors (1990 – 2015)	BCM	Ministry of Water in Egypt
Climate change data projections (2016 – 2050)	°C and mm	CMIP5
Climate variability data (rainfall stations) Malakal station (1965 – 2010) Diem station (1965 – 2010) Khashm El Girba station (1965 – 2010)	mm	Nile basin: water resources atlas
Grand Ethiopian Renaissance Dam (GERD)	BCM	International panel of experts on the GERD project
Population growth projections (2016 – 2050)	Million people	CAPMAS and UN data
Land use change projections (agriculture, Population, and industry) (2016 – 2050)	(Million feddan, Million people, Units number)	Extraction of historical data

5.3.1 Current Situation Data

For the current scenario, the collected data over the base period (1990 – 2015) is used for calibration procedures and the year 2015 is set as the current situation. After calibrating the model and accepting the uncertainty results (Chapter 4), the projection data of specified uncertainty factors is collected to run the WEAP model to assess impacts on water demand, supply, and deficit. The procedures of collecting and manipulating the required data as follows:

5.3.2 Climate Change Data

Uncertainty reduction in climate change projection and its implications is amongst the most urgent research needs, in order to provide stakeholders with accurate knowledge and to better support local communities in their duty to respond to change (Buytaert et al., 2010; Nóbrega et al., 2011; Bosshard et al., 2013; Kundzewicz et al., 2018). Reducing uncertainty of climate change on water demand and supply is based on using the appropriate climate model with good performance and finer resolution to reduce the scale mismatch between the observed data and modelled data (Kundzewicz et al., 2018).

Morsy (2015) reported that the use of global climate models and regional models could attain a higher degree of certainty in the projection of the risk of climate change. The study depends on climate models data rather than a simulation from historical data to quantify how the hydrological system could change in the future. This is because climate models are powerful tools to enhance our understanding and predictability of climate behaviour on annual and decadal time scales. In addition, climate models consider the effects of natural variability, physical processes among various components and human activity on the future climate change. Conversely, a simulation from historical data does not take into consideration the natural changes or human activities effects in the future and it relies on too subjective and empirical assumptions. Unfortunately, research work on selecting the best-projected models and climate change on Egypt has been minimal. Therefore, I adopt the technique of comparison among several models to select the nearest and best models to be used in this study to explore the future. In other words, which a model can be declared good enough for its anticipated use. The historical downscaled data for 15 climate models of CMIP5 is used to apply the comparison technique to select appropriate models for simulating the climate of the catchment area (Table 5.2). The comparison is made with the observed data of temperature and precipitation for seven stations in the catchment area along the Nile River over the period 1990-2005.

Table 5.2 CMIP5 models used in this study for comparison.

Model	**Modelling Centre**	**Country**
BCC_CSM1_1	Beijing Climate Centre, China Meteorological Administration	China
C_CSM1_1_M	Beijing Climate Centre, China Meteorological Administration	China
CCSM4	National Centre for Atmospheric Research	USA
CESM1_CAM5	Community Earth System Model Contributors	USA
SIRO_MK3_6_0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	Australia
FIO_ESM	The First Institute of Oceanography, SOA	China
GFDL_CM3	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory	USA
GFDL_ESM2M	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory	USA
GISS_E2_H p1	NASA Goddard Institute for Space Studies	USA
HADGEM2-ES	Met Office Hadley Centre	UK
PSL_CM5A_MR	Institute Pierre-Simon Laplace	France
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology	Australia
MRI_CGCM3	Meteorological Research Institute	Japan
NORESM1_ME	Norwegian Climate Centre	Norway

According to Chai and Draxler (2014), five statistical measures are used for evaluating model performance and examining the goodness of fit between the observed and simulated data. The statistical measures are Root Mean Square Error (RMSE), Percent Bias (PBIAS), coefficient of determination (R), index of agreement (d), and Mean Absolute Error (MAE) as presented in Table 5.3. After evaluating the climate models, four models are selected based on the closest and best results of statistical measures to use their projections data with the WEAP model. The projected data of mean temperature and precipitation over the period 2016 – 2050 is selected for two representative concentration pathway RCP4.5 and RCP8.5 to explore the risk on water demand and supply.

Table 5.3 Metrics for evaluating performance of climate models.

Metrics	**Equation**	**Purpose**	**Evaluation**
RMSE (Equation 5.1)	$= \sqrt{\left(\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}\right)}$	General standard deviation of simulated error	Lower values indicate better performance
PBIAS (Equation 5.2)	$= \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{i=1}^{n} Y_i^{obs}}$	Compare the average tendency of simulated to the observed data	Lower values indicate better performance
R (Equation 5.3)	$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$	Quantify the correlation and dependence	higher values indicate better performance
D (Equation 5.4)	$= 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}[(\lvert(S_i - \bar{O})\rvert + \lvert(O_i - \bar{O})\rvert)^2]}$	Indicate the degree of model simulation error	higher values indicate better performance
MAE (Equation 5.5)	$= \frac{\sum_{i=1}^{n}(\lvert S_i - O_i \rvert)}{n}$	Average of the error between modelled to the observed data.	Lower values indicate better performance

5.3.3 Climate Variability Data

Climate variability refers to the changing upstream hydrological conditions that affect inflow to Egypt (85% of Egypt's total water resources come from outside its borders). The amount of Nile’s water reaching Egypt at the Dongola Station depends on the variation of annual rainfall on the headwaters of the Nile, which leads to an increase in complexity and uncertainty. It is not possible to forecast future climate variability on the Nile river basin because of the size of required data and influencing factors at this scale. Fortunately, the WEAP model has the water year method (given explanation below) to evaluate the impact of water year variability on the hydrologic system. Future climate variability are estimated by using the water year method in WEAP.

The water year method can be used to analyse the impacts of potential hydrologic pattern shifts in the future of hydrological trends based on the historical data as a reference condition. Future inflows can be simulated by altering the data in the current account, depending on water year definitions and sequences. Water years can be classified as very dry, dry, normal, wet, and very wet through different inflows (e.g., from +25 % to -25 %) from the average of the current account, which is usually a normal inflow year. In this method, five modes are explored for future climatic conditions. The method first involves defining how different climate variability (e.g., very dry, dry, etc) compares relative to a normal year. Different probabilities can then alter the chosen sequence of dry and wet years to assess the impact of natural variation on the water system.

To define the dry and wet years, a regression analysis and sensitivity index are carried out for time series (1965 - 2010) of rainfall stations on rivers feeding the Nile River. The stations are Malakal station for the White Nile, Diem station for the Blue Nile, Khashm El Girba station for the Atbara River, inflow at Dongola Station and outflow from the High Dam. Regression analysis estimates the correlation, represented in Pearson`s R and P-value <0.05. The sensitivity index to indicate the sensitivity range of the flow at Dongola station to the amounts of rain falling on the Nile Basin is:

$$\text{Sensitivity Index} = Q / Q1 \qquad \text{(Equation 5.6)}$$

Where Q indicates relative change in flow and $Q1$ is relative change in rainfall.

SI ranges between +1 to -1, + and values indicates positive and negative change.

According to the results of regression analysis and sensitivity between these drivers, the study can extract the values of wet and dry years depending on the average of inflow and rainfall over the period 1965 – 2010. Hence, to deal with the uncertainty of water inflow to Egypt, the probabilities of water year (very dry, dry, normal, wet, and very wet) over the period 2016-2050 are employed in WEAP as inflow values to estimate the risk in the Egyptian water system.

5.3.4 Population Growth Data

Uncertainties about how much the population increase will affect water demand in future can be shown by projections with different levels of increase in population. To explore the likelihood risk of population growth on the water system, four projections (2016 – 2050) are implemented in WEAP. One projection belongs to the Central Agency for Public Mobilization and Statistics in Egypt, and three are projections of the United Nations (low variant, medium variant, high variant).

5.3.5 Land Use Change Data

Land-use change combines the change in agricultural areas, population growth, and industrial units. Change in these activities increases the water demand. For dealing with the uncertainties linked to the land use change, projections of agriculture areas and industrial units are extracted in Excel by forecasting analysis using Exponential Triple Smoothing (ETS). The forecasting analysis depends on the historical data of agriculture area (1960-2015) and industrial units (1990-2015), except population where UN projections are used. This specific forecasting analysis is used to find out the range within which the forecasted values are likely to fall, and the confidence level is set to 95%. The result of forecast is in three ranges low, medium and high, and the growth rate is calculated for each range as following:

$$Growth\ Rate = \left(\frac{End\ Value}{Beginning\ Value}\right)^{\left(\frac{1}{n}\right)} - 1 \qquad \text{(Equation 5.7)}$$

Where *End value* and *Beginning value* are the last and first year in the Time series and *n* is the number of years in time series.

The resulting potential growth rates for agriculture area, population, and industrial units are used in WEAP to evaluate their impacts on water demand.

5.3.6 The Grand Ethiopian Renaissance Dam

Development in the wider Nile Basin are a source of uncertainty and complexity. Developments in upstream countries could reduce water available to Egypt, from for instance, increased irrigation abstraction. The Grand Ethiopian Renaissance Dam (GERD) is the key developments creating uncertainty. The Ethiopian Dam require 74 BCM of water to fill its reservoir (IPoE, 2013; Mulat and Moges, 2014; Wheeler et al., 2016).

This study assesses the risk of the GERD to Egypt during the filling period and the post-fill discharge policy. The methodology is based on how filling the dam reservoir in three, seven and ten years will affect the flow to Egypt, particularly in the different water years from very dry to very wet. The three, seven, and ten years are those addressed in negotiations between Egypt, Ethiopia, and Sudan. The 74 BCM storage is divided by 3, 7, and 10 years; from which water arriving annually to Egypt is determined. Hence, WEAP will run with different water years after deducting this portion. For the discharge policy after the filling period, the study assumes what reach Egypt is its previously agreed annual share of only 55.5 BCM (which Egypt has in the past often exceeded).

5.4 Results and Discussion

5.4.1 Current State 1990 – 2015

Results of WEAP modelling in previous Chapter 4 (Sections 4.4.4 and 4.4.4.1) (Figures 4.20, 4.25, and 4.26) show that in 2015, water demand was about 80.2 BCM divided into agriculture, domestic, industry, against a reported value of 80.45 in 2015. This result is accepted because the NSE = 0.92 and PBIAS = +2.33. The Ministry of Water reported water supply of 59 BCM in 2015 while WEAP model results found the supply ranged between 55.8 – 71.7 BCM over the period 1990 – 2015. The difference between reported and modelled supply over is due to The Egyptian Ministry of Water reporting withdrawal from HAD of 55.5 BCM, whilst this study uses the actual outflow from HAD, which varies annually according to the flooding year and water level in the HADR. In addition, Egypt does not add the extracted shallow groundwater to the supply side. Furthermore, the WEAP model estimated the rainwater in the catchment area about 3.9 – 5.1 BCM based on the rainfall data of seven stations for the period 1990 – 2015 (Figure 4.23, Chapter 4). While Egypt reported the rainwater amount about 1.3 BCM without any change over the period 1990 – 2015 and there is an uncertainty around this number because no sufficient studies to calculate the rainwater amounts in Egypt accurately. This difference between water demand and supply leads to water deficit (unmet demand), where it was estimated 16.4 BCM in 2015 (Figure 4.26, Chapter 4). Egypt bridges this shortage by Non-conventional resources such as desalination, shallow groundwater, and water reuse.

According to the Figure 4.20 in Chapter 4, agriculture records the largest demand for water resources by 62.15 BCM. The area of agricultural lands is constantly increasing during the period 1960-2015 (Figure 4.18, Chapter 4), where reached 9.09 million feddans in 2015 and the water consumption rate is 4700 m^3 per feddan. Egypt's population is rising rapidly over the period 1950 – 2018, where in 2015 they reached 90 million people. In 2015, water demand was 10.4 BCM. In addition, the water consumption rate per capita reported 87.6 m^3 in 2015. Further, the industrial sector recorded water demand by 5.4 BCM. On the other hand, there is a fluctuation in water inflow at Dongola station and water outflow from the High Dam over the period 1990 – 2015, where the averages for inflow and outflow reached 71 BCM and 58.23 BCM respectively; this leads to fluctuation of volume of the High Dam Lake from year to year.

5.4.2 Mechanisms of Dealing with Future Uncertainty Sources

The causes of future uncertainty are mainly associated with representation of different variables behaviour in the future, such as natural variables, socio-economic variables, and transboundary problems. The uncertainty is linked to the projections of these variables. Practically, this kind of uncertainty is related to how we can assess the impact of uncertainty factors to imagine the future. Therefore, dealing with this kind of uncertainty is through exploring and predicting the risk of the input variables on water demand and supply system. In the present study, I selected five uncertainty factors and their projections to run the WEAP model with them. Selection of these factors as the most factors that could contribute in the uncertainty and threat water demand and supply in Egypt is achieved based on literature and questionnaire with stakeholders in Egypt (Appendix 3). The final list of uncertain factors are climate change, climate variability, Great Ethiopian Renaissance Dam (GERD), population growth, and land use change.

5.4.3 Uncertainty Linked to Climate Change

As mentioned before, uncertainty reduction of climate change on water demand and supply is based on using the appropriate climate model with good performance and finer resolution to reduce the scale mismatch between the observed data and models data (Kundzewicz et al., 2018). Unfortunately, research on selecting the best-projected models and climate change on Egypt has been minimal. One of the key decisions in this study was to select the climate models to assess the uncertain impact of climate change on the study area. The criteria for selection were based on comparison of historical data

1990-2005 for 15-climate model of CMIP5 to observed data of precipitation and mean temperature to the catchment area. Five statistical measures of RMSE, PBIAS, R, d, and MAE were applied in comparison to select the nearest and appropriate models for simulating the climate of catchment area. From results of comparison (Table 5.4), it appears that the closest model to represent the future in the study area are GISS_E2_H p1, MIROC5, FIO_ESM, and ACCESS1-0. Therefore, the projected data of mean temperature and precipitation for these models over the period 2016 – 2050 is applied in the WEAP hydrological model for two representative concentration pathways, RCP4.5 and RCP8.5, to explore uncertainty and risk on water demand and supply.

Table 5.4 Result of comparison metrics for 15 climate model of CMIP5. The green colour refers to the closest model to represent the future according to the comparison of climatic historical data of models with Egypt's observed data.

Model	**Temperature**					**Precipitation**				
	RMSE	PBIAS	R	d	MAE	RMSE	PBIAS	R	d	MAE
BCC_CSM1_1	1.52	6.62	0.04	0.00	1.44	10.06	34.77	-0.31	0.02	9.92
BCC_CSM1_1_M	1.80	8.05	-0.02	0.00	1.75	13.42	46.45	-0.24	-0.01	13.26
CCSM4	2.13	9.60	-0.10	-0.01	2.09	7.63	25.73	0.04	0.01	7.34
CESM1_CAM5	1.95	8.84	-0.21	-0.01	1.92	7.30	24.45	-0.15	-0.02	6.98
CSIRO_MK3_6_0	1.88	8.40	-0.24	-0.01	1.83	12.57	43.65	0.21	0.01	12.46
FIO_ESM	1.19	5.31	0.06	0.01	1.15	8.99	30.69	-0.03	0.00	8.76
GFDL_CM3	3.17	14.41	-0.07	0.00	3.13	10.25	35.33	0.04	0.00	10.09
GFDL_ESM2M	2.23	10.03	-0.22	-0.01	2.18	10.04	34.41	-0.37	-0.02	9.82
GISS_E2_H p1	0.41	0.38	0.30	0.14	0.30	4.36	13.14	0.22	0.10	3.75
HADGEM2-ES	3.04	13.90	0.01	0.00	3.02	8.29	28.52	-0.31	0.02	8.14
IPSL_CM5A_MR	2.97	13.49	-0.36	-0.01	2.93	15.78	55.08	-0.64	0.01	15.72
MIROC5	0.50	1.81	0.27	0.16	0.41	3.38	9.01	0.23	0.17	2.78
ACCESS1-0	2.77	12.61	0.06	0.00	2.74	5.69	18.33	0.35	0.08	5.23
MRI_CGCM3	3.73	17.12	0.04	0.00	3.72	12.47	43.36	-0.39	0.01	12.38
NORESM1_ME	3.53	16.21	0.26	0.00	3.52	6.94	23.37	-0.16	-0.02	6.67

The results of projections data analysis of the four CMIP5 models to determine the uncertainty range for each model has shown a significant change in temperature and rainfall for 2016-2050 for RCPs 4.5 and 8.5. As presented in Table 5.5, the mean temperature change for 2016-2050 for the four models will likely be in the range +0.9 to -1.7 °C. The FIO-ESM and ACCESS 1-0 for

RCPs 4.5 and 8.5 appears a decrease in mean temperature estimated by -3.6%, -2.3%, -7.9%, and -7% respectively, while the GISS-E2-Hp1 and MIROC5 for RCP 4.5 and 8.5 shows an increase estimated by +3%, +4.2%, +2.4%, and +3.2. The model GISS-E2-Hp1 RCP 8.5 is the highest estimation and ACCESS 1-0 RCP 4.5 (Low) is the lowest estimation. In contrast, the rainfall change for the period 2016-2050 for the four models presented high uncertainty in the future, where the change tends to decrease and will likely be in the range -1.6 to -8.9 mm. All the models recorded a decrease in the rainfall, 2016-2050. The model FIO-ESM RCP 8.5 is the highest estimation and MIROC5 RCP 4.5 is the lowest estimation by -31.5%, and -5.7% consecutively. Figures 5.2 and 5.3 compare the projections data for selected CMIP5 models 2016-2050 to the baseline 1990-2015.

Table 5.5 Uncertainty range in temperature and rainfall projections for CMIP5 model, 2016 - 2050.

CMIP5 models	Uncertainty range of temperature **(+0.9 to -1.7 °C)** Increase/Decrease %	Uncertainty range of rainfall **(-1.6 to -8.9 mm)** Increase/Decrease%
FIO-ESM RCP 4.5	-3.6%	-29.8%
FIO-ESM RCP 8.5	-2.3%	-31.5% (High)
GISS-E2-Hp1 RCP 4.5	+3.07%	-10.6%
GISS-E2-Hp1 RCP 8.5	+4.2% (High)	-10.5%
MIROC5 RCP 4.5	+2.4% (medium)	-5.7% (Low)
MIROC5 RCP 8.5	+3.2%	-6.3%
ACCESS 1-0 RCP 4.5	-7.9% (Low)	-15.5%
ACCESS 1-0 RCP 8.5	-7.06%	-15.7% (medium)

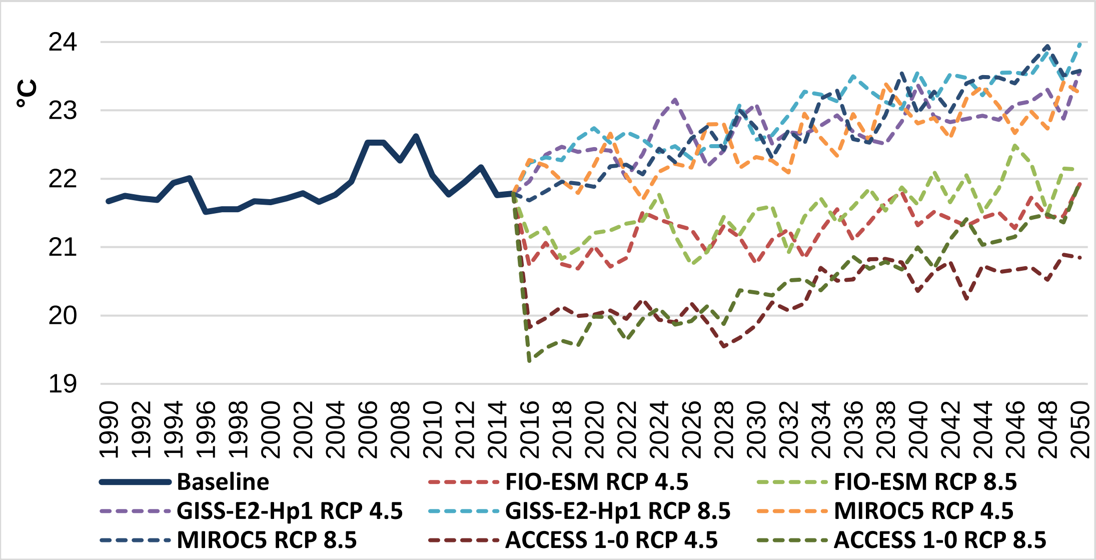


Figure 5.2 CMIP5 climate model projections of temperature over the catchment area 2016 – 2050.

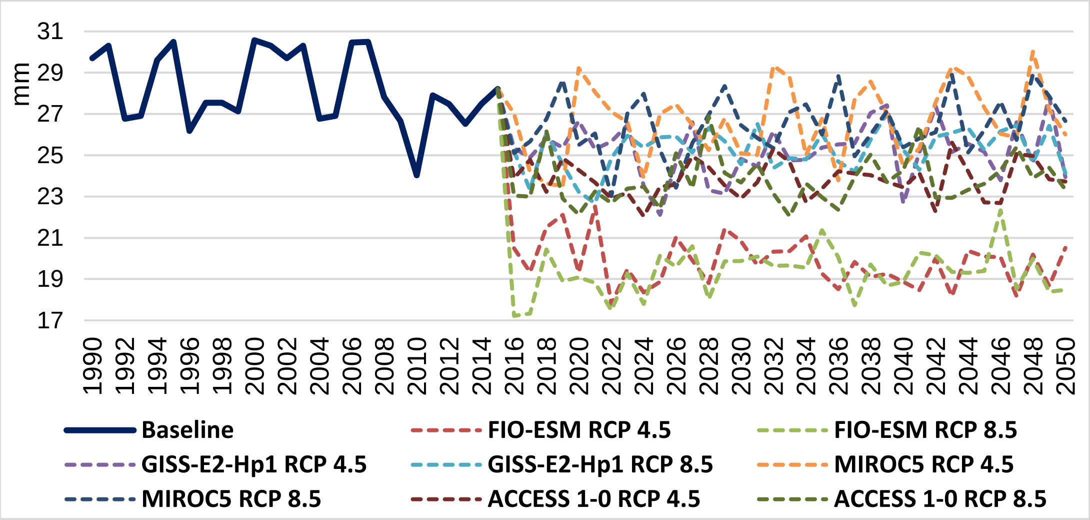


Figure 5.3 CMIP5 climate model projections of rainfall over the catchment area 2016 – 2050.

The projected data 2016-2050 of the CMIP5 models 2016-2050 was input to WEAP to evaluate the risk from climate change in the study area. The result indicates a significant impact on water supply due to the variation in rainfall volume, evapotranspiration, and runoff. The uncertainty range of rainfall volume will likely be 2.8 – 5 BCM over the period 2016 – 2050 in comparison to 3.9 – 5.1 BCM for the period 1990-2015. The most pessimistic climate model FIO-ESM RCP 8.5 recorded the highest risk by 2.8 BCM, while the lowest risk estimated by MIROC5 RCP 4.5 as optimistic model about 5 BCM. This change tends to decrease in the rainfall volume on the catchment area by 0.1 to 1.1 BCM in 2050. Figure 5.4 compares the rainfall volume change over the period 2016 – 2050 based on the projection data of CMIP5 models for two representative concentration pathway RCP4.5 and RCP8.5.

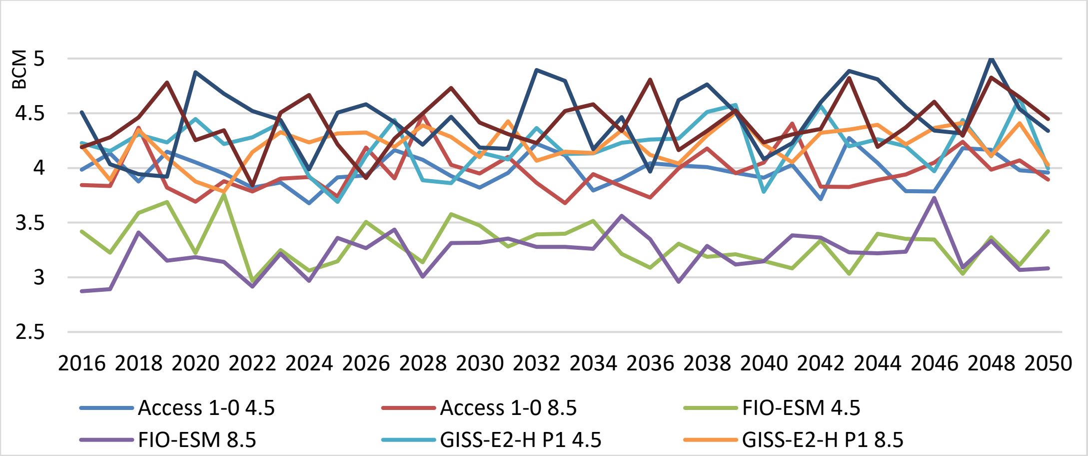


Figure 5.4 Rainfall volume change in the catchment according to CMIP5 models.

The result of climate change on evapotranspiration is shown in Figure 5.5, where the change will likely be in the range 258 - 450 MCM over the period 2016 - 2050 in comparison to 360 – 460 MCM for the period 1990 - 2015. The same models FIO-ESM RCP 8.5 and MIROC5 RCP 4.5 recorded the highest and lowest risk respectively. In addition, the general trend tends to decrease as in the rainfall result over the period 2016 – 2050.

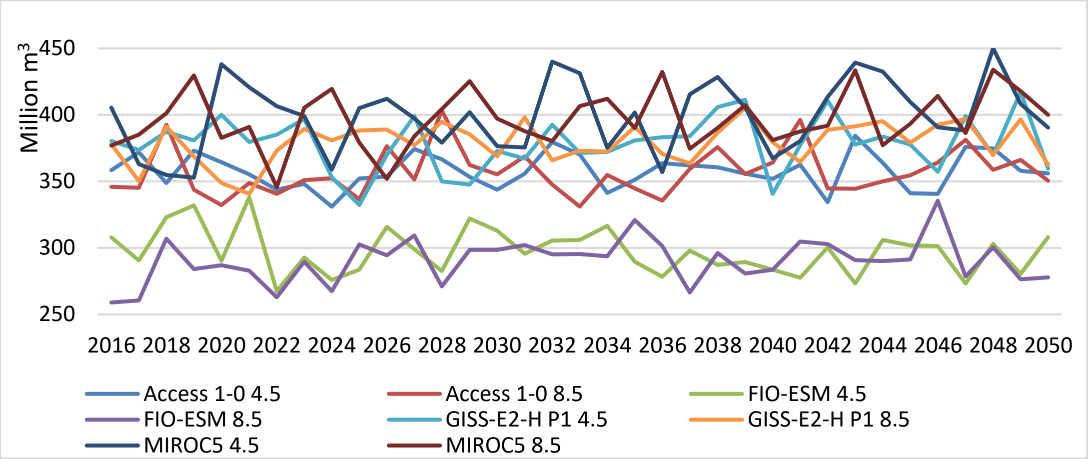


Figure 5.5 Evapotranspiration under CMIP5 models.

The results of surface runoff reports a remarkable downtrend due to the impact of climate change. This impact will likely be in the range 1.06 – 3.07 MCM over the period 2016 - 2050, while the period 1990 – 2015 recorded 2 – 3.24 MCM. According to Figure 5.6, the lowest and highest surface runoff recorded by models FIO-ESM RCP 8.5 and MIROC5 RCP 4.5 respectively. These uncertainty ranges and impact of climate change on rainfall, evapotranspiration, and runoff will influence water supply in the area.

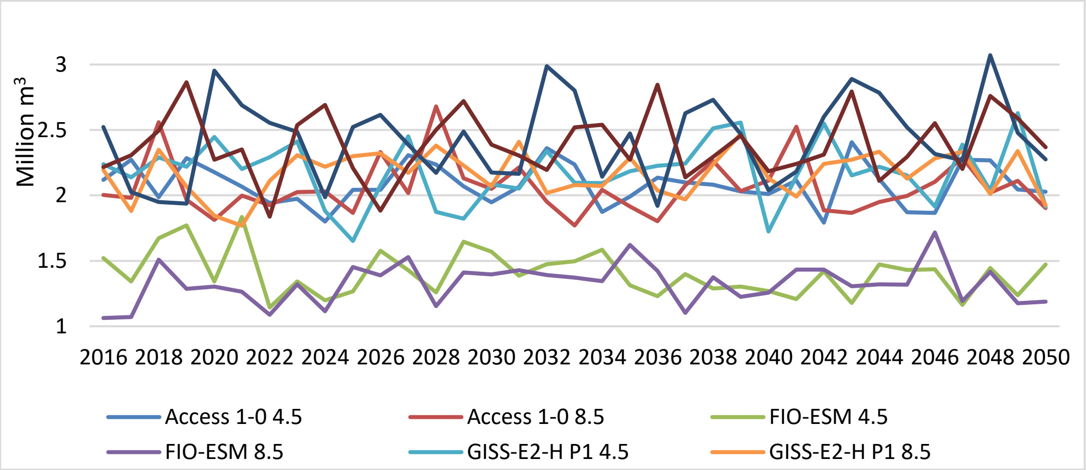


Figure 5.6 Runoff under CMIP5 models.

To evaluate the impact of climate change on water supply I assume the yearly outflow from HAD is 55.5 BCM, as per the water withdrawal from the HAD in 2015. The abstraction from shallow aquifer in delta and valley is 6.9 BCM as in 2015. In addition, abstraction from deep aquifer is 2.26 as reported in 2015, and the climate data for rainfall and temperature is changed inside the WEAP model with the data of climatic models to assess the difference in water supply. Figure 5.7 provides an overview of climate change risk on water supply in the study area over the period 2016 – 2050. The uncertainty range of this risk will likely be in the range -0.52 - -0.57 BCM according to the climate models results based on the variability of rainfall contribution in the catchment area. This means the climate change has limited impact on water supply in the study area due to the most freshwater coming from outside the study area, where the climate variability in the Nile basin plays the key role in water reaching to Egypt. Therefore, the study of impact of climate variability on water reaching the HADR is an urgent necessity in this study as a source of uncertainty.

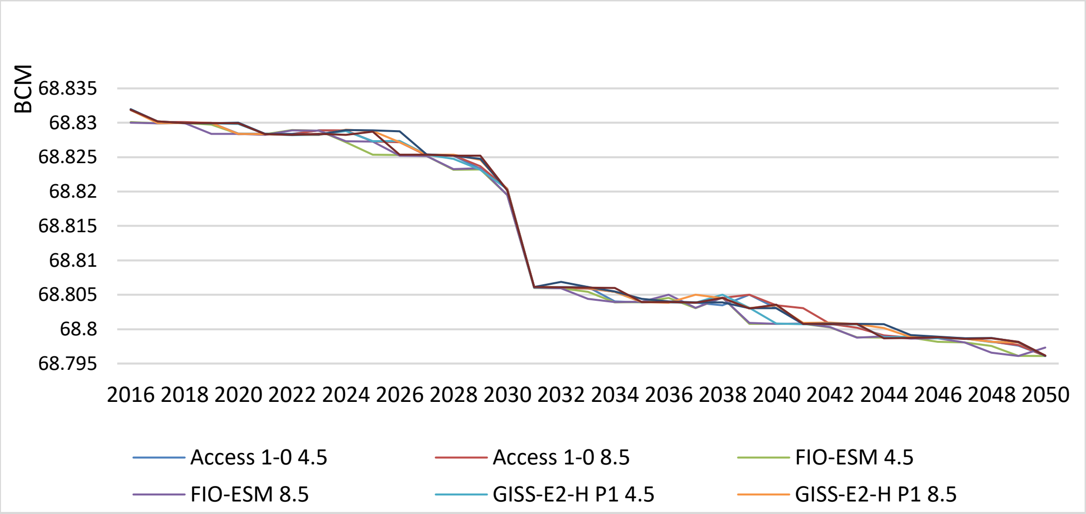


Figure 5.7 Water supply under CMIP5 models 2016 – 2050.

5.4.4 Uncertainty Linked to Climate Variability

In this research, one of the main challenges was how to assess uncertainty in the future Nile water reaching the HADR. As mentioned the Nile River provided Egypt with more than 85% from the total supply, where the average of inflow to Egypt at Dongola station is estimated by 71.23 BCM over the period 1965 – 2010. This amount is different from one year to another depending on the water year, from very dry to very wet. The climate variability in the Nile basin plays an important role in determination of the water year based on the rainfall amount on river branches feeding the Main Nile at Dongola station. To define the water year, the study depended on finding a relation and sensitivity between the amount of Nile’s water reaching Egypt at the Dongola Station and the rainfall on White Nile, Blue Nile, and Atbara River. Hence, the water year is defined based on the distance from the average of each station`s data. The results of the regression analysis and sensitivity index that were carried out on time series (1965-2010) for rainfall stations on rivers feeding the Nile River are presented in Table 5.6.

According to the analysis of rainfall time series over White Nile, Blue Nile, and Atbara River for the period 1965 - 2010, the rainfall change rates over the three sources are estimated to be +0.19 mm, -0.20 mm, and -0.31mm respectively. Overall, these changes led to a decrease in flow to Egypt by -0.11 BCM depending on the data of Dongola station over the period 1965 - 2010. This may indicate that the future of climate over upstream tends to decrease slightly, but it may still be at a normal level.

Obviously, there is a significant relationship between the inflow to Egypt at Dongola station, outflow from HAD, and the climate variability from the perspective of rainfall over the White Nile, Blue Nile, and Atbara river, where Pearson`s R = 0.34, 0.38, 0.50, 0.38 and the P value < 0.05 = 0.0219, 0.0108, 0.0004, and 0.0098, respectively as shown in Table 5.6. In addition, there is a reasonable sensitivity between rainfall on the Nile basin and inflow at Dongola. Figure 5.8 presents the annual variability of rainfall on the Nile basin, Dongola Station Inflow, and Outflow from HAD over the period 1965 - 2010.

Table 5.6 Result of regression analysis and sensitivity index for Inflow and rainfall on Nile basin.

Station	Period	Average	Pearson`s R	SI	P-value <0.05
Dongola inflow	1965 - 2010	71.23 BCM			
Outflow from HAD	1965 - 2010	58.4 BCM	0.34	0.24	0.0219
Rainfall over White Nile	1965 - 2010	755.8 mm	0.38	-0.58	0.0108
Rainfall over Blue Nile	1965 - 2010	1284.7 mm	0.50	0.54	0.0004
Rainfall over Atbara River	1965 - 2010	244.36 mm	0.38	0.35	0.009

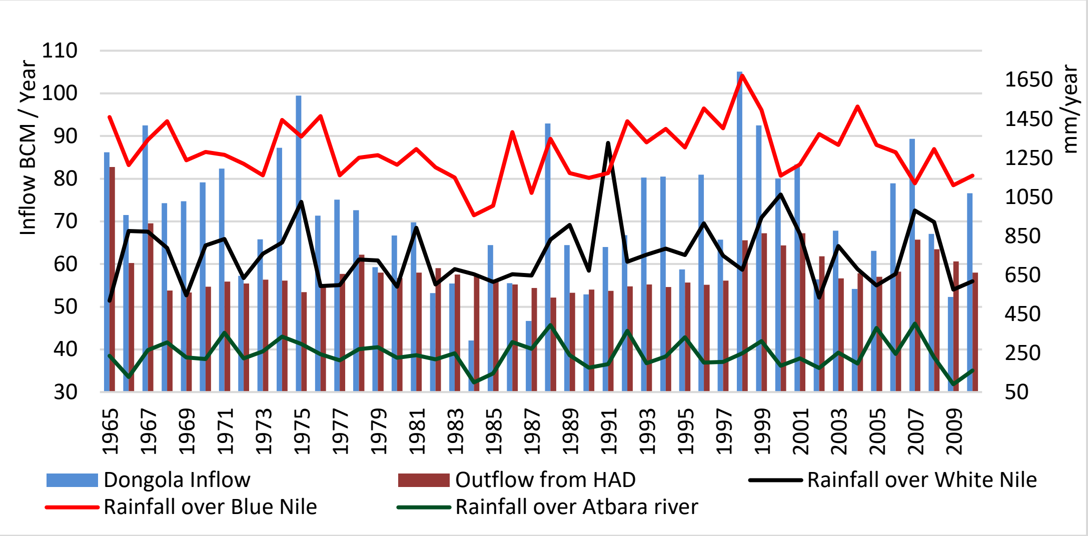


Figure 5.8 Annual variability of rainfall on Nile basin, Dongola station inflow, and outflow from HAD.

According to the significant sensitivity between these drivers, the study can extract the wet and dry years depending on the average of inflow over the period 1965 – 2015. For instance, the average of inflow at Dongola is 71.97 BCM reported as a normal year so equals 100%, with the lowest and highest value at 44 and 99 BCM respectively. Hence, I divided the time series upon to the percentage of 50%, 75%, 100%, 125%, and 150% to indicate the very dry, dry, normal, wet, and very wet year subsequently. The water year type and value for inflow to Egypt at Dongola station, outflow from HAD, and the rainfall over the White Nile, Blue Nile, and Atbara River is given in Table 5.7 and Figure 5.9. Depending on the previous regression and sensitivity analysis and water year method, it can be noted that a high uncertainty range in the rainfall over the Nile basin leads to uncertainty in water reaching Egypt at Dongola station. For example, the variation range is estimated to be ± 95 mm from the average rainfall over White Nile, ± 160 mm from the average over Blue Nile, and ± 30 mm from the average over Atbara River, then the uncertainty range in water amount reaching Egypt will likely be ± 27 BCM from the average of Dongola station. This high uncertainty's range is due to the high variability in rainfall over the Nile basin.

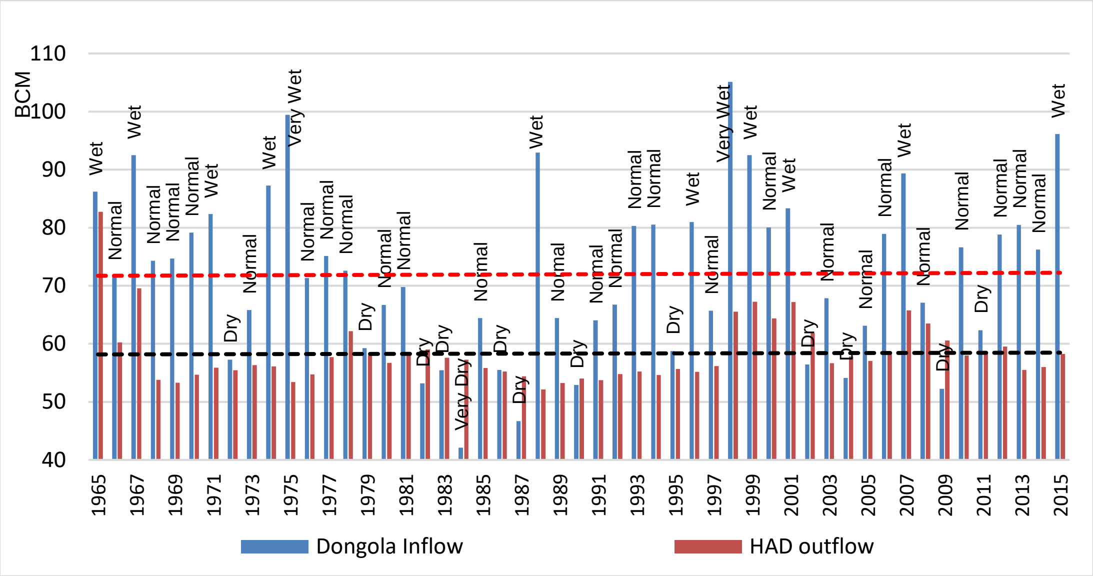


Figure 5.9 Annual variability of water year Egypt`s inflow and outflow depending on the average of the period 1965 – 2015.

Table 5.7 Summary of the water year type and value variability for all drivers.

Water Year Type	Dongola Inflow (BCM)	Selected Value for Model	HAD Outflow (BCM)	Selected Value for Model	Rainfall over White Nile (mm)	Rainfall over Blue Nile (mm)	Rainfall over Atbara River (mm)
Average	71.97		57.90		755.87	1284.72	244.36
Very Dry (50%)	<44.9	44	<43	43	<566	<963	<183.27
Dry (75%)	45 - 62.9	53	43 - 50.9	47	566 - 660.9	963.1 - 1124	183.27 - 213.7
Normal (100%)	63 - 80.9	71	51 - 57.9	55.5	661 - 755.9	1124.1 - 1284.7	213.8 - 244.36
Wet (125%)	81 - 98.9	89	58 - 65	61.5	756 - 850.9	1284.8 - 1445.28	244.4 - 274.9
Very Wet (150%)	> 99	99	>65	67	> 850.9	> 1445.28	> 274.9

Finally, every year in the WEAP model can be defined as normal, wet, very wet, dry or very dry. Different scenarios can then alter the chosen sequence of dry and wet years to assess the impact of natural variation in the Nile basin on the water system in Egypt.

The result of this climate variability impact assessment (as different sequences method) on the water system in the study area is illustrated in Figure 5.10. The different sequences method assumes that the future of climate variability will be like the current situation, which will differ between dry, normal wet and very wet years. The result indicates the total water supply for Egypt for 2016 – 2050 will likely vary in the range 69.8 – 80.2 BCM. The gap between demand and supply will likely be in the range 5 – 15.5 BCM if water demand is steady at 85 BCM. The HADR volume will likely be varied between 41.2 – 115.9 BCM and it is observed the drought period may occur over the years 2035 – 2040 where the inflow to Egypt will be under the average 71 BCM that leads to the volume of HADR will fluctuate between 41 – 57 BCM.

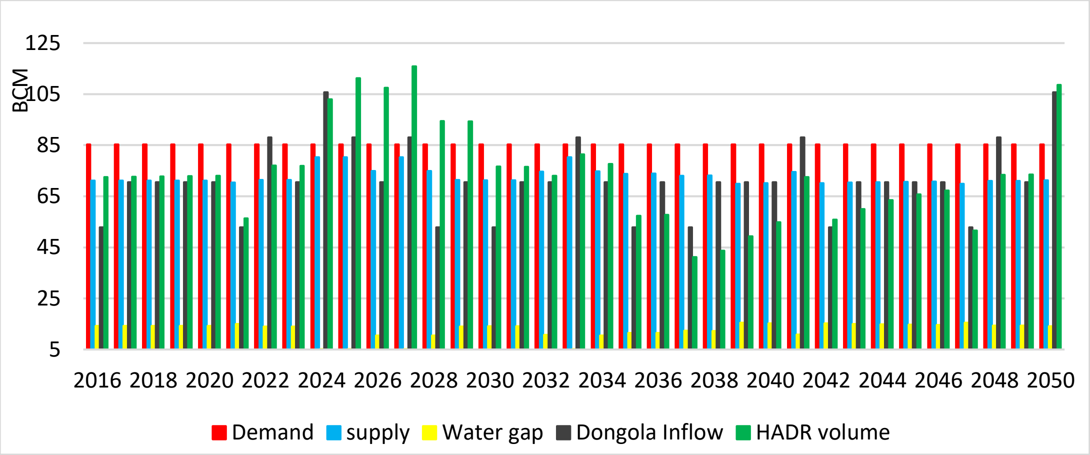


Figure 5.10 Water demand and supply under climate variability (Different Sequence).

Figure 5.11 presents the result of climate variability impact as very wet years sequence on the water system in the study area. The very wet years sequence assumes that the future of climate variability in the Nile basin will be very wet. The result reports the total water supply for Egypt during the period 2016 – 2050 will likely be varied in the range 80.1 – 80.4 BCM. The water gap between demand and supply will likely be in the range 4.9 - 5.2 BCM (demand steady at 85 BCM). This gap can be bridged easily due to the water surplus in the HADR, as the volume of HADR will likely vary between 116 - 287 BCM. The huge amount of water in the reservoir can discharge to the Toshka depression in the western desert (Chapter 4, Section 4.3.6.3, HADR Operation Rules). The probability of the very wet years sequence occurring is however is very low due to the climate variability represented in the relative decrease of rainfall amount in the basin.

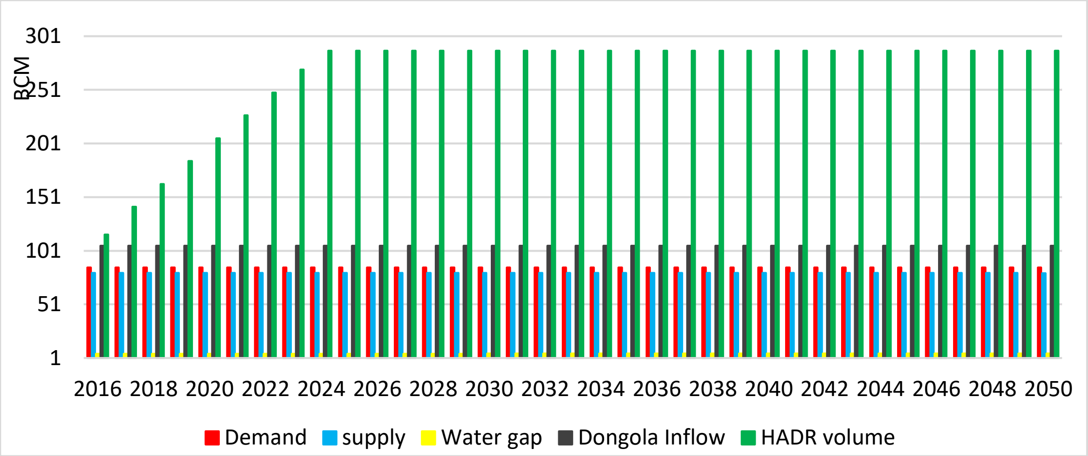


Figure 5.11 water demand and supply under climate variability (Very wet Years Sequence).

The impact of wet years sequence on the water system in the study area is shown in Figure 5.12. The wet years sequence supposes that the future of climate variability in the Nile basin will be wet. The result records the total water supply for Egypt during the period 2016 – 2050 to be varied in the range 74.7 – 74.9 BCM. The water gap between demand and supply will likely be in the range 10.3 – 10.6 BCM (demand steady at 85 BCM). This gap can also overcome the overflow water in HADR, where the volume of HADR will increase to vary between 103 - 287 BCM.

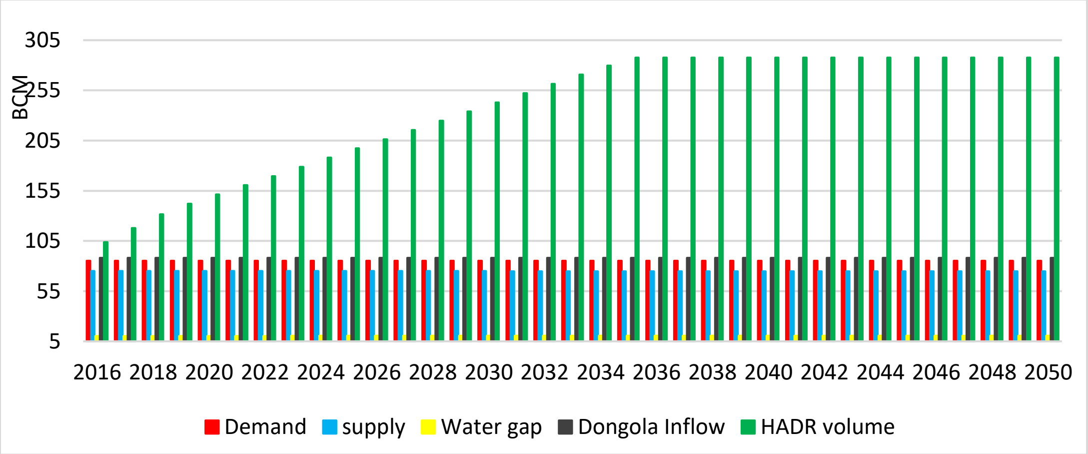


Figure 5.12 water demand and supply under climate variability (Wet Years Sequence).

For the normal year's sequence, the result in Figure 5.13 shows the total water supply for Egypt will vary in the range 71.2 – 71.5 BCM over the period 2016 – 2050. The water deficit will likely be in the range 13.8 – 14.1 BCM (demand steady at 85 BCM). The HADR volume will decrease to between 84.2 – 89.8 BCM. The probability of the normal years sequence occurring is high because it is very close to the current situation in the study area and the Nile basin.

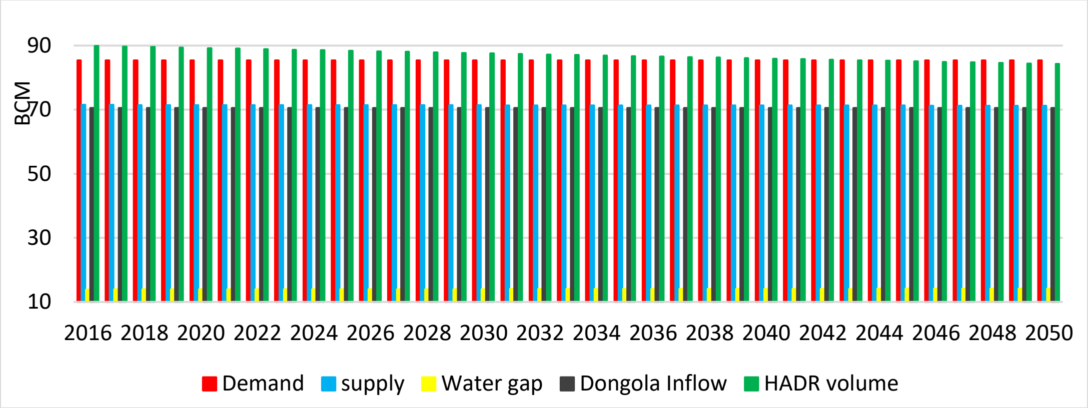


Figure 5.13 Water demand and supply under climate variability (Normal Years Sequence).

If the climate in the Nile basin tends to be dry, the situation will get worse. The result in Figure 5.14 confirms that water shortage will increase to vary between 24.5 – 26.8 BCM due to the clear reduction in water supply that will vary between 58.5 – 60.7 BCM during the period 2016 – 2050. This will cause a serious impact on Egypt and may stop the turbines of the HAD, if the volume reach 36 BCM (dead level of HAD is 31.6 BCM).

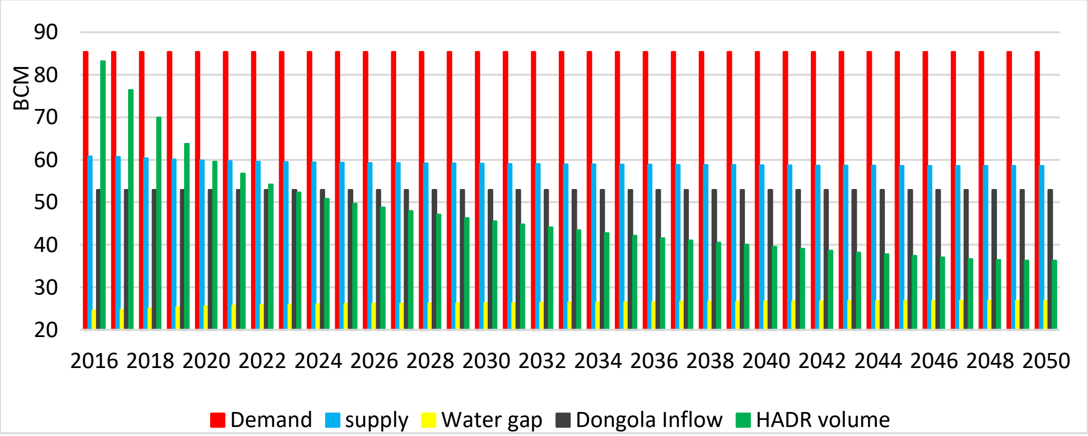


Figure 5.14 Water demand and supply under climate variability (Dry Years Sequence).

If the worst comes to the worst, the very dry years sequence will cause a major risk to Egypt. Figure 5.15 shows a dramatic change in water supply, in the range 43.9 – 56.4 BCM. This will cause an enormous water gap of between 28.9 – 41.4 BCM even after exhausting the HADR water and reaching the dead limit. The probability of the very dry years sequence is very low because this needs a dramatic change in the climate of the Nile basin over a short time.

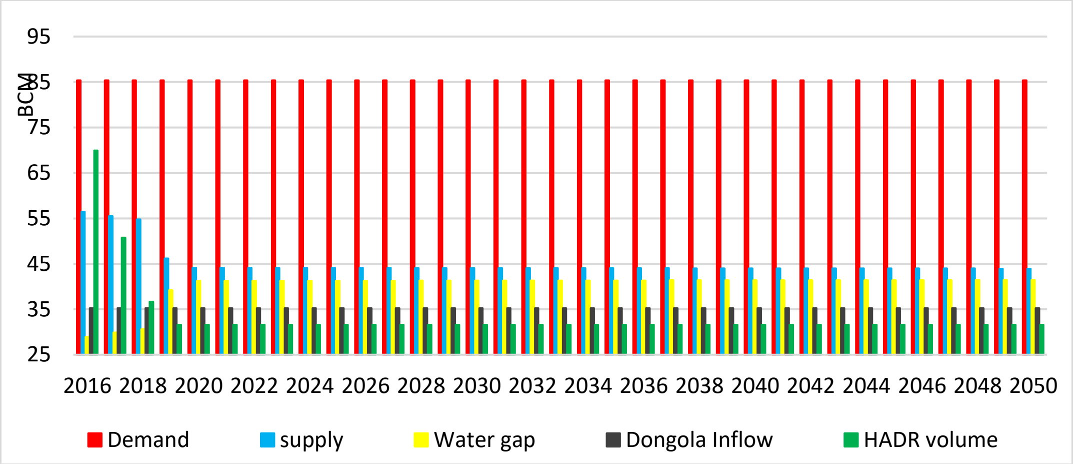


Figure 5.15 Water demand and supply under climate variability (Very Dry Years Sequence).

According to the previous results, there is high uncertainty in the volume of water reaching Egypt due to the climate variability in the Nile basin. This uncertainty was handled by assessing their risk on Egyptian water system using the water year method in WEAP. Although WEAP is an effective tool to address this problem, the study suggest more studies are required that should include more rainfall stations and more advanced analysis to evaluate future uncertainty in the Nile basin.

5.4.5 Uncertainty Linked to the Great Ethiopian Renaissance Dam

The human interventions in the Nile basin, such as building dams or water collection projects from swamps may reduce or increase the water supply to Egypt. The Great Ethiopian Renaissance Dam is discussed as it is the most serious problem currently facing Egyptian water security. Depending on reviewing the IPoE report 2013 and the negotiations since 2010, it is clear that the technical, scientific, and political aspects of GERD are complex and surrounded by considerable uncertainty. Uncertainty with the GERD exist with respect to filling time of the 74 BCM reservoir, with short periods posing greatest risk to Egypt.

In this study, I considered fill times of 3, 7, and 10 years. The WEAP model is run with different sequences of climate to evaluate the risk in the case of the HADR outflow remaining steady at 58 BCM/year, and evaluating the risk after the filling of reservoir by assuming that Ethiopia will release only 55.5 BCM/year for Egypt. These assumptions are extracted from the negotiations review between the three countries, where the downstream countries will be subject to the will and whim of the upstream countries particularly after Ethiopia rejected a water sharing proposal brokered by the USA (IPoE, 2013; DoPs, 2015; Widakuswara, 2020; Mabera et al., 2020; Helal, 2020) (Section 2.3.7, Chapter 2). The result of this method is illustrated in Table 5.8. For example, when the water year is normal, this means the inflow will be 71 BCM. If the GERD's reservoir was filled over 3, 7, 10 years, this means the water reach Egypt will be 46.34, 60.43, 63.6 BCM respectively.

Table 5.8 Values used in WEAP to assess the risk from the GERD on Egypt.

Water Year type	**Selected Value**	**Inflow to Egypt during the filling period of the GERD**		
		Three Years	*Seven Years*	*Ten Years*
Very Dry	*44*	*19.34*	*33.43*	*36.6*
Dry	*53*	*28.34*	*42.43*	*45.6*
Normal	*71*	*46.34*	*60.43*	*63.6*
Wet	*88*	*63.34*	*77.43*	*80.6*
Very Wet	*99*	*74.334*	*88.43*	*91.6*
Egypt withdrawal	*58*	*58*	*58*	*58*
Limited Inflow to Egypt	*55.5 (on a permanent basis)*			

If the GERD reservoir fills over three years, Egypt will face a disastrous water deficit ranging from 16.2 to 56.8 BCM according to the climate variability in the Nile basin between very wet and very dry years. The highest water shortage is estimated to be 56.8 BCM in the third year of filling the GERD reservoir in case of sequencing the very dry and dry years. In this case, Egypt cannot handle this gap by any means, because the HADR volume will be under the inactive zone at 31.6 BCM. Even in the very wet years' sequence, the water deficit will be 16.2 BCM, but Egypt can treat this deficit because the HADR volume will reach 137 BCM as shown in Figure 5.16.

If filling takes seven years, the water gap will likely be in the range 16.2 – 43 BCM and the reservoir volume will range from 92.8 to 240.4 BCM depending on the climate conditions in the Nile basin that control in the water year nature from very wet to very dry. From the beginning of 2023, Egypt cannot treat the water shortage in case of the dry and very dry years' sequence. The water gap will increase dramatically to be about 43 BCM in 2023 if the very dry sequence occurs. In 2024, the water gap is estimated to be 43 and 34 BCM for very dry and dry years respectively. For the sequence of normal, wet and very wet years, this situation will be better and Egypt can overcome the deficit.

The water gap is still a problem even if the GERD reservoir fills over ten years, where the deficit will increase to 38 BCM in 2023 for the very dry years' sequence. The range of water gap over the ten years will be between 16 -39 BCM. It can be concluded that the impact of GERD on water supply to Egypt will be catastrophic if Egypt experiences a drought period (dry or very dry years). Filling over ten years is considered in this study and more appropriate than the three or seven years, given the risk of drought, to keep Egypt in a safe position that can bridge the water gap.

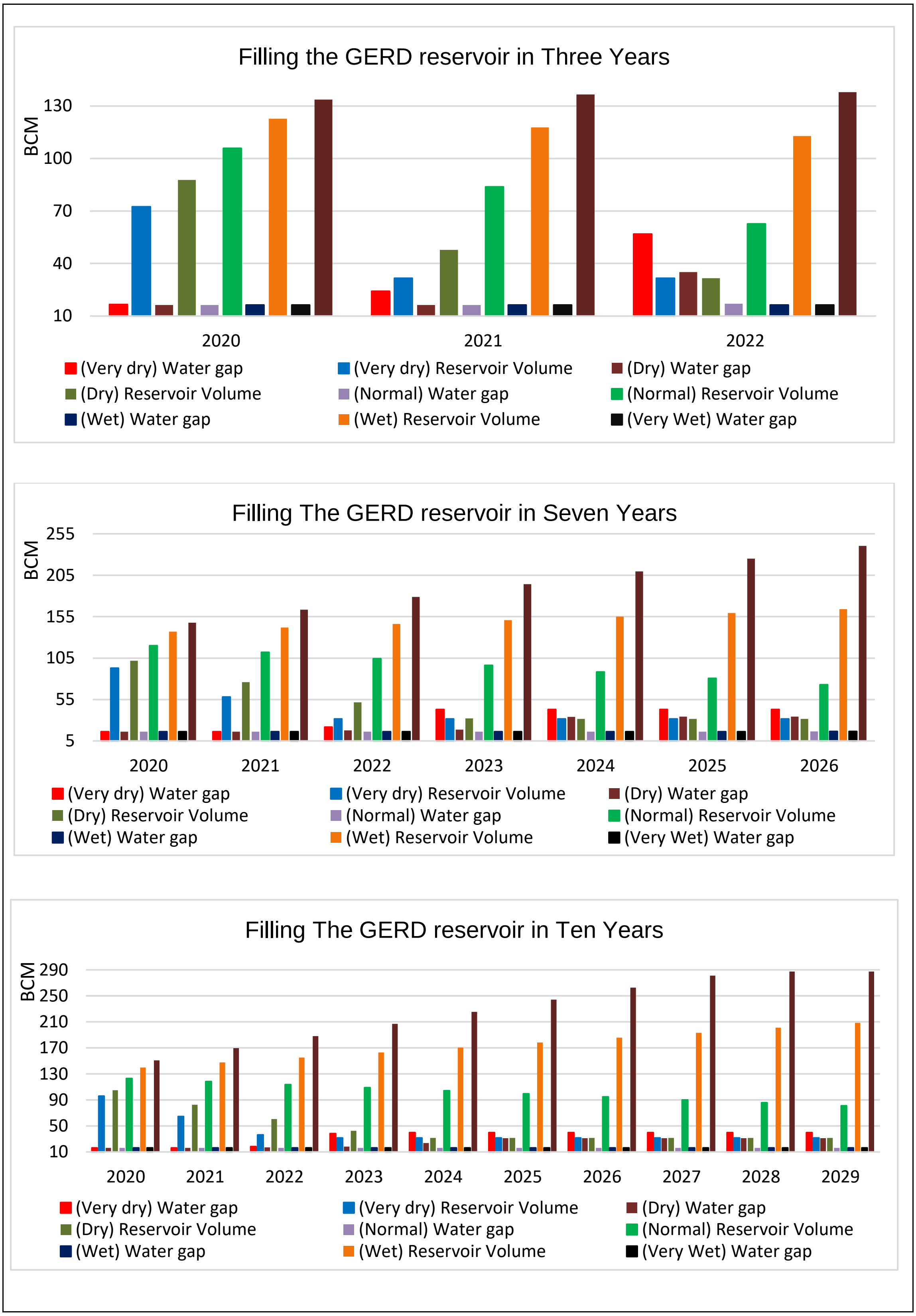


Figure 5.16 Impact of GERD fill duration on HADR volume and Egypt's water deficit.

The study finds that the risk of GERD is not only related to the GERD fill period but also the Ethiopian policy of water discharge from the GERD on a permanent basis. This policy that may be imposed on the downstream countries involves unknown uncertainty and is a source of current transboundary conflict. Therefore, the study assumes that volume reaching Egypt is only its annual share (55.5 BCM) on a permanent basis. Hence, the WEAP model is run to quantify the risk of this policy to water supply in Egypt. The result confirms that the role of the High Dam in Egypt will vanish, as there will be no surplus of water for storage. Additionally, the annual water gap will be about 21.6 BCM as shown in Figure 5.17. For this case, Egypt will not be able to cover this gap due to the depletion of the strategic water reserve in the High Dam Lake. These results agree with Wolters (2016), who confirmed that Egypt will suffer from severe water shortages, not only as a result of climate change but also because of the development of water resources upstream in the Nile Basin.

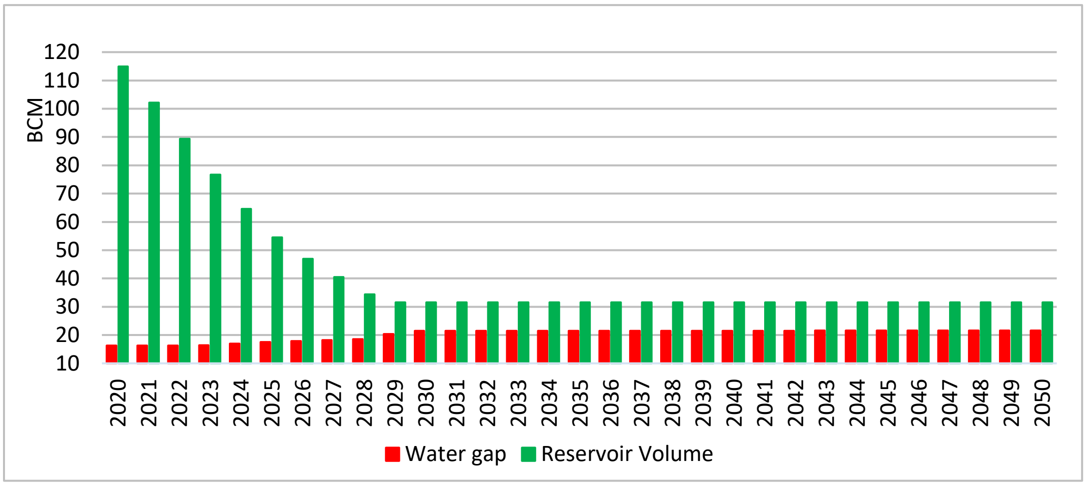


Figure 5.17 Impact of GERD on HADR volume and Egypt's water deficit by assuming that Ethiopia will release only 55.5 BCM/year for Egypt (on a permanent basis).

There is great uncertainty and complexity around the impact of GERD on Egypt. There needs to be an advanced agreement about the rules of filling the reservoir and operating rules for periods of drought that includes detailed measures to mitigate impacts on downstream countries. The present study recommends that the filling of GERD should be achieved during the wet and very-wet years only to avoid affecting downstream countries. In addition, Egypt should focus on increasing the water consumption efficiency and more rational and integrated water management during the storage period and many studies should be undertaken to confirm or deny the risk.

5.4.6 Uncertainty Linked to Population Growth

The uncertainty associated with population growth is represented in the population projections, which play a key role as a basic tool for a wide range of decision-makers and planners. For example, the CAPMAS in Egypt projected (in 2006) the population of Egypt to be 92.6 Million people in 2020 but Egypt's population actually reached 100 Million in that year (CAPMAS, 2020). This uncertainty is due to the unexpected increase in the fertility rate from 3 to 3.5 and not considering other affecting parameters when making projections such as migration factor.

The study explores the likelihood risk of population growth on the Egyptian water system. The uncertainty range of population growth is estimated from the projections of CAPMAS and low, medium, high variants of United Nations to be in the range of 1.3 – 1.85 % over the period 2016 – 2050 as presented in Table 5.9. Figure 5.18 reports a significant increase in population in 2050 to reach 145.6, 159.9, 174.7, 154 Million people covered by low, medium, high variants of UN and CAPMAS respectively (United Nations, 2019; CAPMAS, 2020). It is notable that CAPMAS projections ignore migration and for that, the study used the United Nations projections beside CAPMAS projection to handle this point.

Table 5.9 Uncertainty range of population growth rate used in this study.

	Egypt Projection (CAPMAS)	UN Low Variant	UN Medium Variant	UN High Variant
Growth Rate % (2016 – 2050)	1.54	1.30	1.58	1.85

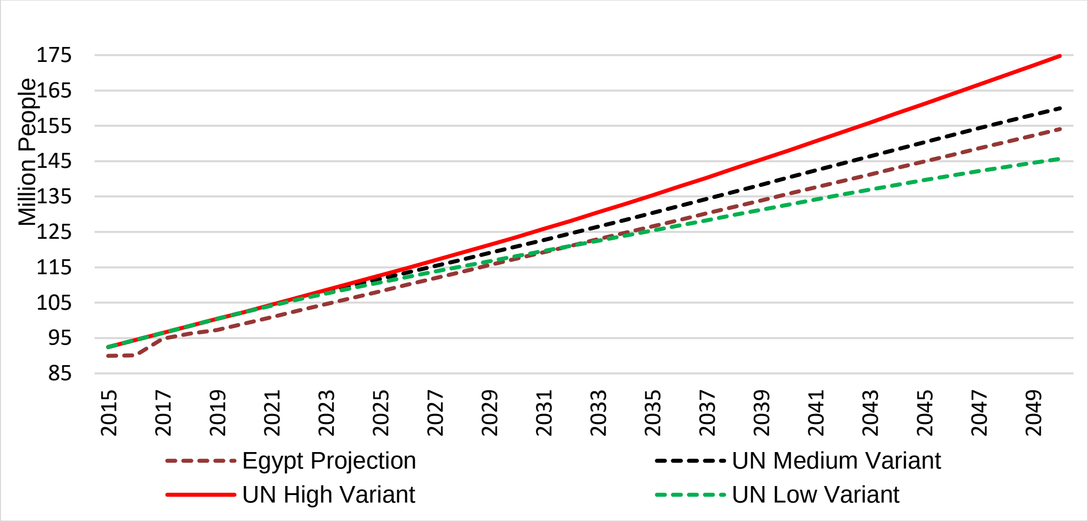


Figure 5.18 Population projections for Egypt 2015 – 2050.

The four projections over the period 2016 – 2050 are implemented in WEAP to evaluate the water risk. The WEAP model was operated under the assumptions of the water withdrawal amount from the HAD is 58 BCM and water consumption per capita is 87.6 m^3/year as in 2015. Results show that population growth presents a serious risk. There is a critical increase in the water demand under different population projections estimated by 91.3, 93, 94.7, and 92.7 BCM for low, medium, high variants of UN and CAPMAS projections in 2050 respectively as presented in Figure 5.19. This means that Egypt will likely face a dramatic increase in water demand; about 9 BCM in 2050 with uncertainty range ± 3.4 BCM.

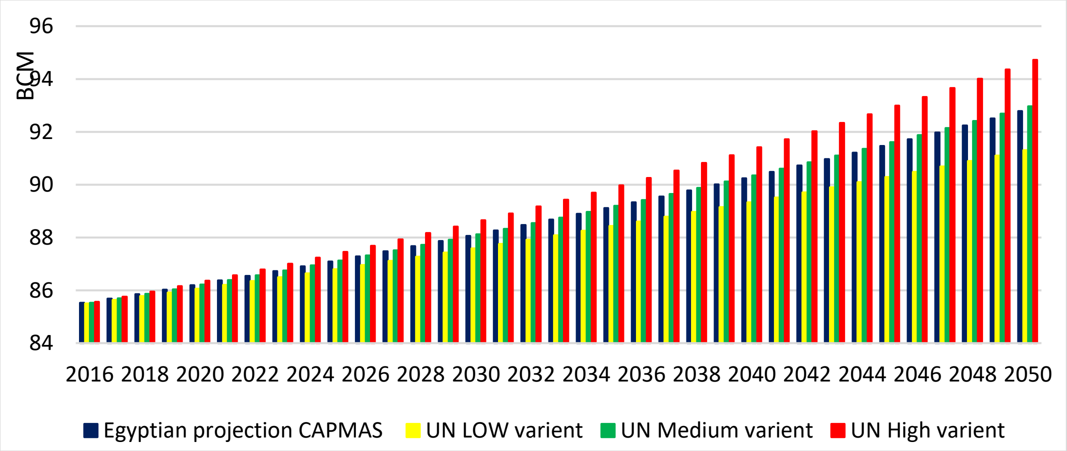


Figure 5.19 Water demand under different population projections 2016 - 2050.

Figure 5.20 reports that the water deficit due to population growth will increase to be 19.74, 21.4, 23.14, and 21.2 BCM in 2050 over low, medium, and high variants of the UN and CAPMAS projections in 2050, respectively.

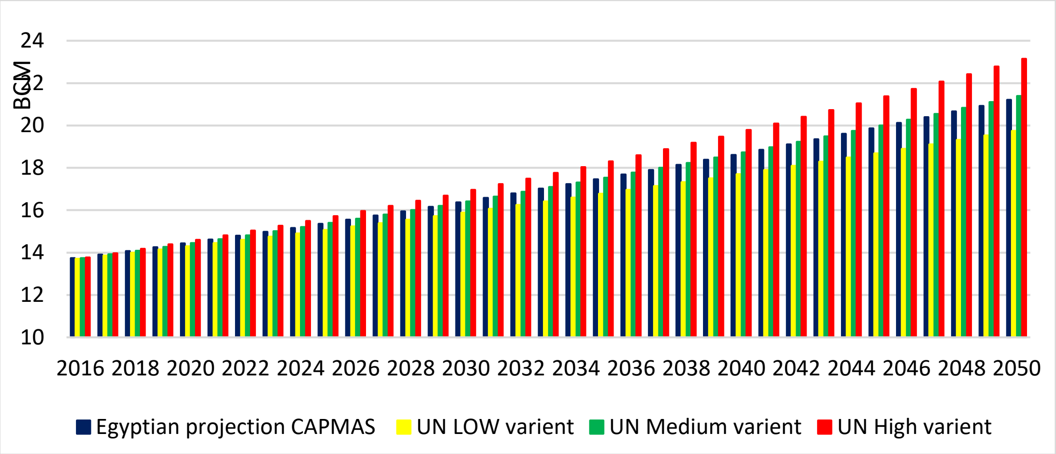


Figure 5.20 Water gap under different population projections 2016 - 2050.

5.4.7 Uncertainty Linked to Land Use Change

Predicting future water demand for agriculture, population, and industry is fraught with uncertainty. For dealing with uncertainties linked to the land use change in the future, projections of agriculture areas, and industrial units' numbers are extracted in Excel for forecasting. The specific forecasting analysis used is Exponential Triple Smoothing (ETS) to extract the low, medium, and high probabilities. The confidence level is set to 95%. The forecasting is implemented depending on the historical data of agriculture, and industry. In addition, future plans of the Egyptian Ministry of Water, Ministry of Agriculture and Land Reclamation, and the Egyptian Ministry of Industry are used for developing theses drivers. For Population projections, the UN projections are used.

The probabilities of growth rate for agricultural area, population, and industrial units of the generated projections were included in the WEAP model to investigate their risk in the future. These growth rates are illustrated in Table 5.10.

Table 5.10 growth rate projections of land use change.

Change Rate / Factor	Low %	Medium %	High %
Agriculture lands	0.13	0.65	1.10
population	1.30	1.58	1.85
Industrial units	0.63	1.83	2.69

The resulting projections of the agricultural area and industrial units are shown in Figures 5.21 and 5.22. The agricultural area will likely increase to be 9.5, 11.3, and 13.06 Million feddans in 2050 over low, medium, and high ranges respectively. This may be attributed to the ambitious program for reclamation to bridge the food gap. The industry demand of water represents high uncertainty because of the inaccurate observed data about the number of industrial units. This inaccuracy is because many industrial units are not registered in the ministry and operate in secret. According to the resulting projections, the industrial units are estimated to be 9457, 14149, and18840 units in 2050 over low, medium, and high ranges respectively.

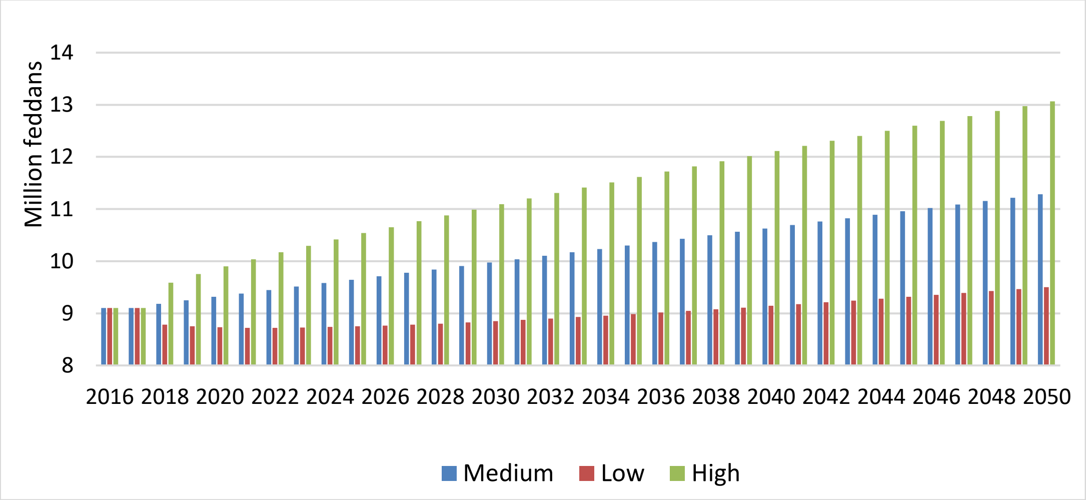


Figure 5.21 Projections of agriculture lands (2016 - 2050).

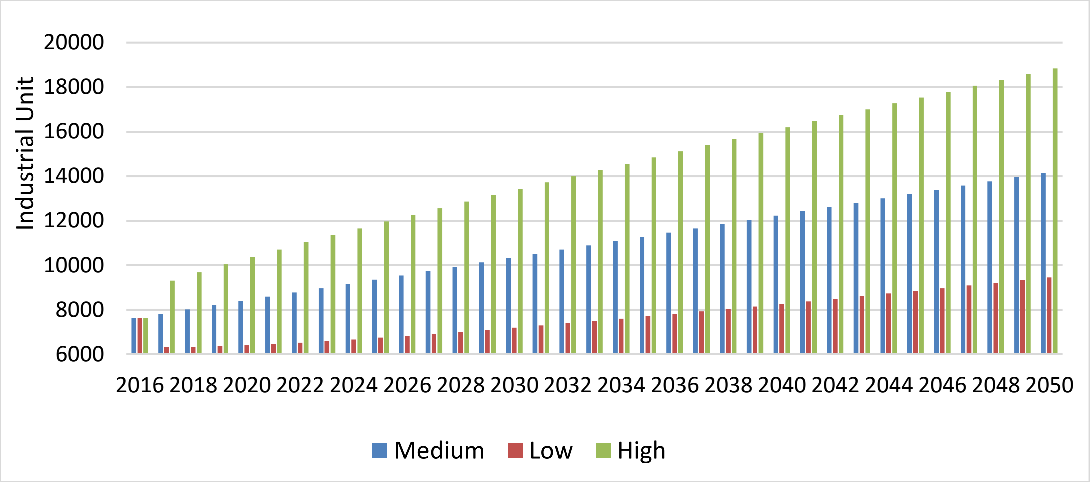


Figure 5.22 Projections of industrial units (2016 - 2050).

The impact of land use change on the water system indicates high risk, where Egypt will face catastrophic increase in water demand in 2050 as shown in Figure 5.23. The water demand is estimated at 95.5 BCM, 113.5 BCM, and 131.9 BCM over low, medium, high ranges respectively with uncertainty range ± 36.4 BCM. Agriculture has the largest share of water demand as a result of land-use change, where irrigation mainly consumes the bulk of the available water supplies. This agrees with Abu-Zeid (1992), NWRP (2005), and MWRI (2010).

The water shortage due to land-use change will increase in 2050 to be 23.9 BCM, 41.96 BCM, and 60.23 BCM over low, medium, high ranges subsequently as presented in Figure 5.24. These results are extracted under current conditions, where the water withdrawal from the HAD is constant at 58 BCM, water consumption per capita is 87.6 m^3, water consumption rate per Fadden is 4700 m^3, and water consumption rate for industry is 200,000 m^3 per industrial unit. If the high projection happens, Egypt cannot bridge the water gap from the beginning of 2030, which will reach 30 BCM.

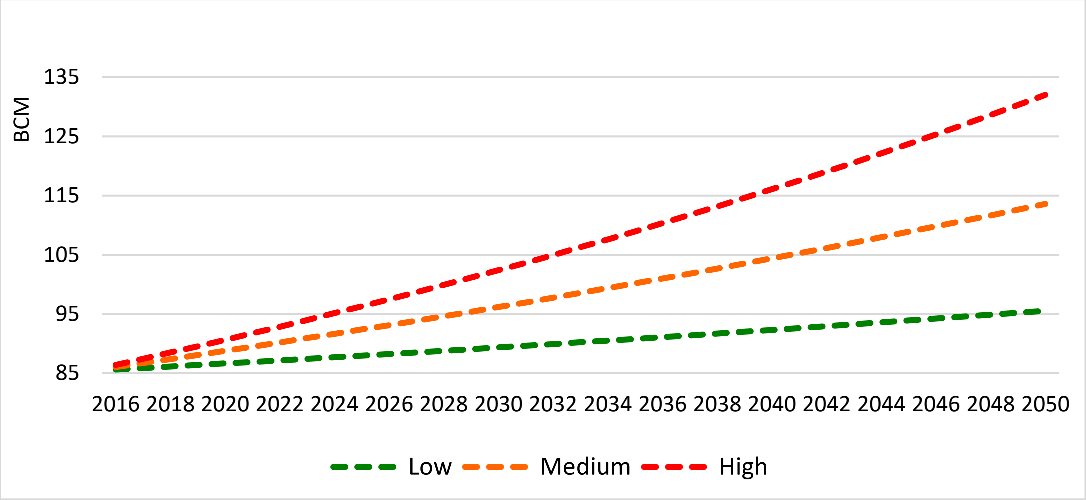


Figure 5.23 Water demand under different Land use change projections 2016 - 2050.

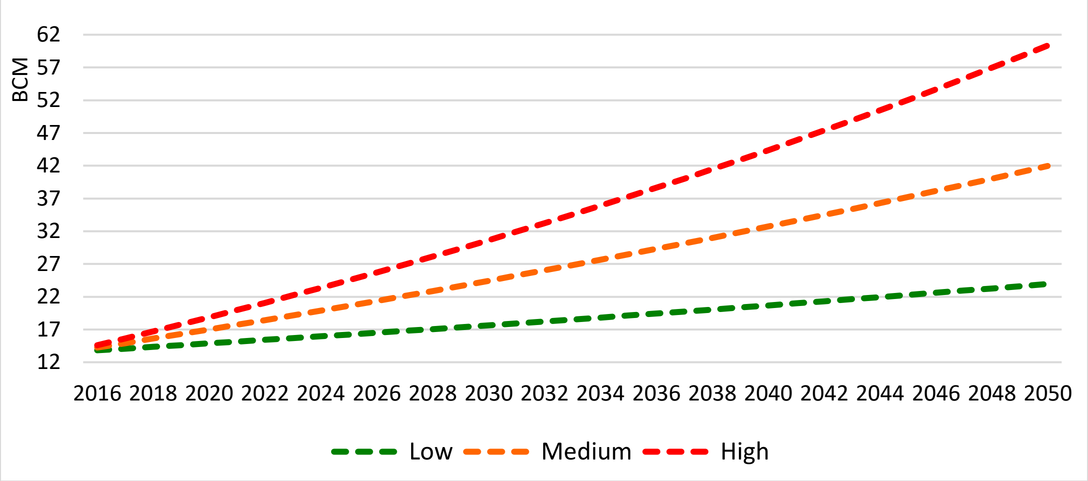


Figure 5.24 Water gap under different Land use change projections 2016 - 2050.

5.5 Conclusions

In this chapter, I have presented a framework for assessing the impacts of uncertainty factors on Egypt’s water deficit, water demand, and supply over the period 2016 – 2050. The uncertainty factors included climate change over Egypt, climate variability in the Nile basin, Grand Ethiopian Renaissance Dam impacts, population growth, and land use change. The WEAP model was used to represent the hydrology and water operations in Egypt over the period 1990 – 2015 to simulate the impacts of uncertain factors on future water demand and supply over the period of 2016 – 2050. The results of this study support water policy makers by shaping and quantifying the risk produced by these uncertainty factors. The conclusions are detailed below.

In 2015, water demand was modelled at 80.2 BCM divided into agriculture, domestic, industry, whilst the observed value is 80.45. This result is accepted because the NSE = 0.92 and PBIAS = +2.33. Ministry of Water reported water supply of 59 BCM in 2015 while the result of WEAP model found the water supply about 63.8 BCM. This discrepancy is due to the changed outflow through the High Dam and rainfall underestimation, and that shallow groundwater is considered as a non-conventional source in the model. This difference between water demand and supply leads to water deficit (unmet demand), where estimated at 16.4 BCM in 2015. Egypt bridges this shortage by non-conventional resources such as desalination, shallow groundwater, and water reuse.

The WEAP model estimated rainwater in the catchment area to be about 3.9 – 5.1 BCM based on the rainfall data of seven stations. While Egypt reported the rainwater amount at about 1.3 BCM without any change over the period 1990 – 2015 and there is an uncertainty around this number because there are no adequate studies to calculate rainwater in Egypt accurately. However, the mean temperature change for the period 2016-2050 for the four models will likely be in the range -1.7 to 0.9 °C. In contrast, the rainfall change for the period 2016-2050 for the four models presented high uncertainty in the future, where the change tends to decrease and will likely be in the range -1.6 to -8.9 mm. The uncertainty range of rainfall volume will likely be 2.8 – 5 BCM over the period 2016 – 2050 in comparison to 3.9 – 5.1 BCM for the period of 1990-2015. The uncertainty range of this risk on water supply will likely be in the range -0.52 - -0.57 BCM over the period 2016 – 2050 according to the climate models results. While the uncertainty range in water amount reaching Egypt will likely be ± 27 BCM from the average of Dongola station. This high uncertainty’s range is due to the high variability in rainfall over the Nile basin.

Although climate change has global impacts, it has limited effects on water supply within the study area because the large amount of freshwater is coming from outside the study area. The impact of greatest interest to the Egyptian water system will be climate variability over the Nile's upstream, population growth, land-use change, and the GERD. These uncertainty factors result in direct consequences to the Egyptian water system. Uncertainty about climate variability over the Nile’s upstream sources affects the flow of Nile water into Egypt, which in turn affects its main reservoir in Nasser Lake, as it influences the ministry's policy on the amount of water that must be released from the reservoir through the gates of the Aswan High Dam.

There is a significant increase in population in 2050 to reach 145.6, 159.9, 174.7, and 154 Million people covered by low, medium, high variants of UN and CAPMAS respectively. In the case of water withdrawal from the HAD of 58 BCM and water consumption per capita at 87.6 m^3/year, a critical increase may occur in Egypt’s water demand, estimated at 91.3, 93, 94.7, and 92.7 BCM for low, medium, high variants of UN and CAPMAS population projections respectively, in 2050. In addition, the water deficit due to population growth will increase to be 19.74, 21.4, 23.14, and 21.2 BCM in 2050 over low, medium, high variants of UN and CAPMAS projections in 2050.

The GERD has the ability to drastically change Egypt’s water supply, where Egypt will suffer from water shortage as follows: if the filling period achieved over three years, water deficit will likely be 16.2- 56.8 BCM, 16.2 – 43 BCM over seven years, and 16 -39 BCM over ten years, varying between very wet and very dry years. Although this study considered ten years as an appropriate filling period to keep Egypt in a safe position, it is not possible to determine the appropriate filling period because it should be achieved based on the state of flooding each year. The present study reported that the risk of the GERD is not only related to the period of filling the reservoir, but also the Ethiopian policy of water discharge by the GERD after the filling period, which is uncertain.

Using Exponential Triple Smoothing (ETS) forecasting analysis, the agricultural area will likely increase to be 9.5, 11.3, and13.06 Million feddans in 2050 over low, medium, and high ranges respectively. In addition, the industrial units will likely be 9457, 14149, and18840 units in 2050 over low, medium, and high ranges subsequently. Therefore, Egypt’s water demand is estimated by 95.5 BCM, 113.5 BCM, and 131.9 BCM over low, medium, high ranges respectively with uncertainty range ± 36.4 BCM. Water shortage due to these changes will increase in 2050 to be 23.9 BCM, 41.96 BCM, and 60.23 BCM over low, medium, high ranges subsequently.

With the use of the WEAP model, it can be confirmed that the water shortage will rise with acuity in Egypt as long as mechanisms of management are not in place to retain the extreme population growth, rapid development, GERD crisis, and climate change and variability. Decision-makers and planners in Egypt face multiple crises, which need a specific and certain water policy that takes into account the effects of future uncertain factors. This research has a significant importance for water managers for planning Egypt's water resources as well as other stakeholders, taking into account the time dimension of socio-economic conditions, climate change projections, and political and development changes in the Nile basin countries. In addition, the proposed methodology of using the exploratory approach and simulation model WEAP serves as a useful tool to simulate the complex water system and assess the impact of different uncertainty factors on water demand and supply. Moreover, this methodology will also allow the water planner and manager to identify and select the most appropriate policy and measure for overcoming the water demand and supply constraints.

Results of the assessment of the future impacts of uncertainty in factors affecting Egypt's water demand and supply were highly sensitive to the methodological choices. For example, the choice of reliance on climate models data rather than a simulation from historical data affected the results by showing limited impacts of climate change over Egyptian inlands. This may attribute to the narrow uncertainty range of selected models that recorded -7.9% to +4.2% for temperature and -31.5% to -5.7% for rainfall, where all models recorded a decrease in rainfall over the projected period. The study did not depend on the simulation from historical data because it relies on too subjective and empirical assumptions and does not take the future natural variability and human activities into consideration. Due to the large scale of the upstream Nile basin area, the study chose the water year method in the WEAP model to detect the potential impacts of climate variability on Egyptian water supply. This choice overcame the complexity of simulating the hydrological conditions in the upstream basin that affect inflow to Egypt. This choice affected the results by obtaining the outcomes of different patterns of hydrological conditions (very dry, dry, normal, wet, very wet, and different sequences) and this made the results more extreme due to using the very dry and very wet sequences. In addition, the choice of running the WEAP model with different water year sequences and assumptions of filling the GERD in 3, 7, 10 years and release only 55.5 BCM/year for Egypt gave us a more accurate view of the potential threats to the GERD on Egypt's water supply. Furthermore, the projection data of population, agriculture and industry provided us with the risk of increasing demand in these different sectors. These methods and choices can be generalized broadly and the results are internally valid and can be used to compare with results of other studies discussing the same issues.

In conclusion, this chapter has dealt with uncertainty in future water demand and supply by analysing and assessing the impacts of uncertainty in future factors affecting Egypt’s water system. These factors are climate change, climate variability, population growth, the Grand Ethiopian Renaissance Dam and land use change. The next chapter combines those future factors projections into a range of plausible scenarios to predict the potential future of water demand and supply and water gap. The next chapter uses scenarios analysis in the WEAP model to investigate combined 19 variables through six scenarios.

Chapter 6
Uncertainty of Egypt's Future Water Demand and Supply

6.1 Overview

In the previous chapter 5, I examined variability in demand, supply and water deficit, as a function of variability in individual driving variables, projected to 2050. To understand more comprehensively, the uncertainty in demand, supply and water deficit, driving variables must be considered collectively. This chapter therefore develops a scenarios approach to predict the potential future of Egypt's water demand and supply and water deficit. Namely, the transition from chapter 5 to 6 is from single variables to combinations.

This chapter adopts future uncertainty as being represented by multiple plausible futures, and uses different scenarios to analysis and identify uncertainty in Egypt's future water demand and supply. The WEAP model and scenarios developed were used to predict an uncertain future based on well-defined drivers with clear assumptions. Six scenarios were developed for dealing with uncertainty and complexity in Egypt’s future water demand and supply. These scenarios included hypotheses related to hydrological fluctuations such as climate, potential policies, technology and infrastructure development, socio-economical drivers, and human behaviour change. The scenarios are Business as Usual (BAU), Critical, Optimistic, Balanced, Pessimistic, and Hybrid.

6.2 Introduction

The main goal of this chapter is framing the future of Egypt’s water demand and supply under uncertainty and complexity, which is addressed using a scenarios framework. This approach is popular for determining possible future ranges of identified uncertainties (e.g. Peterson et al., 2003; Kok and Van Delden, 2009; Gal et al., 2014; Bárcena et al., 2015; Lan et al., 2015; Beh et al., 2015; Maier et al., 2016), and allows the modeller to avoid the idea of single uncertain future.

Scenarios are a suitable and tested approach for dealing with uncertainty as they can consider a long-term view in uncertain complex systems, can consider non-quantifiable variables, and provide integration, breadth, and insight, to support better understanding for decision-making (WWAP, 2012). Scenarios modelling requires a description of the relationships between driving variables, represented as the scenario form. It is worth noting that these involve probabilities so involve risk of error, but they are still very useful for illustrating processes and predicting potential futures, including within the water sector (Skoulikaris, 2008). Scenarios are important because they give an approximated view of the potential future to provide a buffer around the risk of uncertainty sources. In addition, they help in developing the rules of the plan by which individuals act under a set of constraints to produce optimal outcomes. The importance of scenarios analysis is to gain a better understanding of the implications of uncertainty sources in the future and the implications of making certain decisions, such as those related to water consumption, desalination, groundwater abstraction, or agricultural expansion. Identifying such implications and risks and knowing their causes greatly supports decision-makers.

Clear knowledge of the interconnection between the factors of water demand and supply is necessary when dealing with a highly uncertain future. Therefore, this chapter provides a framework of different types of scenarios that have different degrees of suitability combining water demand and supply factors to explore the range of uncertainties through multiple potential futures. Addressing future uncertainty in water demand and supply requires describing the ranges of uncertainties with the aid of scenarios that reflect meaningful future pathways based on different assumptions. Scenarios development, although probably useful and rewarding, risks going into the same problems as other planning methods or modelling processes. However, a set of factors such as over-weighting the present and overestimating our ability to control the future can be taken into consideration to reduce the range of uncertainty (Section 6.3.2) (Peterson et al., 2003).

Future demand and supply are impacted by many sources of uncertainty including assumptions regarding future climate conditions, activity levels, and water consumption intensities (Singh et al., 2010; Beven, 2016). The process of addressing uncertainty comprises defining and quantifying the key uncertainties in these future components (Chapter 5) then considering these uncertainties collectively, through the scenarios approach. This chapter thus has a primary objective, which is tracing the effects of uncertainty factors, in combination, on water demand and supply to predict the potential future of water demand and supply. Although observations and analyses can minimize these uncertainties, in most cases, no evidence or experimental findings can provide firm answers to remove them.

The key components of the scenarios address the hydrology of the study area, water demand by sector, climate and human factors. The scenarios explore the probabilities of water demand and supply in the future taking into account current water consumption policy. The scenarios developed in the WEAP model as a planning tool allow a comprehensive analysis to better understand the different facets of water demand and supply. WEAP’s transparent set of model features and procedures are used to examine the wide variety of issues relevant to water resources planners in Egypt, including climate variability and change, water demand and supply status, anticipated demands and supplies, ecological needs, the policy and regulatory environment, operational objectives, and available infrastructure (Yates et al., 2005). The key outcomes addressed by the scenario analysis are the future demand for, and supply of, water, and any resulting deficit.

This chapter aims to provide insight into how water demand and supply may change to 2050, taking note of key assumptions and sources of uncertainty. Such a long-term outlook is necessarily burdened by uncertainty, but the methodical inclusion of the set of future drivers and uncertainty factors in this way is widely used for planning and framing debates in water resource management. The most complicated issue is how to predict the future under limited water resources coupled with a rapidly growing population, agricultural area, and industrial units. In addition, the extent to which water scarcity feedbacks to input measures, for example, the feedback effect of scarcity on water conservation policy/behaviour. This represented in the scenarios such as variability range of water consumption per capita, per feddan, per industrial units, water reuse. This chapter concentrates on detecting the risk of uncertainties factors on water demand and supply, and prediction of demand and supply to 2050 under those uncertainties.

6.3 Data and Method

Having assessed the effect of uncertainty in individual driving factors on demand and supply using the WEAP model as hydrological model (Chapter 5), I now use the scenarios-based approach, again using the WEAP model as a planning model (distributed model) to assess effects across combinations of factors. Understanding the multi-factor uncertainty further helps to manage future risk to the water system. This scenario approach depends on incorporating multiple assumptions into the WEAP model to investigate future demand and supply probabilities. I address 19 drivers in six scenarios to frame the future of water demand, supply and deficit. Assumptions and probabilities related to these drivers are based on historical data, projections data in Chapter 5, ministries' plans for development and literature review. The required data is detailed in Table 6.1.

Table 6.1 WEAP model data to frame the future of water demand and supply in Egypt to 2050.

Data	Unit	Source
Agricultural area (1960 – 2015) Agriculture area (2016 – 2050)	Million feddan	Ministry of Agriculture and Land Reclamation. Extracted from the historical data and national plan (given more details in Chapter 5, Section 5.3.5 and 5.4.7)
Population census (1950 – 2018) Population growth (2016 – 2050)	Million people	Central Agency for Public Mobilization and Statistics. CAPMAS and UN data
Numbers of industrial units (1990 – 2015) Numbers of industrial units (2016 – 2050)	Units number	Ministry of Trade and industry. Extracted from the historical data and national plan (given more details in Chapter 5, Section 5.3.5 and 5.4.7)
Water consumption in different sectors (1990 – 2015)	BCM	Ministry of Water
Environment demand	BCM	Ministry of Water
Rainfall (1990 – 2015)	BCM	Ministry of Water
River supply (1965 – 2015)	BCM	Ministry of Water
HAD outflow (1965 – 2015)	BCM	Ministry of Water
Shallow groundwater (1990 – 2015)	BCM	Ministry of Water
Deep groundwater (1990 – 2015)	BCM	Ministry of Water
Desalination (1990 – 2015)	BCM	Ministry of Water
Reused water by sector (1990 – 2015)	BCM	Ministry of Water
Water loss by sector (1990 – 2015)	BCM	Ministry of Water

The scenario analysis method is as follows:

1. Modifying the schematic of WEAP to use it as a planning tool to represent the components of Egypt's water balance and frame the future of water demand and supply and deficit to 2050. To operate the WEAP model as a planning tool, I added the water consumption data (1990 – 2015) as one of key components of water balance (MWRI, 2017). There is a difference between water demand and consumption, where water demand is the total amount of water withdrawn from its source to be used in different sectors including leakage and other losses. Water consumption is the portion of water consumption that is not returned to the original water source after being withdrawn, which is lost from the system through evaporation or incorporated into a product or plant and is no longer available for reuse. water consumption is calculated for each sector by multiply an annual activity level (e.g. agricultural area, population number, industrial units' number) by an annual water consumption rate (e.g. per feddan, per capita, per unit) (Sieber and Purkey, 2015). In addition, water reuse and water loss data by sector (1990 – 2015) were input in the WEAP model. Water losses refers to distribution losses, network leakage, unmetered water consumption in public parks and buildings, and clandestine connections...etc. For simplicity, water loss rate increases demand but is not lost from the system, whereas water consumption is lost from the system.

2. The rainfall and flood node was added and connected to the WEAP schematic, where the annual amounts of harvested rainwater (1.3 BCM/year) and announced by the Ministry of Water will be input. The seawater desalination node was added, which will be relied upon in the future. In addition, the evaporation from the Nile and irrigation canals was input as annual quantities (2.5 BCM) as announced by the Ministry of Water. Furthermore, the used water to preserve the ecosystem was added as a node, which is discharged to the Mediterranean sea annually, which does not exceed 0.2 BCM (MWRI, 2014; MWRI, 2018) (Figure 6.1).

3. Operating the WEAP model on annual time step (1990 – 2015) and the current situation is set for (2015).

4. Determining the timeframe of the future scenarios to be extended to 2050.

5. Preparing the required data and assumptions for 19 drivers over the period (2016 – 2050) to use in the WEAP model (Section 6.3.2) (Table 6.2).

6. Developing six scenarios to imagine the potential future of water demand and supply based on combination of influential 19 drivers in the Egyptian water system. Each scenario is developed depending on a set of assumptions that have a reference basis in the historical data and trend of the driver (Section 6.3.2) (Table 6.3).

7. The coefficient variation is used to quantify the variability and uncertainty associated with the scenarios for expressing the risk of each scenario.

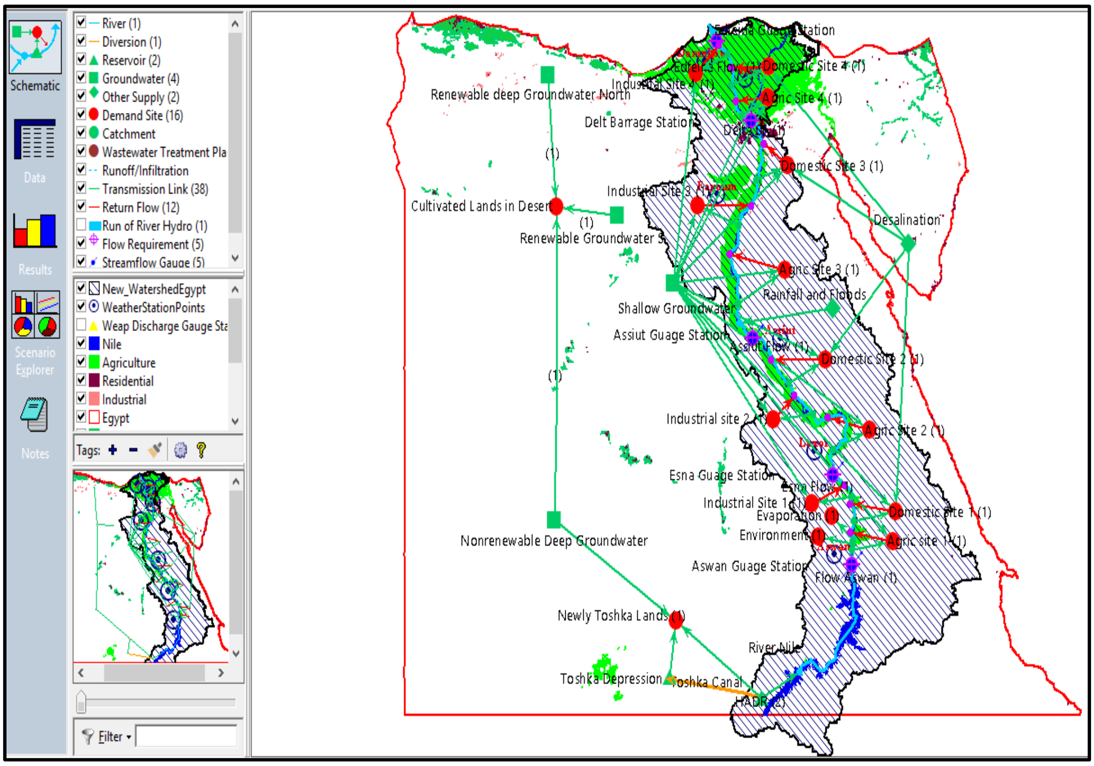


Figure 6.1 WEAP schematic for the current water demand and supply system in Egypt.

6.3.1 Current Situation Data

The current state represents water demand and supply in the 2015 base year, selected according to available data. Observed data on water demand and supply for 2015 was reported by the Egyptian Ministry of Water in 2015 (Table 6.2).

6.3.2 Future Scenarios Development

Scenario analysis is a means of assessing responses to potentially very different futures, based on how drivers develop and interact (WWAP, 2012). Too many drivers contribute to uncertainty of future demand and supply, of which 19 keys were included in the WEAP modelled scenarios (Table 6.2). These drivers were outlined by stakeholders' judgment (Appendix 3) based on the efficient causes of water deficit and components of water demand and supply. In addition, these drivers were selected to cover the different aspects that affect water demand and supply such as socio-economical and climatic aspects, ecological needs, human interventions (regulatory environment and operational objectives), technological features (available infrastructure) and water policy. The uncertainty range for each driver is estimated using historical data trends by over-weighting the present, overestimating the future and stakeholders' judgment to represent likely realistic future circumstances (Appendix 3). For example, the Nile supply and HAD outflow to Egypt are vary in the range of 52-71 BCM and 53-58 BCM respectively based on the historical data analysis and the stakeholders' expectations.

Table 6.2 Scenarios drivers and uncertainty ranges used with WEAP model.

	Key Drivers	**Aspect**	**Current 2015**	**Uncertainty Ranges**
1	Agricultural expansion (million feddan)	Socio-Economy (Water demand)	9.096	9.09 - 13.9
2	Annual water consumption rate for feddan (M^3)		4700	4000 - 4800
3	Population growth (million people)		89.95	141 - 192
4	Annual water consumption rate for person (M^3)		87.6	80 - 95
5	Industrial expansion (Units number)		7590	10752 - 19218
6	Annual water consumption rate for industrial Unit (M^3)		200000	200000 – 300000
7	Environment use (BCM)	Ecology	0.6	0.6 - 1
8	Rainfall (BCM)	Climate	1.3	1.3 - 2
9	River supply (BCM)		71	52 - 71
10	HAD outflow (BCM)	Water supply and human interventions	58.2	53 – 58.23
11	Shallow groundwater (BCM)		6.9	6 – 8.5
12	Deep groundwater (BCM)		2.2	2.2 – 4.9
13	Desalination (BCM)		0.1	0.10 - 2
14	Reused water from agriculture (BCM)	Technology, human interventions and water policy	11.9	19.15 – 30 %
15	Reused water from domestic and industry (BCM)		1.2	11.54 – 25 %
16	Reused water from industry (BCM)		1.2	11.54 – 25 %
17	Water loss from agriculture (BCM)		23	30 – 40 %
18	Water loss rate from domestic (BCM)		3.01	25 – 30 %
19	Water loss rate from industry (BCM)		4.2	50 – 77.8 %

Having identified the most influencing drivers on water demand and supply, the next step involved building multiple scenarios based upon a set of selected drivers trends to identify the spectrum of possible futures Egypt could face. The scenario should meet three criteria: (i) it should be plausible to assume the scenario could actually happen (ii) it should be connected to a clear assumption relevant to water demand and supply (iii) the scenario should consider Egypt’s status quo and cover all the selected drivers. The scenarios are based on assumptions about different relationships between demand and supply drivers. For example, agricultural areas may decrease as a result of increased urbanization, reducing the supply or vice versa. Agricultural areas may increase and consumption will decrease as a result of using technology to reduce losses or vice versa. In other words, demand drivers may increase and the supply drivers decrease or vice versa or permutational trends may occur.

Six scenarios were developed to represent different trends of key drivers according to the specified uncertainty ranges in Table 6.2 and each scenario frames supposed case from specified trends and assumptions. The Business As usual and Pessimistic scenarios represents high trends with permutational values of drivers between decrease and increase to be more realistic (Pessimistic scenario represent the worst case). Optimistic and Hybrid scenarios represent low trends with permutational values of drivers (Optimistic scenario is the best case and refers to low trends more than Hybrid scenario). Critical and Balanced scenarios represent the average trends with permutational values of drivers (both scenarios refer to average trends but critical scenario tends to be worse slightly than Balanced scenario) detailed in Table 6.3 and described below.

Each scenario takes a variety of drivers at a time, changing their values, and evaluating their combined influence on the variables that are likely to be of importance in shaping the future. For instance, agricultural expansion, water consumption per feddan, population growth, water consumption per capita, loss rate, reuse rate...etc. Each scenario must capture the criteria of hydrological fluctuations, institutional policy plans, technology and infrastructure, and human behaviour to evaluate as much as possible the impacts that one might expect in the future from the system being considered. The six scenarios are implemented using the WEAP model over the period (2016 – 2050). The results of these scenarios and projections may then be used in the policy and planning response assessment, to optimize benefits and/or mitigate losses in achieving the desired state.

a. Business As Usual scenario (BAU). This scenario assumes the continuity of current circumstances and policies. It is based on the trends of the current situation (2015) and extended to 2050. The data of drivers are input with a view to simulating continuing evolution of the system, where the growth rates will continue as they are in all sectors of demand as shown in Table 6.3. No major change in the supply side is assumed, except for desalination, where desalination growth rate will rise by 5.6% per year to contribute to the supply side by 0.68 BCM in 2050. This assumption is based on Egypt's expansion desalination capacity due to the construction of the GERD. In August 2019, the Egyptian government announced its intention to build 39 desalination plants with a capacity of 1.4 million m^3/day. In addition, there is no change in the rate of water reuse or loss, but the absolute amount of reuse and loss will increase due to increased demand. Water losses include evaporation losses, field application losses, distribution losses, and conveyance losses (leakage); the Ministry of Water estimates these losses in 2015 were 37%, 29%, and 77.8% of total demand in the agriculture, domestic, and industry sectors respectively. Agricultural practices and human behaviours to use water will continue to increase slightly, where water consumption per feddan, per capita, and per industrial unit will be 4,800m^3, 90m^3, and 250,000m^3 respectively. Further, there is no change in the exploitation of groundwater as Egypt approaches the safe limit.

Table 6.3 Scenarios for Egypt's water demand and supply, 2016–2050.

Key Drivers	**Current 2015**	**BAU scenario**	**Critical scenario**	**Optimistic scenario**	**Balanced scenario**	**Pessimistic scenario**	**Hybrid scenario**
Agricultural expansion per year	9.096 MF	0.74%	0.65%	0.5%	0.65%	1.1%	0.5%
Annual water consumption rate for feddan per year (M^3)	4700	4800	4400	4000	4500	4800	4500
Population growth per year	89.95 MP	2.2%	1.85%	1.30%	1.58%	1.85%	1.58%
Annual water consumption rate for person per year (M^3)	87.6	90	80	85	90	95	85
Industrial expansion per year	7590 Units	2.04%	2.69%	1%	1.83%	2.69%	2.04%
Annual water consumption rate for industrial Unit per year (M^3)	200000	250000	300000	260000	280000	300000	260000
Environment per year (BCM)	0.6	0.6	1	0.6	0.7	1	0.6
Rainfall per year (BCM)	1.3	1.3	1.5	1.3	1.5	2	1.3
River supply per year (BCM)	71	71	52	58	65	52	65
HAD outflow per year (BCM)	58.2	58.2	55.5	53	58	55.5	54
Shallow groundwater per year (BCM)	6.9	6.9	8.5	7	7.5	8.5	6
Deep groundwater per year (BCM)	2.2	2.2	3	4	3.5	4.9	3
Desalination per year (BCM)	0.1	0.68	2	1	1.5	2	1.25
Reused water from agriculture per year	11.9 BCM	19.15%	22%	20%	25%	30%	20%
Reused water from domestic per year	1.2 BCM	11.54%	15%	20%	22%	25%	22%
Reused water from industry per year	1.2 BCM	11.54%	15%	20%	22%	25%	22%
Loss rate from agriculture per year	23 BCM	37%	30%	35%	37%	40%	30%
Loss rate from domestic per year	3.01 BCM	29%	27%	25%	27%	30%	29%
Loss rate from industry per year	4.2 BCM	77.8%	65%	50%	70%	77%	60%

b. Critical scenario. The basic premise of this scenario is a combination of factors will create a critical situation for the water problem such as industrial and population growth takes priority, the dry climate over Nile's upstream occurs and restrictions of discharge from the GERD. This scenario considers an expected slight decrease in agricultural area due to urban encroachment on agricultural lands as a result of increasing population growth of 1.85%. The scenario assumes that development will favour industry and technology, where the industrial sector is likely to witness a firm growth rate of 2.69 % from 2016 to 2050. By using modern technology, annual water consumption per feddan and per capita will decrease to be 4400 m^3 and 80 m^3 respectively. For the supply side, the scenario supposes that the Nile basin climate will tend towards drought relatively; the supply at Dongola station will be 52 BCM, and Egypt will commit to withdrawing only its share, of 55.5 BCM. In addition, Egypt is likely to harvest more rainwater estimated by 1.5 BCM. Further, there is expansion in water desalination and groundwater consumption to bridge the water gap due to the climate change in Nile basin. As a result of increased water consumption in the domestic and industrial sector, and use of modern technology (e.g. in drinking water network, irrigation network, drip irrigation, water treatment), a relative increase in water reuse is expected and a relative decrease in water losses.

c. Optimistic scenario. This scenario refers to the best case. Optimistic scenario adopts an ambitious outlook of reducing water demand, which corresponds to a reduction in growth rates of agriculture, population and industry to be 0.5%, 1.30%, and 1% respectively. The annual water consumption rate per feddan will likely decrease significantly to be 4000 m^3 due to changes in cropping patterns and use of modern irrigation methods such as drip, bubble irrigation and mist spraying. On the other hand, the supply side will be normal, with supply at Dongola estimated at 58 BCM, the HAD outflow at 53 BCM, and the harvested rainwater of 1.3 BCM/year. There will be an increase in exploitation of deep and shallow groundwater to reach 4 BCM/year and 7 BCM/year respectively. In addition, Egypt may expand the water desalination sector due to problems with the Nile Basin countries to contribute about 1 BCM on the supply side. A significant increase in water reuse and a considerable decrease in water loss is expected.

d. Balanced scenario: The basic philosophy of the scenario is the moderate growth in demand sectors will occur and a moderate increase in supply. This means the relation between demand and supply will be balanced (moderated).

It is expected that the annual growth rate for agricultural area, population, industrial units will be gone down slightly due to the prudent policies of the government to reach 0.65%, 1.58%, and 1.83% respectively. In contrast, the annual water consumption rate for different demand sectors will increase slightly to 2050. Similarly, it is assumed that the supply side will improve a little due to the climate change over Egypt and stability of climate variability over the upstream region. Egypt may collect around 1.5 BCM from rainwater; the river supply is likely to be 65 BCM at Dongola station, and the HAD outflow could be 58 BCM as the average of withdrawal to Egypt. Furthermore, the withdrawal from shallow and deep groundwater will continue to reach 7.5 BCM and 3.5 BCM respectively. It is likely that water reuse rates will increase markedly due to use the modern technology of water treatment, while losses will reduce due to the moderate growth in demand sectors and renewing the drinking water network.

e. Pessimistic scenario. This scenario presents conditions, which have a very bleak outlook. This scenario supposes that the future will get worse over the time; where the growth rates of agriculture, population, and industry may rise to be 1.1%, 1.85%, and 2.69% respectively. Water consumption rates will run to extremes of 4800m^3 per feddan, 95m^3 per capita, and 300,000m^3 per industrial unit due to the exaggerated consumer behaviour and implementation of irrational policy. This irrational policy will be represented in the flood-irrigation system in old lands, reclaiming more land in areas with harsh climate, ignoring the use of modern technology in irrigation and drinking networks to reduce losses and tradition of sprinkling water in the streets to beat the heat in the summer. On the supply side, the climate may worsen in the upstream countries but be somewhat better over Egypt. Therefore, Egypt may harvest about 2 BCM from rainfall; water supply at Dongola is assumed to be 52 BCM, and the outgoing water from HAD is expected to be 55.5 BCM. Moreover, the dependence on shallow and deep groundwater may rise to reach the safe yield 8.5 BCM, and 4.9 BCM respectively. Further, Egypt may be forced to increase the proportion of water desalination to about 2 BCM to compensate for losses on the supply side. The scenario assumes that water losses will increase sharply as a result of dilapidated infrastructure, while the rate of water reuse will increase dramatically to mitigate water scarcity.

f. Hybrid scenario. The philosophy of this scenario is to combine the drivers of Balanced and optimistic scenarios permutationally. This scenario assumes the annual growth rates in agriculture, population, and industry sectors by 0.5%, 1.58%, and 2.04% respectively, while the annual water consumption is fluctuated to be 4500m^3 per feddan, 85m^3 per capita, and 260000m^3 per industrial unit. For the supply side, this scenario is developed to include 65 BCM as inflow at Dongola station; 54 BCM as outflow from HAD; 1.3 BCM as accumulated water from rainfall, and 1.25 BCM the contribution of desalination sector in the supply side. In addition, shallow and deep groundwater utilization is expected to be 6 BCM and 3 BCM consecutively. Water reuse percentage is estimated by 20%, 22%, and 22% for agriculture, domestic, and industry sequentially, while the losses are assumed to be 30%, 29%, 60% for those same sectors.

It is worth noting that agricultural wastewater in Egypt is ultimately drained into the northern lakes to overcome seawater intrusion into northern delta lands. Therefore, Egypt drains very little freshwater to the sea, only about 0.2 BCM/year (MWRI, 2005; MWRI, 2010; MWRI, 2012). The present study assumes that the volume of water drained to the sea in the future, to preserve the ecosystem, ranges from 0.60 to 1 BCM depending on the scenarios drivers.

After implementing the scenarios in the WEAP model and framing the future of water demand, supply and deficit, the values of demand and supply for each scenario over the period 2016 – 2050 were obtained. Then, the coefficient of variation is applied to demand and supply values for each scenario to compare the uncertainty or the variation associated with the output of each scenarios. CV reflects the uncertainties/variabilities in the various variable values in the six investigated scenarios. CV can express the variation of each scenario by using the following equation:

$$CV\ (\%) = \left(\frac{Standard\ deviation}{Mean}\right) \times 100 \quad \text{(Equation 6.1)}$$

The coefficient of variation (CV) is a simple standard measure of uncertainty refers to the relative variability (Hackanson and Peters, 1995). It is the ratio of the standard deviation to the mean (average). The standard deviation and the mean are calculated for demand and supply values for each scenario outcomes, and then calculate the CV of demand/supply for each scenario. The CV is useful when we want to compare results from different scenarios that have different values. For example, if demand scenario "A" has a CV of 15% and demand scenario "B" has a CV of 20%, this refers to scenario B has more variation, relative to its mean. For simplicity, a lower CV implies a low degree of variation while a higher CV points out a higher variation. Basically, the acceptable range of CV is (CV<10 is very good, 10-20 is good, 20-30 is acceptable, and CV>30 is not acceptable) (Gomez and Gomez, 1984).

6.4 Results and Discussion

6.4.1 Current state 2015

Results of the WEAP modelling shows that in 2015 (Table 6.4), water demand was 81.05 BCM from agriculture, domestic, industry, environment, and evaporation; supply reached 61.79 BCM from the Nile, deep groundwater, and rain water harvesting. It is noted that Egypt reports rainwater of 1.3 BCM, unvarying over the period 1990 – 2015 and there is an uncertainty around this amount as there are no adequate studies of rainwater for in Egypt. The difference between demand and supply leads to a deficit estimated at 19.26 BCM, when including the environmental use and evaporation from the Nile and irrigation canals as reported by the Ministry of Water. Egypt currently bridges this deficit by non-conventional resources of desalination, shallow groundwater, and water reuse, in the amounts of 0.1BCM, 6.9BCM, and 12.26BCM respectively.

Agriculture records the largest consumption and demand for water resources by 45.92 BCM and 62.15 BCM sequentially. The area of agricultural lands constantly increased from 1960-2015, reaching 9.09 million feddans in 2015, with a water consumption rate of 4700 m^3 per feddan. Egypt's population rose rapidly over the period 1950 – 2018, and in 2015 reached 90 million people. In 2015, water consumption in the domestic sector recorded 8.09 BCM, while water demand was 10.4 BCM. Water consumption rate per capita was 87.6 m^3 in 2015. There are significant water losses for the industrial sector, as consumption reached around 1.51 BCM, while demand is 5.4 BCM, and the loss rate is set at about 72%. These losses may be attributed to many industrial units operating without a government license or with any water monitoring. Therefore, there is uncertainty about the number of industrial units with estimates of 7590 units in 2015 and the water consumption rate is 200,000m^3. There is fluctuation in water inflow at Dongola station and water outflow from the High Dam from 1965–2015, which reached 71 BCM and 58.23 BCM respectively by 2015.

Table 6.4 Water balance for Egypt in 2015

Water Supply	Quantity BCM/year
Conventional	
River Nile	58.23
Deep underground water	2.2
Underground water in Sinai	0.04
Underground water in North	0.02
Rainfall and floods	1.3
Total	**61.79**
Non-conventional	
Desalination	0.10
Shallow underground water	6.9
Water reuse	12.26
Total	**81.05**
Water Consumption	
Agriculture	45.927
Domestic	8.09
Industry	1.51
Evaporation	2.5
Environment	0.6
Total	**58.62**
Water Demand	
Agriculture	62.15
Domestic	10.4
Industry	5.4
Evaporation	2.5
Environment	0.6
Total	**81.05**
Water deficit	**19.26**
Water shortage after addition of non-conventional resources	**0.0**

6.4.2 Scenarios Analysis

This section presents the results of the WEAP modelling to 2050 for the six scenarios detailed above. For each modelled scenario is summarized in a water balance table.

6.4.2.1 Business As Usual

The BAU scenario 2016–2050 represents no change in policies regulating water demand and supply, in combination with continuance of the same growth rates. The yearly demand will increase significantly to 115.05 BCM in 2050 due to increased growth rates in agriculture, population, and industry. The actual water consumption is likely to be 83.15 BCM for the same reason. It is noted that there is a big difference between demand and actual consumption, this is due to increase of annual activities and annual water consumption rate (agriculture, population, industry) and increase of water losses due to lack of infrastructure development, absence of technology usage, and existing the same practices in all sectors leads to increase of water demand (Section 6.3). Water supply will grow to a record 106.15 BCM in 2050 due to the increased water reuse as a result of increased water demand. Even though water supply is increasing, it will not meet all demand, and a water gap remains estimated at 8.9 BCM in 2050 (Table 6.5).

Table 6.5 Water balance for Egypt in 2050 under BAU scenario.

Water Supply	Quantity BCM/year
Conventional	
River Nile	58.23
Deep underground water	2.2
Underground water in Sinai	0.04
Underground water in North	0.02
Rainfall and floods	1.3
Total	**61.79**
Non-conventional	
Desalination	0.68
Shallow underground water	6.9
Water reuse	36.79
Total	**106.15**
Water Consumption	
Agriculture	58.82
Domestic	17.35
Industry	3.88
Evaporation	2.5
Environment	0.6
Total	**83.15**
Water Demand	
Agriculture	74.84
Domestic	21.62
Industry	15.49
Evaporation	2.5
Environment	0.6
Total	**115.05**
Water deficit	**53.26**
Water shortage after addition of non-conventional resources	**-8.89**

While demand and consumption increase sharply 2016 – 2050, supply only rises due to increased water reuse (Figure 6.2). It is evident that Egypt will not be able to overcome the water deficit, starting in 2043, under this scenario with current policies. Agriculture remains the most consuming and demanding sector, with a significant increase leading to 74.8 BCM as demand and 58.8 BCM for consumption by 2050 (Figures 6.3 and 6.4). Due to population growth, domestic sector consumption and demand will reach 17.35 BCM and 21.62 BCM respectively by 2050. The industrial sector sees a modest rise in consumption to 3.88 BCM with a strong rise in demand to 15.49 BCM; this difference may attribute to the huge loss rate due to the absence of advanced technology and existence of many industrial units that operate without a government license or monitoring. The evaporation from the Nile and canals is estimated at 2.5 BCM according to the Ministry of Water, whilst environmental usage is assumed to be 0.6 BCM to mitigate seawater intrusion in northern delta lands.

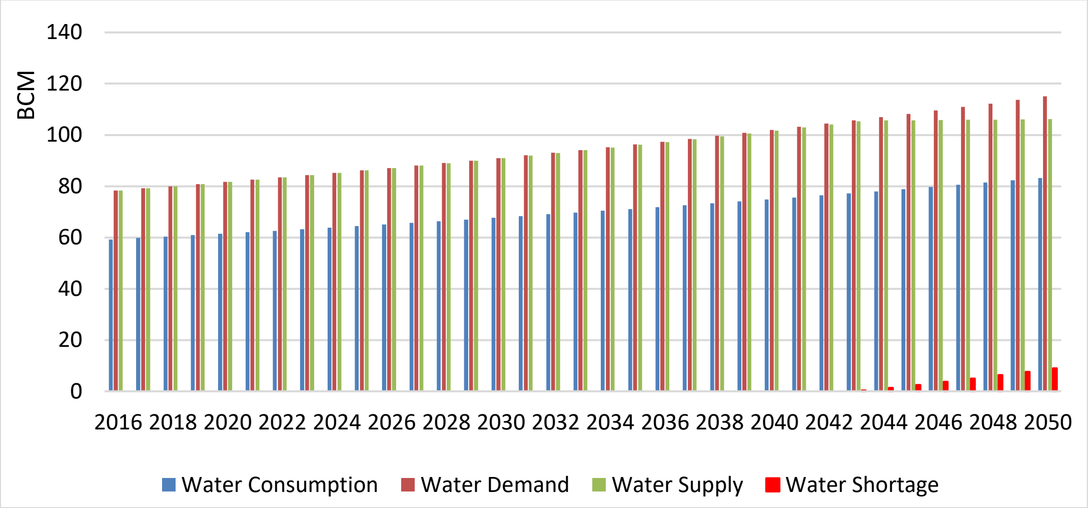


Figure 6.2 Water demand, supply, and shortage under BAU scenario to 2050.

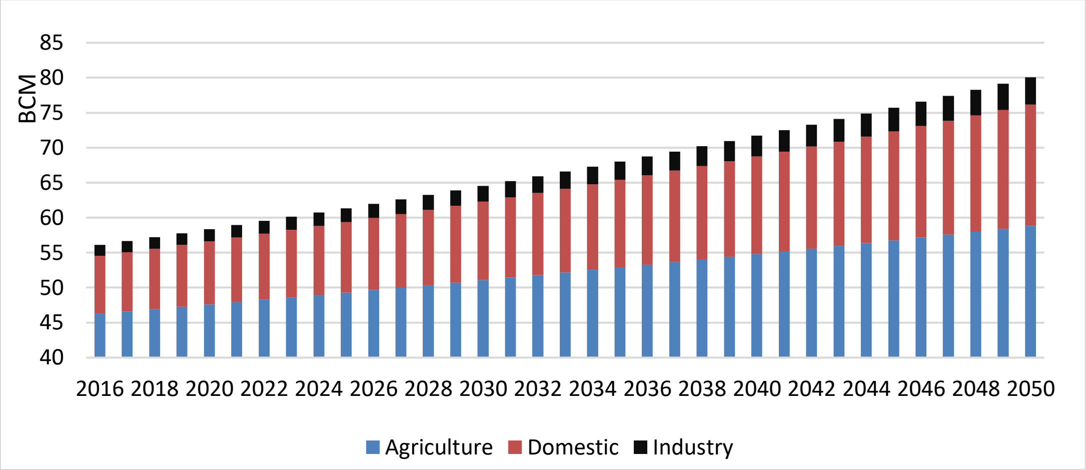


Figure 6.3 Water consumption by sectors under BAU scenario 2050.

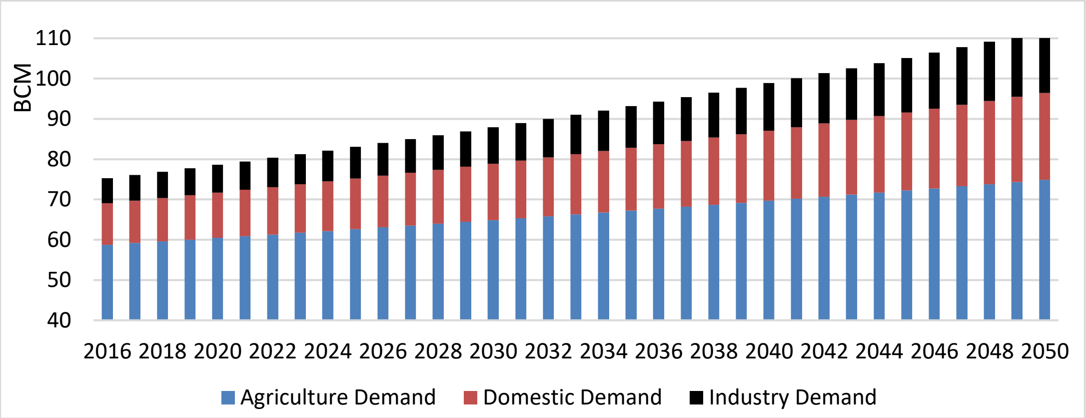


Figure 6.4 Water demand by sectors under BAU scenario 2050.

Although Egypt may not bridge the water deficit with the modelled water supply with HAD outflow of 58.23 BCM, it can withdraw additional water from the High Dam reservoir to bridge the gap, as the reservoir volume will reach about 128.45 BCM in 2050. Figure 6.5, shows the HADR volume will decrease over 2016 – 2050 owing to the higher demands and steady inflow at Dongola station.

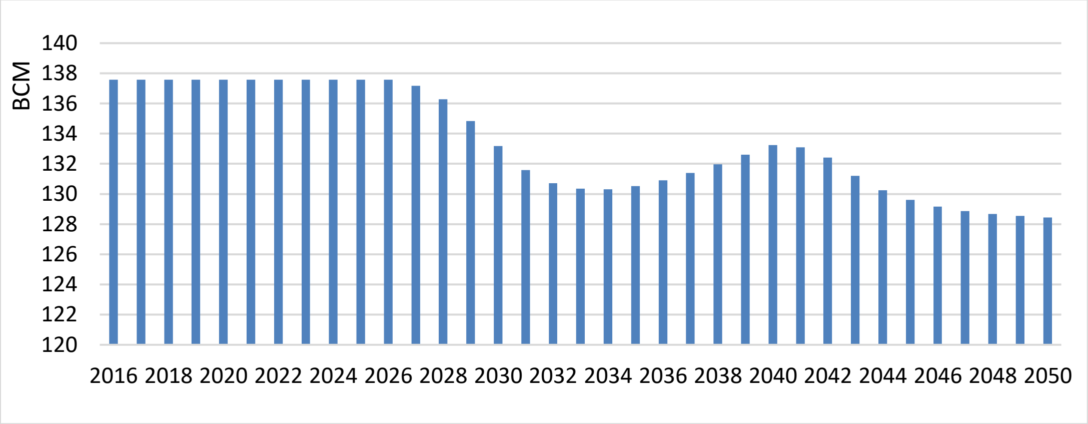


Figure 6.5 HAD reservoir volume under BAU scenario to 2050.

6.4.2.2 Critical Scenario

The critical scenario assumes a dry climate upstream, impacts of the GERD, increased growth of population and industry, and relative decrease in agricultural area. Water consumption and demand will record 75.4 BCM and 94.1 BCM respectively by 2050. The smaller difference between consumption and demand is due to lowering losses achieved by the expanded use of technology and development of network infrastructure. In addition, the environmental use will increase, where about 1 BCM will discharge into the Mediterranean Sea to protect the Nile ecosystem from expansion in industrial usages (Table 6.6). In terms of supply Egypt withdraws only its agreed 55.5 BCM from the high dam, with inflow at Dongola station assumed to be 52 BCM due to the dry climate upstream and impact of the GERD. This leads to expansion in rainwater harvesting to 1.5 BCM and exploitation of groundwater to a safe yield (as sustainable groundwater use) of 4.9 BCM for deep groundwater and 8.5 BCM for shallow groundwater in 2050. The water gap prompts use of desalination and expanded water reuse to close the gap (Table 6.6 and Figure 6.6).

Table 6.6 Water balance for Egypt in 2050 under Critical scenario.

Water Supply	Quantity BCM/year
Conventional	
River Nile	55.5
Deep underground water	3
Underground water in Sinai	0.04
Underground water in North	0.02
Rainfall and floods	1.5
Total	**60.06**
Non-conventional	
Desalination	2
Shallow underground water	8.5
Water reuse	23.23
Total	**93.7**
Water Consumption	
Agriculture	52.47
Domestic	13.67
Industry	5.76
Evaporation	2.5
Environment	1.0
Total	**75.4**
Water Demand	
Agriculture	58.21
Domestic	15.91
Industry	16.47
Evaporation	2.5
Environment	1.0
Total	**94.1**
Water deficit	**34.04**
Water shortage after addition of non-conventional resources	**-0.31**

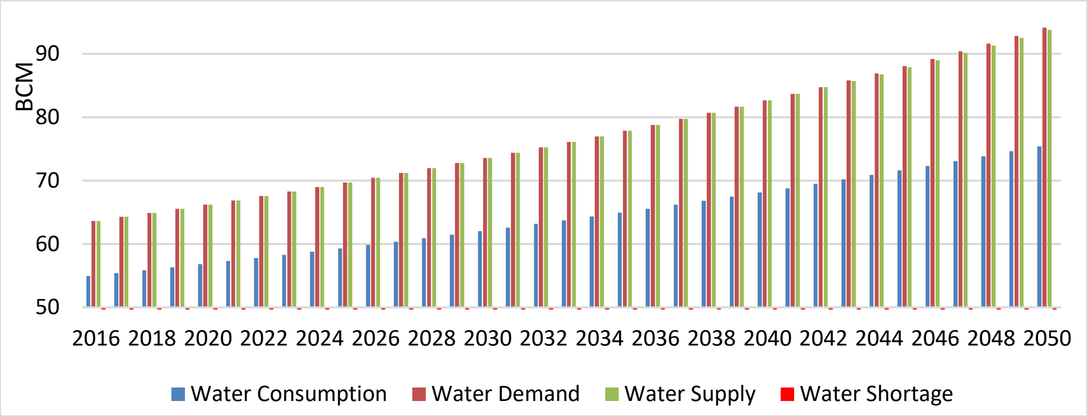


Figure 6.6 Water demand, supply, and shortage under Critical scenario 2050.

Despite reduced expansion of agricultural lands and lower water consumption per feddan under this scenario, agriculture remains the largest consumer of water simply due to the huge agricultural area, some 11.3 million feddans in 2050. Industrial consumption and demand reach 5.76 BCM and 16.47 BCM respectively in 2050, while domestic consumption and demand reach 13.67 BCM and 15.91 BCM (Figures 6.7 and 6.8).

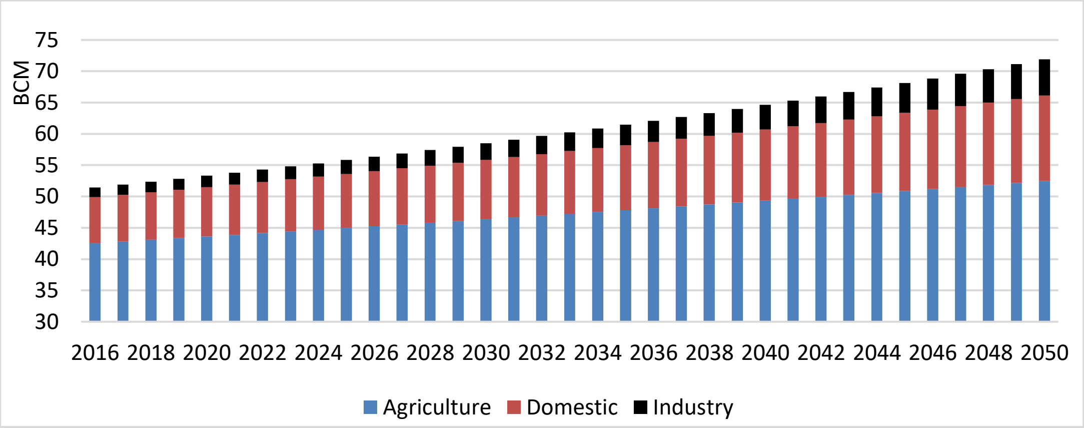


Figure 6.7 Water consumption by sectors under Critical scenario 2050.

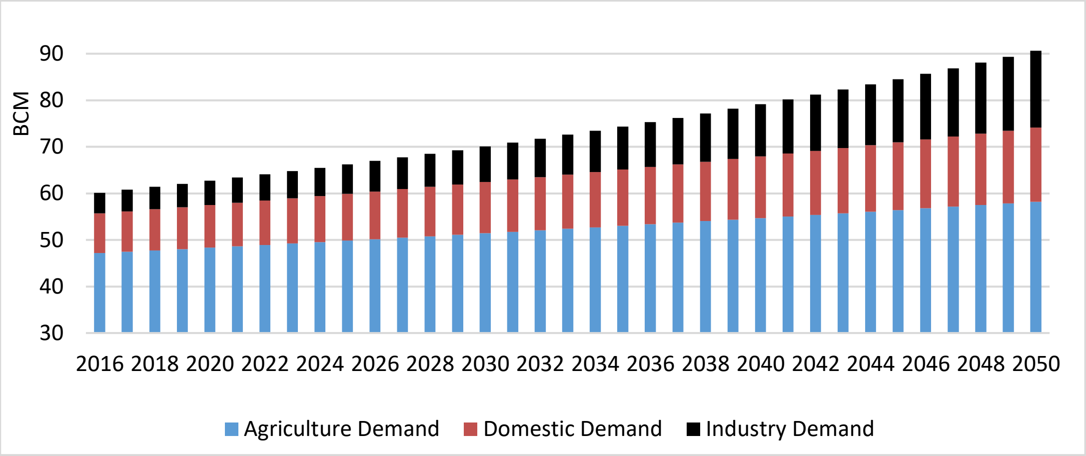


Figure 6.8 Water demand by sectors under Critical scenario 2050.

Although Egypt can bridge the deficit for most of the scenario period, by increasing desalination, water reuse, and groundwater exploitation of, a deficit arises by 2050 which cannot be overcome this way, as the water level in HADR decreases dramatically due to the little inflow relative to outflow. From 2041, Egypt cannot withdraw from the HADR, as the volume falls below 40 BCM (Figure 6.9). The High Dam turbines may be inoperable if Egypt faces this critical scenario.

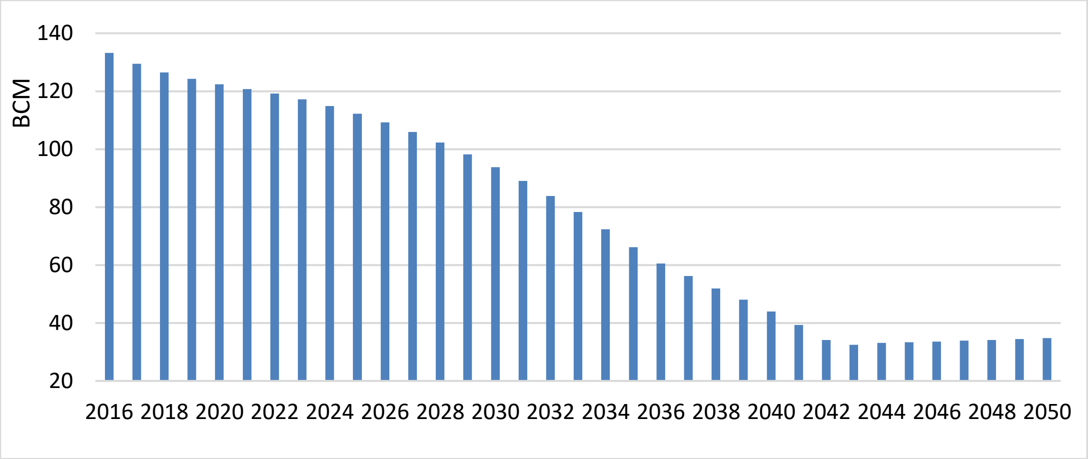


Figure 6.9 HAD reservoir volume under Critical scenario 2050.

6.4.2.3 Optimistic Scenario

When dealing with uncertainty, it is natural to focus on the worst case, but uncertainty is neutral and we cannot know with what will happen, hence other cases merit consideration. This scenario considers the best case adopting an ambitious view on demand and supply. According to this scenario, demand decreases reaching 76.01 BCM in 2050, with consumption at 63.52 BCM, due to slower growth in all demand sectors and reducing the losses and leakage of networks. On the supply side, there is sufficient to meet needs in spite of little withdrawal and low inflow. Due to the decline in water demand and loss rates, water reuse drops to 9.67 BCM. Groundwater consumption increases slightly to 4 BCM for deep groundwater and 7 BCM for shallow groundwater. The relative increase in the utilization of groundwater is due to the decrease of river supply due to the development in riparian countries and relative climate change in upstream. There is no deficit by 2050 (Table 6.7 and Figure 6.10).

Table 6.7 Water balance for Egypt in 2050 under Optimistic scenario.

Water Supply	Quantity BCM/year
Conventional	
River Nile	53
Deep underground water	4
Underground water in Sinai	0.04
Underground water in North	0.02
Rainfall and floods	1.3
Total	**58.3**
Non-conventional	
Desalination	1
Shallow underground water	7
Water reuse	9.67
Total	**76.01**
Water Consumption	
Agriculture	45.59
Domestic	12.01
Industry	2.82
Evaporation	2.5
Environment	0.6
Total	**63.52**
Water Demand	
Agriculture	55.58
Domestic	12.81
Industry	4.51
Evaporation	2.5
Environment	0.6
Total	**76.01**
Water deficit	**17.7**
Water shortage after addition of non-conventional resources	**0.0**

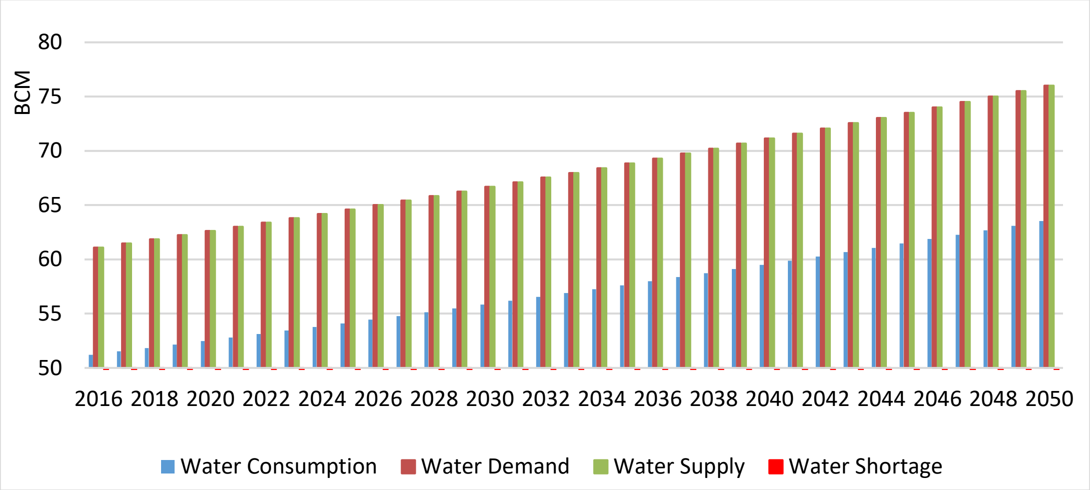


Figure 6.10 Water demand and supply under Optimistic scenario 2050.

Consumption and demand for the agricultural, domestic, and industrial sectors displays a slight decrease to 2050 in comparison to other scenarios. This decrease is attributed to slow growth rates in all activities (agriculture, population, industry) and decrease of annual water consumption rates due to the population behaviour and efficient policy in water management. By 2050, agriculture will consume 45.59 BCM, with demand at 55.58 BCM; industrial consumption will be about 2.82 BCM and demand 4.51 BCM, whilst domestic consumption will be 12.01 BCM and sector demand 12.81 BCM. It is noticeable that the gap between consumption and demand is reduced in all sectors due to minimizing the water losses as a result of renewing drinking and irrigation networks, reducing leakage and eliminating clandestine connections. (Figures 6.11 and 6.12).

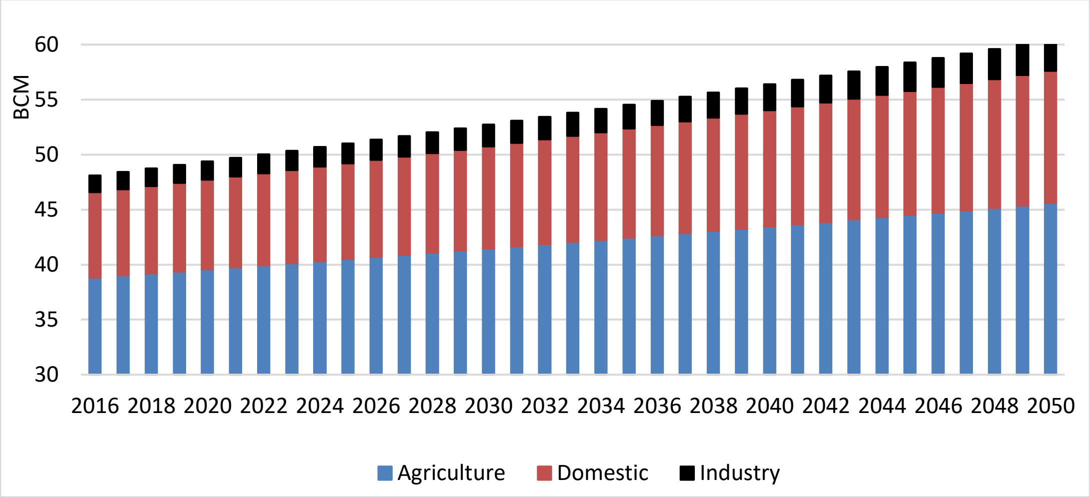


Figure 6.11 Water consumption by sectors under Optimistic scenario 2050.

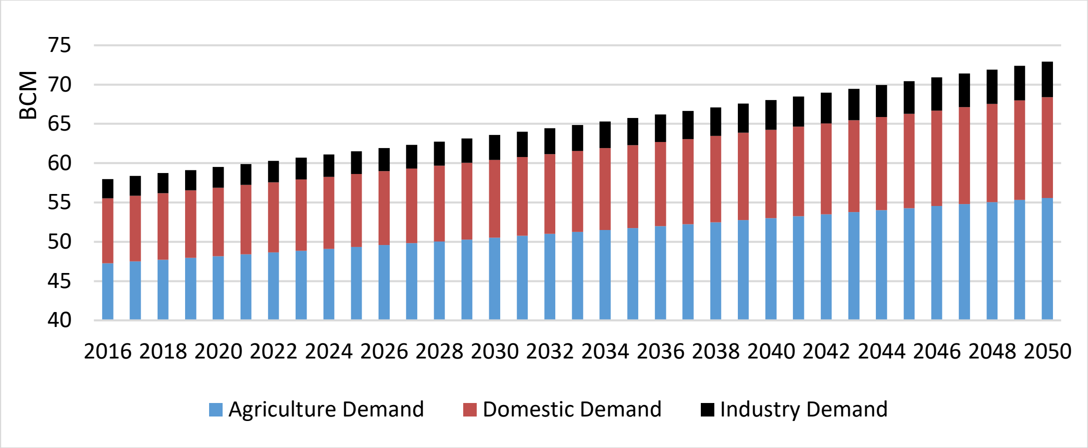


Figure 6.12 Water demand by sectors under Optimistic scenario 2050.

The HADR volume falls to 2050 due to annual withdrawal of 53 BCM to meet demands and low inflow at Dongola station of about 58 BCM. However, under this scenario, Egypt can still bridge the water shortage easily without further drawdown of the High Dam reservoir, as volume in 2050 remains at a satisfactory 119.23 BCM (Figure 6.13).

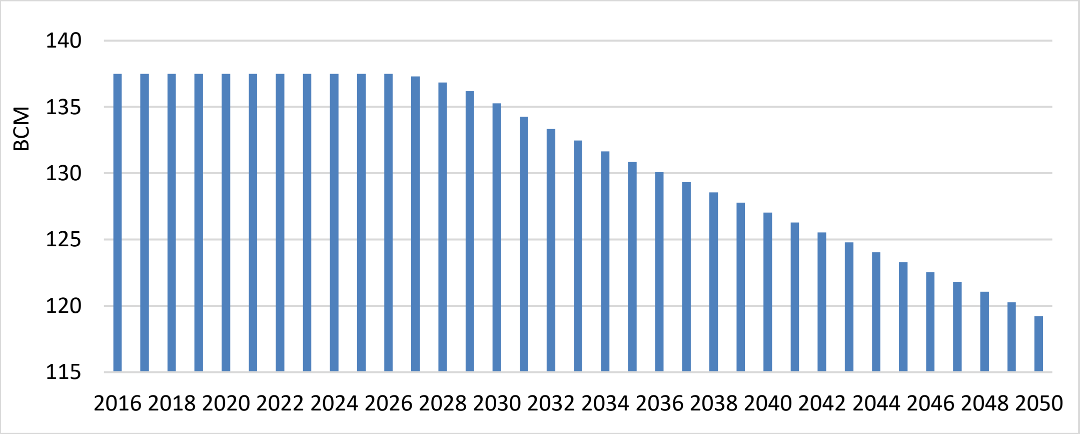


Figure 6.13 HAD reservoir volume under Optimistic scenario 2050.

6.4.2.4 Balanced Scenario

Due to prudent government policies such as spreading awareness of the rapid population growth, stopping low-feasible land reclamation projects and monitoring industrial units, annual growth rates for different sectors may fall moderately. In addition, raising awareness of water consumption and reducing the losses may control the increase in water consumption and demand. Due to these policies, water consumption and demand may record a slight increase to reach 74.88 BCM and 92.07 BCM respectively. This increase is due to a slight increase in agricultural area, population, and industrial production, and increase in water consumption rates by sector, assumed to be 4500 m^3 per feddan, 90 m^3 per capita, and 280,000 m^3 per industrial unit. Water supply is estimated at 92.07 BCM, where the drivers of supply are assumed to be balanced. Upstream climate results in 65 BCM inflow at Dongola station, so the HAD outflow can increase a little to 58 BCM. Egypt will be able to collect 1.5 BCM from rainwater, 1.5 BCM from desalination, with shallow and deep groundwater supply of 7.5 BCM and 3.5 BCM respectively by 2050. Water reuse offers 20.02 BCM. In this scenario, the water deficit 2016–2050 can be eliminated (Table 6.8, Figure 6.14).

Table 6.8 Water balance for Egypt in 2050 under Balanced scenario.

Water Supply	Quantity BCM/year
Conventional	
River Nile	58
Deep underground water	3.5
Underground water in Sinai	0.04
Underground water in North	0.02
Rainfall and floods	1.5
Total	**63.05**
Non-conventional	
Desalination	1.5
Shallow underground water	7.5
Water reuse	20.02
Total	**92.07**
Water Consumption	
Agriculture	53.65
Domestic	14.02
Industry	4.01
Evaporation	2.5
Environment	0.7
Total	**74.88**
Water Demand	
Agriculture	63.44
Domestic	14.98
Industry	10.45
Evaporation	2.5
Environment	0.7
Total	**92.07**
Water deficit	**29.02**
Water shortage after addition of non-conventional resources	**0.0**

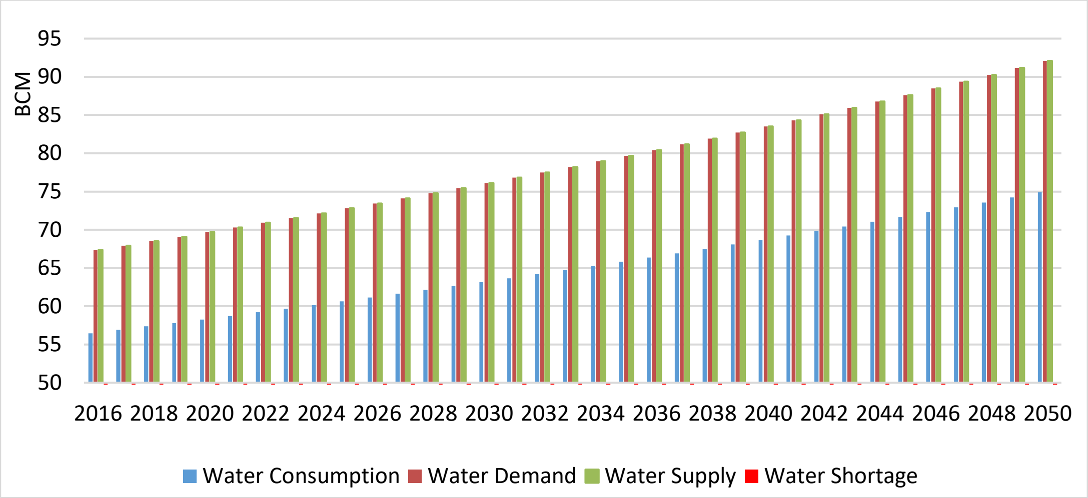


Figure 6.14 Water demand and supply under Balanced scenario 2050.

Under the Balanced scenario, agricultural land, population, and industrial units reach 11.3 million feddans, 159.9 million people, and 14,149 units respectively in 2050, based on projected growth rates. There will be a remarkable growth in consumption and demand for all sectors, estimated at 53.65 BCM and 63.44 BCM for agriculture; 14.02 BCM and 14.98 BCM for the domestic sector, and 4.01 BCM and 10.45 BCM for industry, by 2050. The difference between consumption and demand arises due to different loss rates of 37%, 27%, and 70% for agriculture, domestic, and industry respectively. Figures 6.15 and 6.16 show water demand and consumption for the different sectors under the balanced scenario.

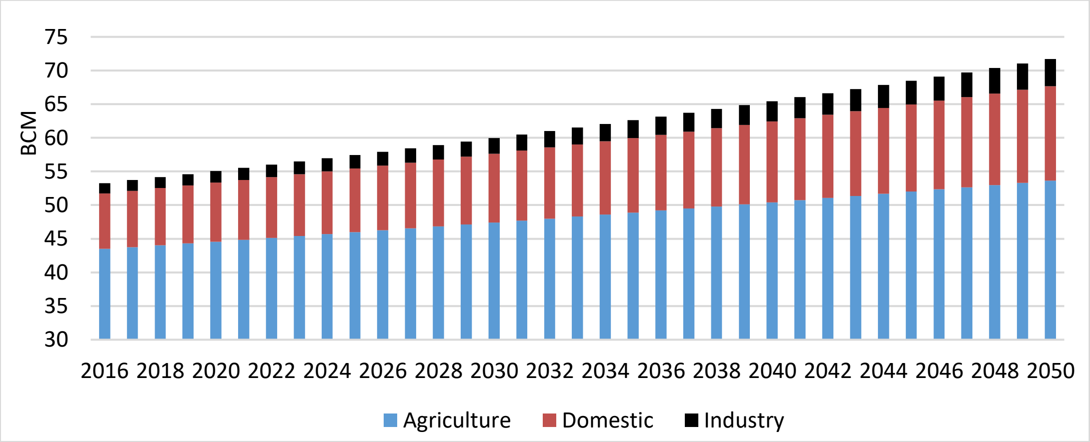


Figure 6.15 Water consumption by sectors under Balanced scenario 2050.

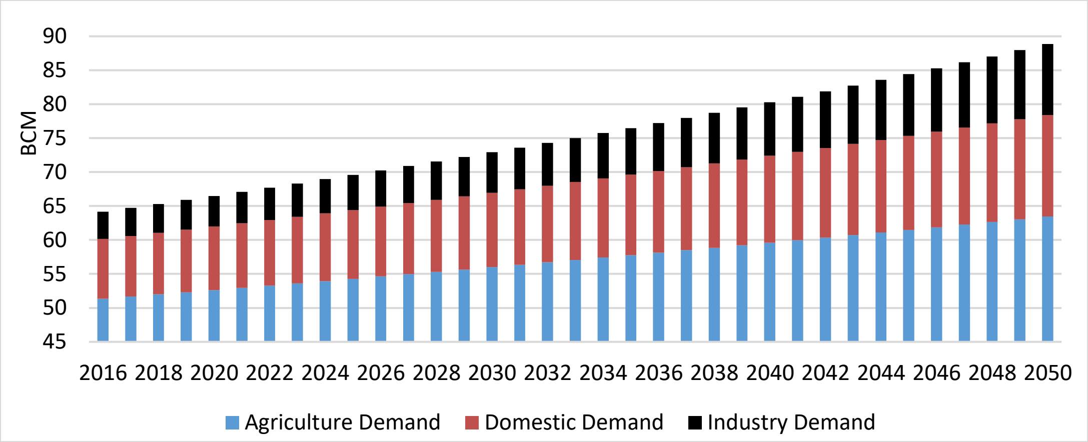


Figure 6.16 Water demand by sectors under Balanced scenario 2050.

Due to moderate inflow at Dongola station, about 65 BCM, and reasonable outflow from the HADR to Egypt, there will a water surplus in the High Dam reservoir reaching 118.36 BCM by 2050 (Figure 6.17).

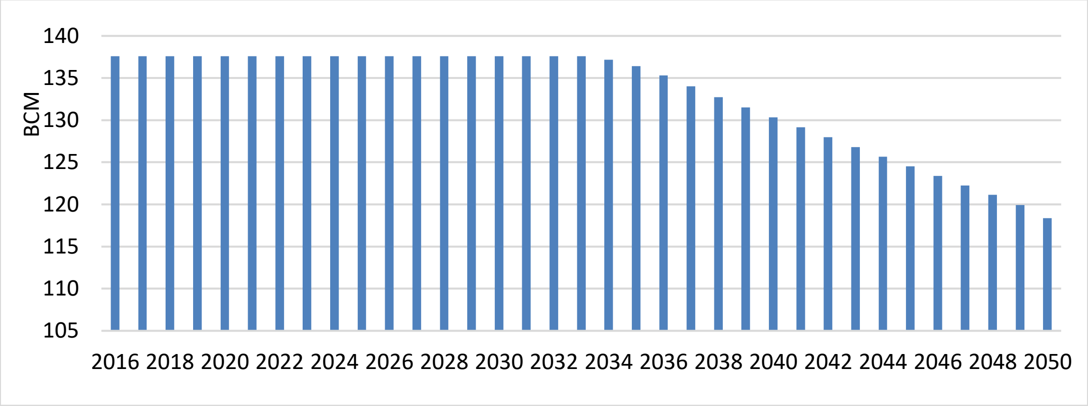


Figure 6.17 HAD reservoir volume under Balanced scenario 2050.

6.4.2.5 Pessimistic Scenario

In contrast to the optimistic scenario, the pessimistic scenario represents a worst case scenario, with a bleak view of demand and supply. Water demand is likely to increase sharply to about 116.74 BCM, with consumption at 91.85 BCM in 2050. This dramatic increase is due to accelerated growth in all demand sectors, improper policies, and large water losses due to the deterioration of infrastructure networks. Supply from the Nile River will reach its worst condition, reaching only 52 BCM annually due to climate variation and the construction of dams in upstream countries. In this case, Egypt will be forced to rely on unconventional resources such as water reuse and desalination. Supply in 2050 is 98.65 BCM and it will be insufficient to meet demand. It will get worse when groundwater exploitation reaches its safe yield (as sustainable groundwater use). Exploitation of shallow and deep groundwater exceeds the safe yields of 8.5 BCM/year and 4.9 BCM/year respectively; desalination reaches 2 BCM by 2050, rainwater harvesting reaches 2 BCM, and water reuse reaches a maximize of 25.7 BCM/year. All of these sources will be insufficient to bridge the water deficit due to the low supply from the Nile River and high demand of different sectors. The difference between the demand and supply sides appears from the beginning of 2029 and lead to a huge water deficit, estimated at 18.09 BCM by 2050 (Table 6.9 and Figure 6.18).

Table 6.9 Water balance for Egypt in 2050 under Pessimistic scenario.

Water Supply	Quantity BCM/year
Conventional	
River Nile	55.5
Deep underground water	4.9
Underground water in Sinai	0.04
Underground water in North	0.02
Rainfall and floods	2
Total	**62.4**
Non-conventional	
Desalination	2
Shallow underground water	8.5
Water reuse	25.7
Total	**98.65**
Water Consumption	
Agriculture	66.34
Domestic	16.24
Industry	5.77
Evaporation	2.5
Environment	1.0
Total	**91.85**
Water Demand	
Agriculture	77.02
Domestic	17.40
Industry	18.82
Evaporation	2.5
Environment	1.0
Total	**116.74**
Water deficit	**54.29**
Water shortage after addition of non-conventional resources	**-18.09**

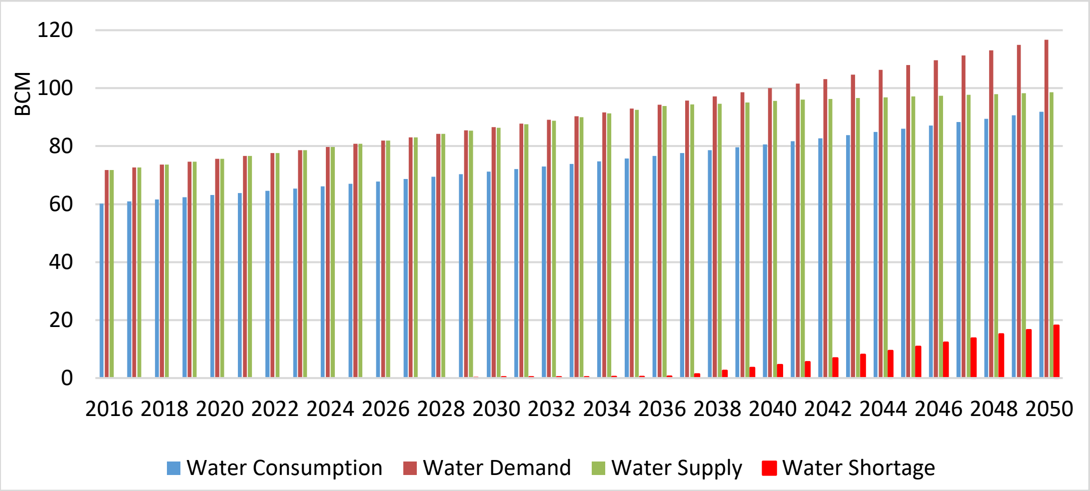


Figure 6.18 Water demand and supply under Pessimistic scenario 2050.

For the pessimistic scenario, the agricultural land and industrial units will report 13.06 million feddans and 18840 units respectively in 2050 based on the projected growth rates to meet the needs of an overpopulation that estimated by 174.7 million people by 2050. This will cause a huge water demand and consumption for each sector, where is estimated by 77.02 BCM and 66.34 BCM for agriculture; for domestic is reported 17.40 BCM and 16.24 BCM and 18.82 BCM and 5.77 BCM for industry by 2050 as shown in Figures (6.19) and (6.20). The loss rates causes the difference between water usage and demand, which indicate 40%, 30%, and 77% for agriculture, domestic, and industry consequently.

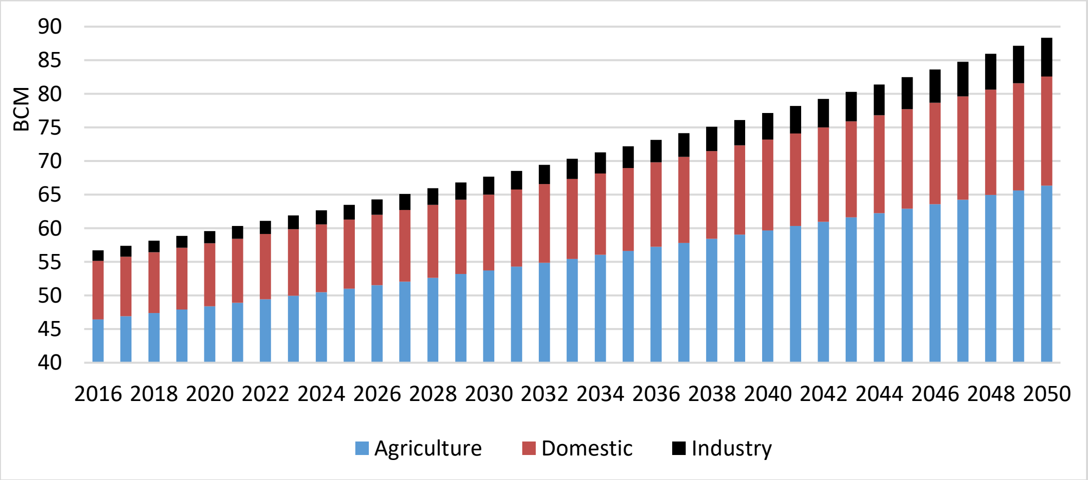


Figure 6.19 Water consumption by sectors under Pessimistic Scenario 2050.

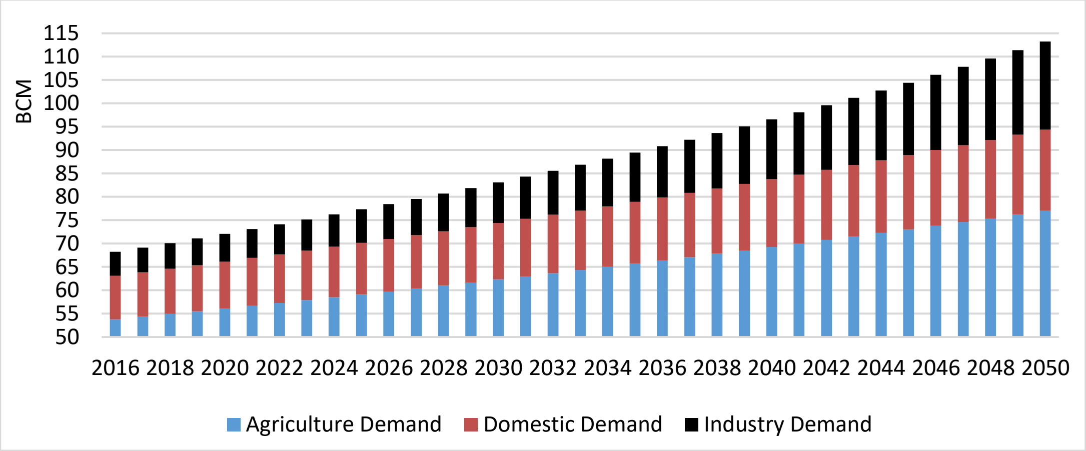


Figure 6.20 Water demand by sectors under Pessimistic Scenario 2050.

From the beginning of 2024, the water level in HADR will decrease dramatically due to the little inflow 52 BCM versus much outflow 55.5 BCM. It is noted that from the beginning 2028, Egypt cannot withdraw from the storage of HADR, where the volume of HADR will be under 40 BCM as shown in Figure (6.21). This means that the High Dam turbines will stop if Egypt faces these serious conditions. In addition, depending on the results of this scenario, Egypt should adopt another policy and look for an alternative water resource to bridge the water gap in the future.

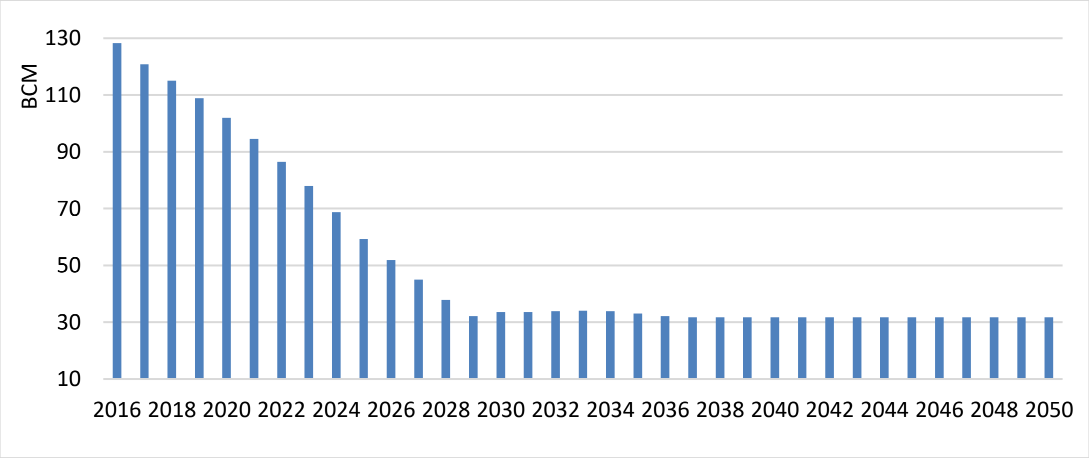


Figure 6.21 HAD reservoir volume under Pessimistic scenario 2050.

6.4.2.6 Hybrid Scenario

This scenario combines the probabilities of balanced and optimistic scenarios permutationally. Results (Table 6.10 and Figure 6.22) show that all demands are met to 2050. Consumption and demand rise slightly to 71.42 BCM and

83.52 BCM respectively by 2050. Supply increases to 83.52 BCM due to increased water reuse. The water deficit is easily overcome, even though the outflow from the High Dam is only 54 BCM. Rainwater harvesting rates remain at 1.3 BCM/year under assumption of no climate change over Egypt, while desalination expand to 1.25 BCM/year by 2050. Groundwater exploitation is below its normal level, and will be 3 BCM for deep groundwater and 6 BCM for shallow groundwater.

Table 6.10 Water balance for Egypt in 2050 Hybrid scenario.

Water Supply	Quantity BCM/year
Conventional	
River Nile	54
Deep underground water	3
Underground water in Sinai	0.04
Underground water in North	0.02
Rainfall and floods	1.3
Total	**58.35**
Non-conventional	
Desalination	1.25
Shallow underground water	6
Water reuse	17.92
Total	**83.52**
Water Consumption	
Agriculture	51.04
Domestic	13.24
Industry	4.04
Evaporation	2.5
Environment	0.6
Total	**71.42**
Water Demand	
Agriculture	58.00
Domestic	14.55
Industry	7.87
Evaporation	2.5
Environment	0.6
Total	**83.52**
Water deficit	**25.17**
Water shortage after addition of non-conventional resources	**0.0**

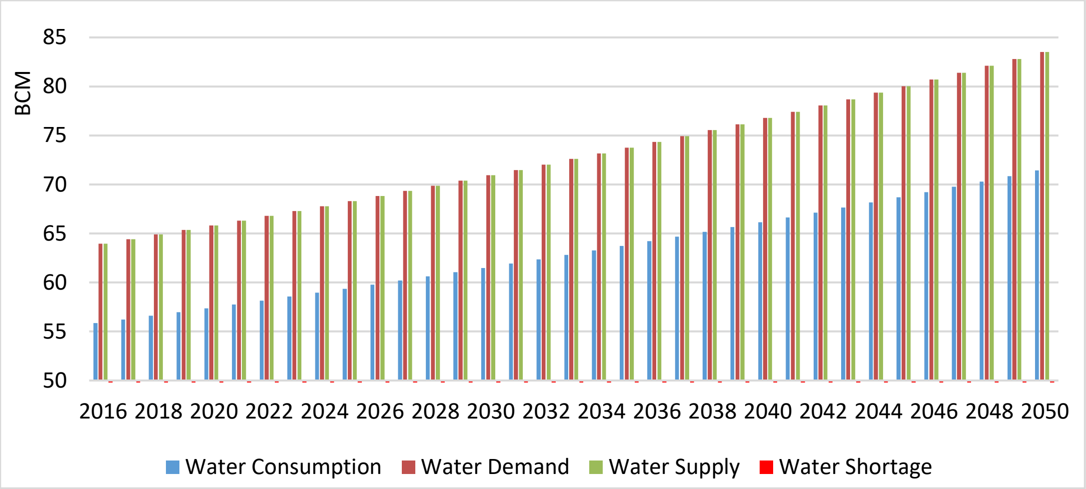


Figure 6.22 Water demand and supply under Hybrid scenario 2050.

In the Hybrid scenario agricultural land, population and industrial units are estimated at 10.83 million feddans, 160 million people and 15,387 industrial units by 2050. This leads to a reasonable water demand and consumption for each sector, water demand is very close to current levels. Water consumption and demand are 51.04 BCM and 58 BCM for agriculture; 13.24 BCM and 14.55 BCM for the domestic sector, and 4.04 BCM and 7.87 BCM for industry, in 2050 (Figures 6.23 and 6.24). This modest increase attributes to the decrease in annual water consumption rates and losses rates for different sectors.

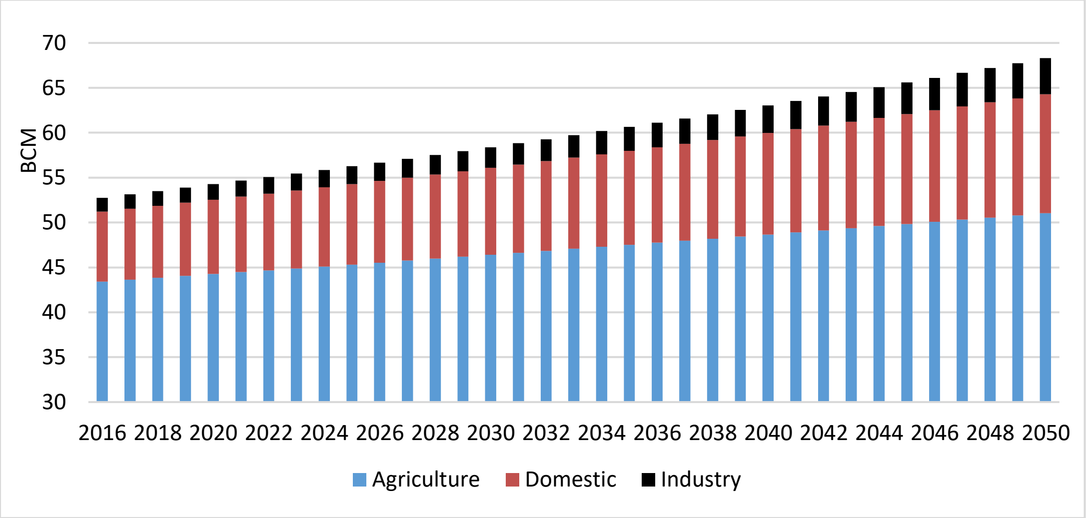


Figure 6.23 Water consumption by sectors under Hybrid Scenario 2050.

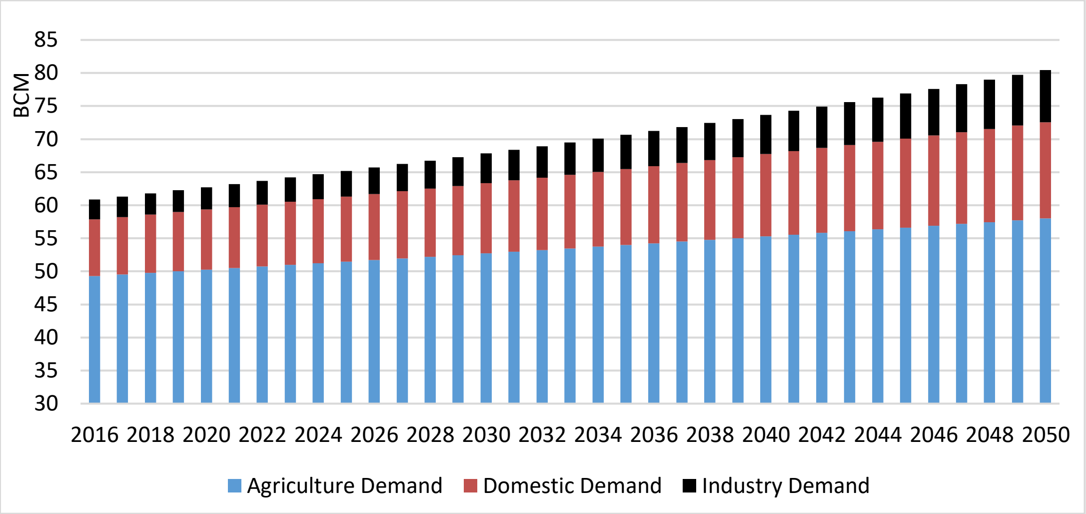


Figure 6.24 Water demand by sectors under Hybrid scenario 2050.

Inflow at Dongola station will be 65 BCM under this scenario and outflow from the HADR will be 54 BCM, giving a surplus in the High Dam reservoir reaching 137.5 BCM along the scenario period and 132.5 BCM by 2050. This means that Egypt should release the HADR water surplus to Toshka depression in the Western desert. Under these conditions, Egypt can close the water gap without difficulty. Figure 6.25 presents the storage volume of HADR over the period 2016 – 2050 under the Hybrid scenario.

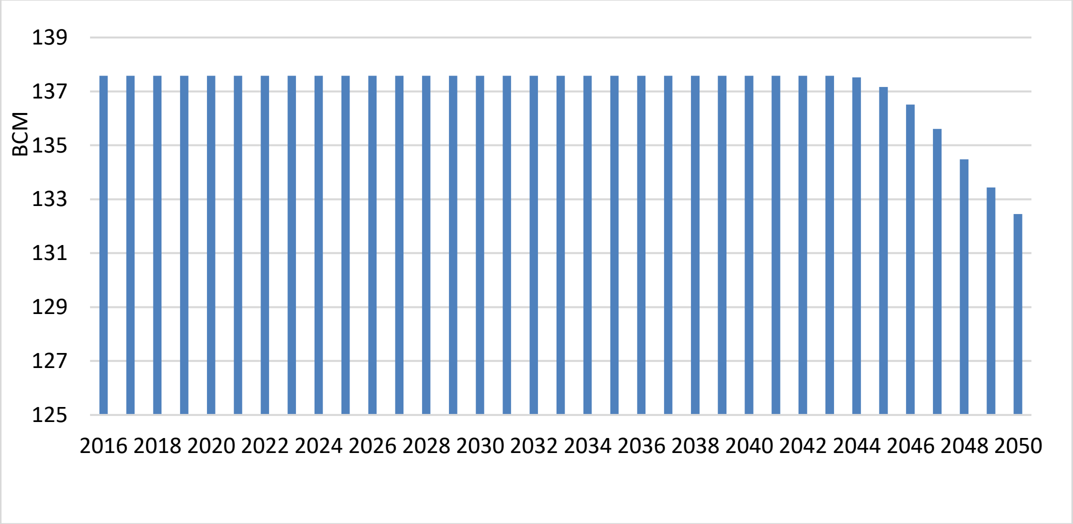


Figure 6.25 HAD reservoir volume under Hybrid scenario 2050.

6.4.3 Uncertainty and Complexity Analysis

To compare the uncertainty or variation associated with the scenario, the coefficient of variation (CV) was derived. The CV denotes the risk associated with each scenario allowing comparison across them. Because of the differences in the mean value of water demand and supply for each scenario, the coefficient of variation (CV) is a better measure. The results reported above for each scenario were used to produce means and standard deviations. This implies that for each scenario two means were computed for water demand and supply, allowing calculation of standard deviations of demand and supply separately (Section 6.3.2). Using these metrics, the coefficient of variation (CV) can be determined for water demand and supply in each scenario, and the relative variability/uncertainty between them determined. Results are available for the 2016 – 2050 simulation period as shown in Table 6.11.

The results indicate that the uncertainty range is reasonable fair with standard deviation values in the range of 4.4 -13.4 BCM for the six scenarios (Section 6.3.2). For the Optimistic, Hybrid, and Balanced scenarios, CV values are 0.06, 0.08, and 0.09, respectively. CV increases slightly to 0.11 and 0.10 for the demand and supply sides respectively of the BAU scenario. The CV for the Critical scenario is 0.11 for both demand and supply, and for the Pessimistic scenario is a higher 0.14 and 0.10 for demand and supply, indicating greater uncertainty. The higher uncertainty of the Pessimistic scenario and difference in uncertainty for the other scenarios is attributed to variability in growth rates for agriculture, population, industry, and supply. Increasing agricultural areas, population, and industrial units places a high demand on water resources, while the water supply is limited; the point that affects the enlargement of the water shortage.

It is noted that uncertainty is growing with widening the water gap between supply and demand, where the water gap represents the difference between the demand and supply values. In addition, uncertainty in water demand increases slightly compared to water supply, especially in the Pessimistic and BAU scenarios, due to the relative stability of supplies. Furthermore, considering the water gap and the mean values of all scenarios, one can rank them easily. According to the resulting water gap, the Optimistic scenario leads to the best results for Egypt and the Pessimistic scenario the worst.

The risk of each scenario is reflected in the CV, where the Optimistic scenario is lowest risk and the Pessimistic scenario highest risk. However, the uncertainty ranges show that the six scenarios differ relatively for demand and supply for the period 2016 - 2050 and they may vary greatly from each other, particularly in the near future after 2050. Table 6.11, and Figures 6.26 and 6.27 depict a summary of the uncertainty analysis of the WEAP model scenarios, using the water demand, supply, and gap as the performance index.

Table 6.11 Demand, supply, and deficit (BCM) by modelled scenarios.

Measure	**BAU scenario**		**Critical scenario**		**Optimistic scenario**		**Balanced scenario**		**Pessimistic scenario**		**Hybrid scenario**	
	Demand	Supply	Demand	Supply	Demand	Supply	Demand	Supply	Demand	Supply	Demand	Supply
Demand & Supply (BCM)	115.0	106.1	94.1	93.7	76.0	76.0	92.0	92.0	116.74	98.6	83.5	83.5
SD	11.0	9.5	9.1	9.03	4.4	4.4	7.4	7.4	13.4	8.9	5.8	5.8
Mean	95.0	93.9	77.0	77.0	68.1	68.1	78.7	78.7	91.7	87.9	73	73
CV %	11.6	10	11.8	11.7	6.5	6.5	9.4	9.4	14.7	10	8	8
Consumption (BCM)	83.1		75.4		63.5		74.8		91.8		71.4	
Non-conventional sources (BCM)	44.3		33.7		17.6		29.0		36.2		25.1	
Loss Rate % (agriculture)	37		30		35		37		40		30	
Loss Rate %(domestic)	29		27		25		27		30		29	
Loss Rate %(industry)	77.8		65		50		70		77		60	
Water gap (BCM)	8.9		0.31		0.00		0.00		18.09		0.00	

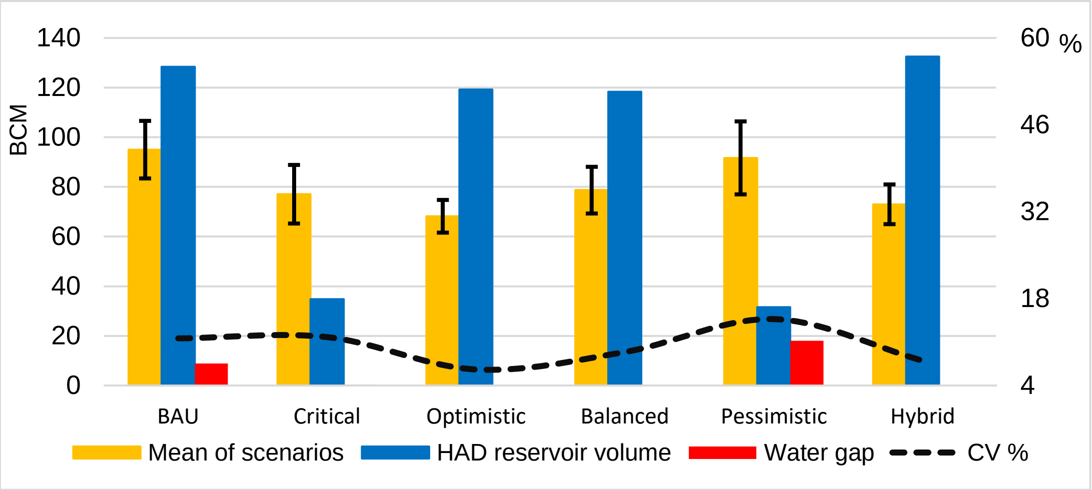


Figure 6.26 Water demand averages, HAD reservoir volume, Water gap under the various scenarios and its uncertainty.

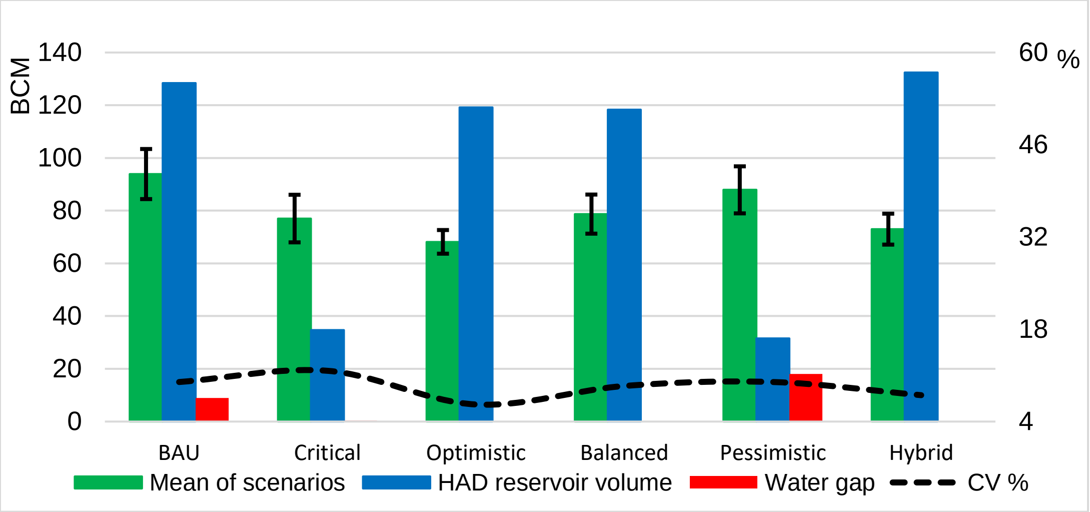


Figure 6.27 Water supply averages, HAD reservoir volume, water gap under the various scenarios and its uncertainty.

Every water system has some complexity presenting challenges to overcome to achieve sustainable water management goals. The complexity in developing water demand and supply scenarios is represented in selecting the appropriate model, system representation, data availability limitation, determining the scenarios drivers, and identifying spatial and time scale. All these factors contribute to complexity in developing the demand and supply scenarios.

The WEAP model offers sophisticated and flexible tools to develop scenarios and explore options for the future, where implications of various probabilities and policies can be evaluated. Even though Egypt’s water system is very complex due to the large spatial scale and attributes of its demand and supply factors, WEAP performed well in simulating this system. Data availability issues add complexity in the modelling process in general and in developing scenarios in particular, as data influences model selection, scenario drivers, and time and spatial range.

An advantage of WEAP is that it can run in different time frames, daily, monthly, or yearly. This reduces complexity by adding flexibility during the process of collecting and making data available to the model. Furthermore, running WEAP with an annual time step greatly reduces the complexity of dealing with big data given the extensive temporal and spatial scales. Figure 6.28 provides an integrated view of the complexity factors and their interrelationships and interconnections faced in the development of the water demand and supply scenarios.

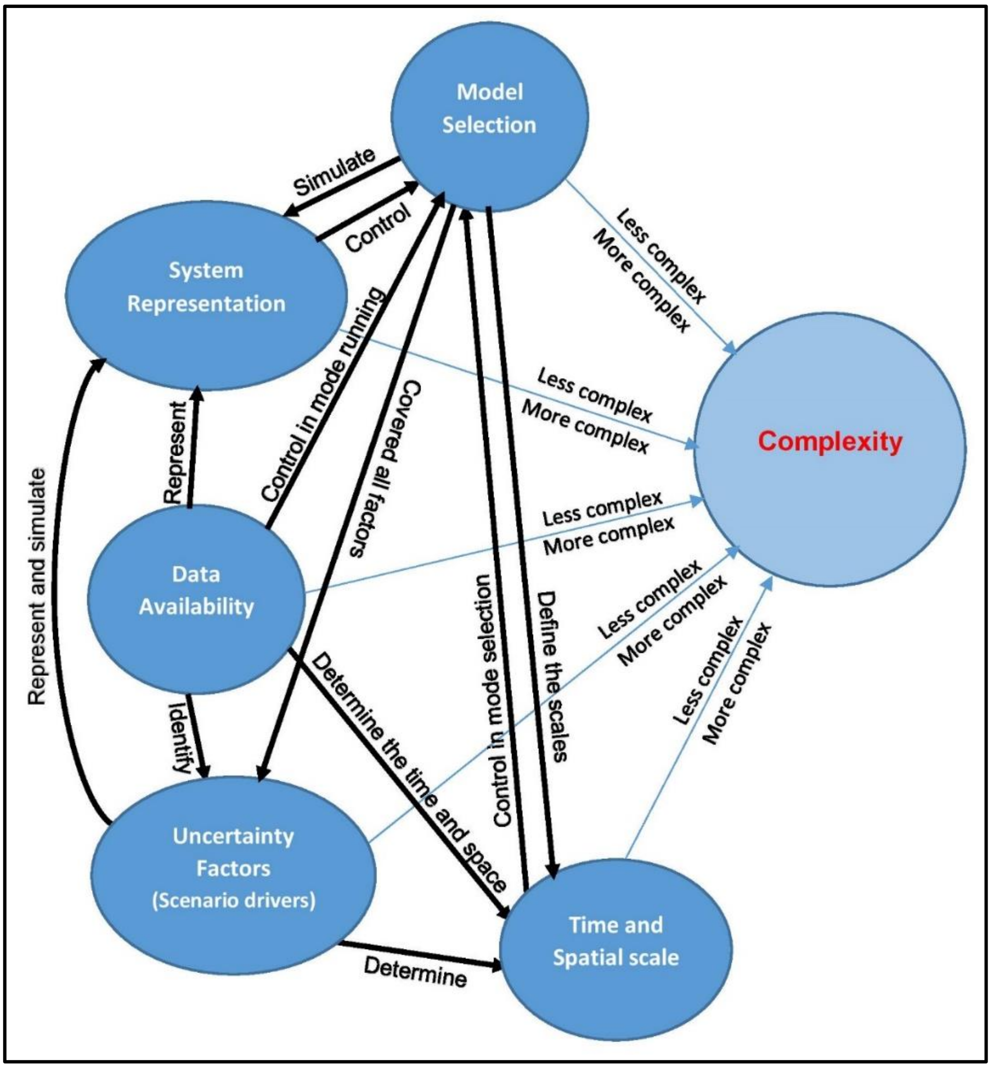


Figure 6.28 Complexity factors and interrelationships in development of water demand and supply scenarios.

6.5 Conclusion

The study developed and evaluated six scenarios for Egyptian water resources from 2016 - 2050 using the WEAP model to address uncertainty in future water demand, supply and consequent deficit. The current water gap is 19.2 BCM in 2015 and Egypt bridges this gap by unconventional resources such as water reuse, desalination, and withdrawal of shallow underground water in the Nile valley and Delta. Agriculture is the largest user of water followed by domestic and industrial users for the current state and over the six scenarios. In three scenarios (BAU, Critical, and Pessimistic), Egypt faces a widening water gap, but three other scenarios (Optimistic, Balanced, and Hybrid) are more optimistic. The findings show that the extremely high population growth rate, increased agricultural expansion, and industrial expansion in Egypt have a crucial role in pushing the water shortage to alarming rates. A water gap in 2050 that Egypt could not bridge under current policy and practice would be 8.9 BCM, 0.31 BCM, and 18.09 BCM according to the BAU, Critical, and Pessimistic scenarios respectively.

Egypt can bridge the deficit in the BAU and Critical scenarios by using an available surplus in the HADR. However, in the Pessimistic scenario Egypt cannot overcome the deficit as there will be no HADR surplus, and storage falls below the dead zone level. The scenario modelling indicates that Egypt's future water needs could far exceed anticipated supply. This potential outcome is alarming and requires proactive policy and management to reduce losses, curb demand, and possibly develop new resources.

The scenarios approach for analysing water demand and supply using WEAP is a useful approach to evaluate the future of water demand and supply and teste different measures and policies to bridge the water gap. Furthermore, the study offers a way for policymakers to benefit from the emerging research in uncertainty and complexity of the development of water demand and supply scenarios.

The methodological choices of this chapter adopted scenarios analysis approach and six scenarios were developed to frame the potential future of water demand and supply. The scenarios were developed based on a coherent and internally consistent set of assumptions about driving forces and key relationships. The choice of using the WEAP model to achieve these scenarios affected the framing the scenarios accurately, running the model easily and reducing the computational time due to the flexibility of the model structure. The results were sensitive to the selected drivers' changes, especially when combined with the change of water outflow and inflow. In addition, choice of selecting these drivers and their uncertainty ranges strongly affected the results of all scenarios in comparison to the results of other studies. Furthermore, results of the scenarios showed variation in the output of water demand, supply, and deficit due to the difference in the drivers' values and the coefficient of variation helped in showing the variation associated with the output of each scenario. These methods and choices can be generalized broadly and the results are internally valid and can be used to compare with results of other studies discussing the same issues.

In brief, this work has contributed to framing the future water demand and supply scenarios under the uncertainty and complexity factors in the Egyptian water system. These scenarios frame the potential future of water demand and supply for supporting water planners and mangers by expecting the consequences that they may face in the future. Attention should be drawn to optimizing water resource use where water resources available may not meet the future need. From that, it is hoped that this model will be validated in areas experiencing similar problems.

In conclusion, this chapter frames the potential future of Egypt's water demand, supply and shortage to 2050, and the pessimistic scenario has been determined as the worst case based on the high water gap that Egypt cannot bridge it and the storage volume in HAD reservoir falls below the dead zone. The next chapter will develop a model of integrated water resources management (IWRM) in the WEAP model by identifying the optimal measures and policies to bridge the water gap under this pessimistic scenario as the worst case.

Chapter 7

Integrated Water Demand and Supply Management

7.1 Overview

In the previous chapter, the potential future of Egypt's water demand, supply and deficit was detected through six scenarios. These scenarios support water planners and mangers by expecting the consequences that they may face in the future. The pessimistic scenario was identified as the worst case Egypt faces according to the outcomes of the water gap and storage volume of HAD reservoir. This potential outcome is alarming and requires proactive policy and management to reduce losses, curb demand, and possibly develop new resources. Chapter 7 aims to answer the research question about addressing the uncertainty and complexity in water demand and supply management to bridge the water gap resulted from the pessimistic scenario. The chapter will identify the optimal measures to bridge the future water gap through addressing and eliminating the uncertainties about these measures to help planners and decision-makers to find alternative solutions. The chapter will evaluate the multiple sources of uncertainty associated with planning measures such as feasibility of measures, implementation restrictions, cost, risk, compatibility with environment, effectiveness, and public and political acceptability (Section 7.3.2). The study presents a methodology adopting a precautionary approach, which uses the WEAP model and Delphi method-led questionnaires based on group communication to identify critical uncertainties and find optimal measures and robust solutions to water deficit (Section 7.3).

This chapter begins with an overview of the chapter methodology steps (Section 7.3), the methodology of stakeholders selection (Section 7.3.1), preparing the questionnaire (Section 7.3.2), Delphi method workflow (Section 7.3.3), and building the IWRM model based on the pessimistic scenario outcome (Section 7.3.4). These followed by presentation of results and discussion (section 7.4) in three points: Questionnaire results (7.4.1), Integrated water resources management model (Section 7.4.2), Water Balance 2050 (Section 7.4.3).

7.2 Introduction

Integrated Water Resources Management (IWRM) is a complex process that requires monitoring and adjustment of the effects of the water management measures as new information and technology become available under changing, uncertain external effects (Van der Keur et al., 2008). IWRM is a practical concept, developed from the hands-on experience of practitioners (Hassing et al., 2009). This chapter presents a multi participatory perspective on how the proposed measures fit together to facilitate the development of integrated management processes that are best suited to dealing with an extremely uncertain future. This process is created among a broad group of stakeholders through questionnaire.

The main objective of this chapter is to implement a modelling approach for the analysis and integrated management of water demand and supply in Egypt. This approach attempts to deal with the uncertainty and complexity of supply and demand management through stakeholder participation and testing of proposed precautionary measures and policies to close Egypt's future water gap identified by WEAP modelling. Therefore, it is hoped to identify the optimal measures and policies to help decision-makers and planners manage water resources under the case of the worst conditions in the future (Section 7.3.4).

Water resource management analysis and policy development is particularly complex, as it extends across many disciplines and involves human behaviour. This complexity poses a challenge to deal with uncertainty in demand and supply, where a wide range of hydrological, technical, economic, and political drivers must be incorporated into the model. The task of IWRM models is to bring together the numerous aspects of water demand and supply so that projections, analyses, and decisions can consider all the relevant and important variables simultaneously. Integrated management modelling can offer the following advantages:

- Ability to address policy-relevant questions (Van Delden et al., 2007);
- Considers long-term problems and planning issues (Geertman and Stillwell, 2003; Van Delden et al., 2007);
- Facilitates group interaction and discussion (Newham et al., 2007; Van Delden et al., 2011);

- Applicable to complex decision domains, with a large number of participants, variables and relationships, and having a high degree of uncertainty and complexity (McIntosh et al., 2007);
- Is user friendly regarding input, output and results analysis (Volk et al., 2008);
- A flexible system based on components that can be extended over time by further modules (Argent, 2004; Van Delden et al., 2009); and
- Integrates economic, environmental, and social drivers (Van Delden et al., 2011).

In Egypt, as elsewhere in the world, the government is struggling to ensure water supply to the population, industry and irrigated areas. This is one of the water management complexities, where limited water supply is not enough to meet demand. In the face of this issue, planners and decision-makers seek to urgently develop and implement policies and strategies for the optimum use of water resources. This process can be supported by development of integrated water management models based on a combination of variables relating to demand and supply as well as the imperative management measures.

In Egypt, IWRM faces five major challenges: a rapidly growing population; reduction of the Nile flow due to climate change and dam building; water pollution due to domestic, industrial and agricultural activities; institutional setting of water management, which is a governmental and central by nature; and sea level rise (Nour El-Din, 2013). These factors contribute to increasing uncertainty and complexity in water resources management. To face these challenges, measures and plans were prepared by the MWRI and researchers, which comprise the following policy strategies:

- The Mono strategy to adapt to individual challenges such as policies of adaptation to climate change (Eid, 1997; Sayed and Nour El-Din, 2002; Attaher et al., 2009; Metwalli, 2010; NSACC, 2011; Blanken, 2012) or sea level rise (e.g. El-Raey et al., 1999; RIGW, 2011; Nofal et al., 2014);
- The Limited strategy, where a strategic package of management measures is developed, but applied only to a small area within Egypt such as Delta, Fayoum and Nasser Lake (Radwan, 1998; Zaghloul et al., 2011; Omar, 2013),

- The Comprehensive strategy, where includes many measures and variables to contribute to IWRM nationally (Abu-Zeid et al., 1992; MWRI, 1997; NWRP, 2005; MWRI, 2010; Mohie El Din and Moussa, 2016).

These strategies did not include sufficient actions to face the consequences of challenges of the current and expected water gap. Furthermore, they did not identify or address uncertainty of measures or actions in terms of their ability to bridge the water gap. This may be attributed to insufficient communication with all sectors and governorates. Water managers and policymakers need to integrate a series of complex matters, actions and measures to overcome the water gap now and in the future. These measures and actions need to identify and evaluate associated uncertainty, determining their feasibility in the water plan, within a precautionary approach.

To deal with uncertainty and complexity in water management and adaptation policies, Wilby and Dessai (2010) suggested a framework for testing proposed measures against a list of plausible scenarios of future conditions, asking how well these measures would perform under these future scenarios? This study looks for options that are likely to perform well across the Pessimistic scenario, the future worst-case. This is consistent with Kundzewicz et al. (2018) who report that managing uncertainty requires application of the precautionary principle and adaptive management. In the presence of uncertainty, many measures and actions taken to bridge the water gap have impacts that one cannot now predict. Dealing with this uncertainty and complexity requires establishment of a framework to assess programs of measures for the future water system in order to reach the set IWRM targets. This framework should use an integrated approach to include societal, economic, administrative and technological measures (Rekolainen et al., 2003). In this chapter, uncertainties in water management are thus dealt with by examining uncertainties associated with precautionary measures and actions to overcome the water gap, considering cost, risk, implementation restrictions, environmental compatibility, political acceptability, feasibility, effectiveness, solve the problem, and public acceptability (Section 7.3.2).

This chapter aims to evaluate uncertainty of measures proposed to bridge the water gap. This will assist planners and managers in selecting the optimum measures to overcome the water shortage from now to 2050 (a stated goal of the Egyptian Ministry of Water in 2015), under the Pessimistic scenario. Decision-makers and stakeholders engaged in a participatory process of evaluating actions and measures that can be taken nationally to overcome vulnerability and maximize the resilience of water systems to uncertainty from climate change, population growth, developmental changes, and transboundary problems.

The participatory process applied with decision-makers and stakeholders is facilitated by the Delphi method, originally developed by the RAND project to forecast the impact of technology on war at the beginning of the Cold War (Custer et al., 1999). The Delphi technique is now widely used in resolving complex water resource management issues (e.g. De Loe, 1995; Taylor and Ryder, 2003; Kim et al., 2011; Chung et al., 2014; De Carvalho et al., 2017). It is a group communication method where a panel of experts arrive at a consensus over a series of questions and issues. It is used with estimating and forecasting, where it relies on a panel of experts (Thangaratinam and Redman, 2005; Hsu and Sandford, 2007).

7.3 Data and Methods

Egypt will face fewer problems in water demand and supply under the optimistic scenario, but serious consequences are expected under the Pessimistic scenario. Therefore, it is essential that IWRM build on the assumption of a pessimistic scenario occurrence using the precautionary approach. This approach is consistent with the adage "better safe than sorry". The main objective of this study is to select the optimal measures for integrated management to bridge the water gap in the future. The process of selecting the optimal measures for integrated water resources management is based on a participatory communication process among stakeholders across disciplines and sectoral silos. To achieve the goal of this chapter, I depended on Delphi method-led questionnaires and integrated modelling in the WEAP model. The principle of the model is investigating and presenting the water demand and supply to compare between them and giving the unmet demands in the results, then developing the exploratory analysis to identify the impacts on increasing or decreasing the water demand and supply, and examining the measures to select the optimal measures to overcome the deficit. The methodology of this chapter can be illustrated in Figure 7.1 and summarized in the following steps:

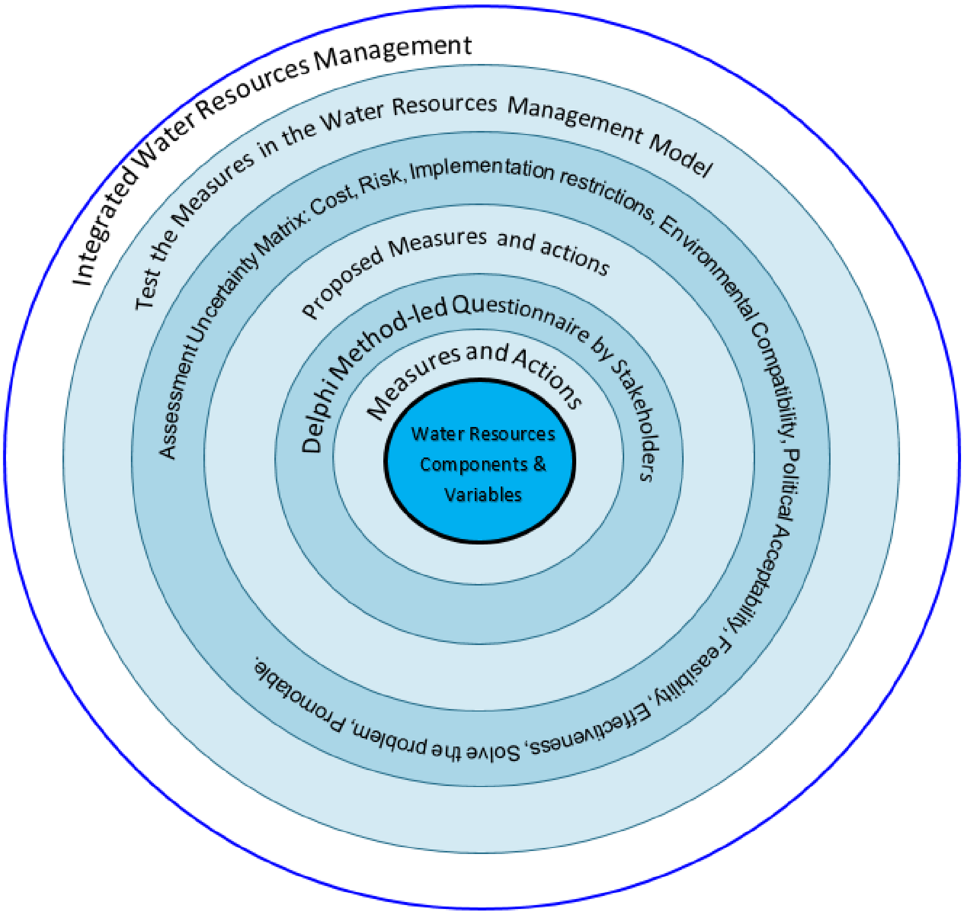


Figure 7.1 Methodology for dealing with uncertainty and complexity in water management with the precautionary principle.

1. Identify water demand and supply components and variables, and current measures;
2. Identify stakeholders and select the participants;
3. Prepare the questionnaire and method of application;
4. Conduct fieldwork to apply questionnaire;
5. Questionnaire analysis and extraction of information on proposed measures and actions;
6. Prepare the data for the IWRM model using WEAP;
7. Create and set the WEAP model to the Pessimistic scenario to test the proposed measures;
8. Run the WEAP model with the proposed measures and actions to bridge the water gap under the pessimistic scenario until 2050.

This methodology was designed to deal with the uncertainty and complexity in demand and supply management and so develop an IWRM package to support policymakers.

7.3.1 Selection of Stakeholders

Stakeholder identification is the first step in the process, and is important to ensure stakeholders with sufficient expertise and ability to judge uncertainty of management and measures are included. Stakeholders are those people who have a direct relationship and relevant influence and power over water resources management and water policy makers. In other words, the stakeholders are parties interested in water resources that influence or are influenced by the water strategy or policy. For this study, stakeholders from nine different organizations plus specialized researchers in water resources participated (Table 7.1). Although 66 people were identified as suitable stakeholders for questionnaire, only 44 people responded due to obstructions and difficulties in the work environment of a political and administrative nature including issues of confidentiality (Table 7.1). The criteria for selecting stakeholders were previous relevant work, current tasks, participation in water management plans in Egypt, and their power over my work and their interest in it. For example, the Ministry of Water and National Water Research Centre are key players in water management in Egypt, with the highest power and interest of any stakeholder organisation. They should engage in the questionnaire more than people in other organizations because they are in water management closely; this priority is ranked in Table 7.1.

Table 7.1 Distribution of the 44 expert stakeholders by institution.

Priority	**Stakeholders and interested parties**	**Responders number**	**Non-responders number**	**Reason**
1	Ministry of Water Resources and Irrigation (MWRI)	10	3	Administrative and confidential issues
2	National Water Research Centre (NWRC)	7	5	Not returning the questionnaire (lost in a pile of paperwork)
3	University professors specialized in water resources	5	4	Not returning the questionnaire & Too busy to participate
4	Ministry of Agriculture and Land Reclamation (MALR)	5	4	Administrative and confidential issues
5	Ministry of Health and Population (MOHP)	3	1	Too busy to participate
6	Ministry of Industry (MoI)	4	1	Too busy to participate
7	Ministry of Housing, Utilities and New Communities (MHUNC)	3	1	Too busy to participate
8	Egyptian Environmental Affairs Agency (EEAA)	4	3	Not returning the questionnaire & Too busy to participate
9	Ministry of Local Development (MoLD)	3	--	

7.3.2 Preparing the Questionnaire

The first round questionnaire was based on an extensive review of the literature, and the subject to several iterations with stakeholders to identify further items. The questionnaire comprised 27 questions covering the experts opinion of the water gap issue, reasons for it, expectations in 2050, water demand, water supply, water resources management, the current water plan, proposed measures, and uncertainty associated with management measures based on an uncertainty assessment matrix (See Appendix 3 for details). In the questionnaires, a mix of open and closed questions were used to collect data and information on water resources management in Egypt. The questionnaire included categorical, ordinal questions, and interval/ratio questions such as matrix questions, and textbox questions. The questionnaires was conducted in Arabic or English depending on stakeholder preference with Arabic answers later translated to English. All translations were reviewed by Dr. Reham Hosny, Lecturer at Department of Arabic, University of Leeds and Department of English, Minia University.

In addition, the questionnaire included an assessment matrix designed to assess the uncertainty and complexity of fifteen proposed water management measure (Question No. 25, Appendix 3). These measures were collected from the global and national water plan, and literature review, taking into consideration the measures proposed by stakeholders (Section 7.4.1.3 and 7.4.1.4) during implementing the Delphi method (Section 7.3.3). Thus, the measures were evaluated by stakeholders based on a set of criteria as follows:

- ***Cost:*** The uncertainty associated with the cost of a specific measure may necessitate finding cost-effective alternatives. The most cost-effective measures should be chosen in water management models, which requires taking into account the overall costs (Rekolainen et al., 2003). For example, the high cost of desalination may prevent the expansion of this measure. The stakeholder judgment of the measures in terms of cost was divided into low, medium, or high.
- ***Risk:*** Risks may be associated with the proposed measures, which affect their efficiency in the water management process. For example, reducing discharges to sea may increase water pollution, or the risks that desalination leads to increased costs and energy dependency (Orr et al., 2009). Avoiding high-risk measures may address the cognitive uncertainty in the water management process. In this study, uncertainties relevant to

risks of measures were identified in the assessment matrix as low, medium, or high (Section 7.4.1.4).

- **Implementation restrictions:** There may be limitations in implementing a measure in the water management process. For example, not exceeding the safe limit for groundwater withdrawal; presence of wars and conflicts that prevent the completion of water projects or funding problems.
- **Environmental compatibility:** There must be a certainty that the actions and measures are non-hazardous to the environment and are compatible with it.
- **Political acceptability:** This refer to the attitudes of decision-makers' towards a specific management measure, such as changes in water tariffs, changes in crop patterns, or implementing a project. Water acts and initiatives are determined and enforced in what is usually a highly politicised environment (DEPA, 2002).
- **Feasibility:** The feasibility of measure aims to uncover the strengths and weaknesses, opportunities and threats existing in the economic and financial feasibility, and the probabilities of success by choosing from two metrics feasible or infeasible. Briefly, the feasibility evaluates the value of a measure to water resources management according to the opinion of the stakeholders.
- **Effectiveness:** To what degree the measure or action succeeds in achieving the desired outcome. The desired result of any management action is to save water.
- **Solve the problem:** Is the measure able to solve the water gap problem or contribute to reducing the water gap?
- **Public acceptability:** The acceptability of the measure to promotion and increase depending on the attitude of citizens, for example, measures such as increasing the water tariff or increasing the desalination may be less acceptable and more dispensable due to the economic situation of the citizens and the state.

Thereafter, stakeholder opinions were collected using the Delphi method (Section 7.3.3) and measures ranked based on the highest score for each measure that had the support of stakeholders (Section 7.4.1.4).

7.3.3 Delphi Method

IWRM entails multiple data and components but is vulnerable to data inadequacy. The Delphi method is thus useful as it can provide missing information based on assessing experts. The Delphi technique was used to conduct the questionnaires to determine the expectations, needs, and requirements of water resources management to be brought into the integrated modelling effort using WEAP with other water supply and demand components.

To implement the Delphi process (Figure 7.2), the experts were identified and invited to participate in the questionnaire. In every round of the Delphi study, each participant was asked the same set of questions individually, without disclosing their identities to others. Consequently, in the first round of the opinion gathering session, participants had no need to worry about being forced to a final outcome. In subsequent rounds, they had the ability to change their answers in light of others' answers – without knowing the identity of the others – or to hold to their original opinion. Three rounds of opinion-gathering sessions were held until participants reached a consensus about all the questionnaire questions and the measures proposed to overcome water gap under the pessimistic scenario. The researcher arranged, coded, and evaluated the answers after the first round of questionnaires then prepared a second round of questions. In the third round, the same procedure was repeated to achieve close consensus in the answers to the questions. It is worth noting that Delphi method is complex in its implementation in Egyptian institutions where there is often more than one participant in the same room and we could not separate them. In addition, they are worried about participating in the questionnaire without the permission of the heads of the institutions.

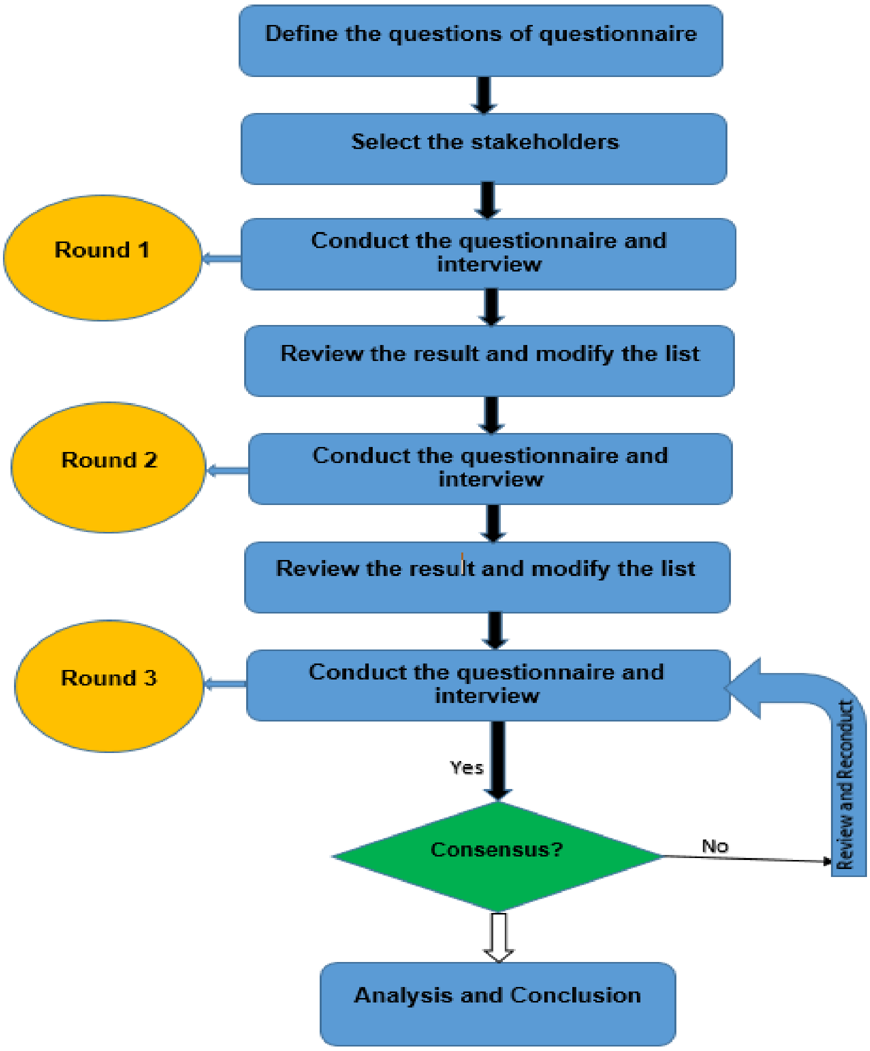


Figure 7.2 Delphi process workflow.

7.3.4 Building the IWRM Model

By observing the future scenarios in Chapter 6, the water deficit issue has remained only on the level of the Pessimistic scenario. In 2050, there would be a water deficit of 18.09 BCM, which cannot be bridged by current measures and policy as shown in Table 7.2. Therefore, the integrated water resources management model is developed on the basis of the worst-case scenario considering economic development and population growth and the consequent change in demand, as well as the transboundary stress on Egypt's water system from climate variability, and building dams in other Nile basin countries. The WEAP model is used to test the adaptation measures considered optimal by stakeholders in the Delphi process, to overcome the future water deficit. This IWRM application of the WEAP model was built as follows:

- A WEAP schematic for water demand and supply components was created;
- WEAP model components and data set to the Pessimistic scenario to 2050 as in Table 7.2;
- Data and measures from the questionnaire process are entered into WEAP;
- The WEAP model is run with the proposed measures and actions to examine their ability to bridge the water gap.

Table 7.2. Key drivers and data of Pessimistic scenario used in the IWRM model.

Agricultural expansion	1.1%	Shallow groundwater	8.5 BCM
Annual water consumption rate for feddan	4800 M^3	Deep groundwater	4.9 BCM
Population growth	1.85%	Desalination	2 BCM
Annual water consumption rate for person	95 M^3	Reused water from agriculture	30%
Industrial expansion	2.69%	Reused water from domestic	25%
Annual water consumption rate for industrial unit	300000M^3	Reused water from industry	25%
Environment	1 BCM	Loss rate from agriculture	40%
Rainfall	2 BCM	Loss rate from domestic	30%
River supply	52 BCM	Loss rate from industry	77%
HAD outflow	55.5 BCM		

7.4 Results and Discussion

Water institutions, both formal and informal, water plans, water policy, and water management are experiencing dramatic changes around the world (Saleth and Dinar, 1999). These changes may be attributed to the changes in water demand and supply components and the uncertainty of measures and actions to bridge the water gap. In Egypt, the Ministry of Water Resources and Irrigation (MWRI), the key authority responsible for water management, is devoting its utmost efforts to promoting IWRM measures to ensure water for all sectors. Currently, despite the water deficit reaching more than 19 BCM, Egypt is able to bridge this gap through water reuse, desalination, rainwater harvesting, and withdrawal from the strategic water reserve in the High Dam Lake reservoir. Unfortunately, Egypt may not be able to bridge this gap in future due to unsustainable exploitation of its water resource because of population increase, development, and climate change across Egypt; climate variability in the headwaters of the Nile, and rapid development and building of dams in the countries of the upper Nile basin. Therefore, this study contributes in this point to bridge the water gap in the future.

7.4.1 Questionnaire Results

7.4.1.1 Water Gap, Reasons, and Expectations

The priority challenge facing water policy planners in Egypt is managing and controlling the water gap. Estimations of the worst-case ‘’the Pessimistic scenario’’ indicate that the gap cannot be covered by current policies and measures, and will reach 18.09 BCM by 2050. In comparison, 64% of stakeholders questioned anticipated that the water gap will be higher by 2050, at 21-25 BCM (Figure 7.3). This overestimate of the water gap was not based on precise calculations but on the current gap and allowing for a slight increase over time. Some respondents relied on the critical scenario result of the MIWR who estimate the water gap under the worst-case scenario to be 26.3 BCM before adding unconventional resources (water reuse, shallow underground water, and desalination). The MIWR expect its plan can close the gap under the critical scenario, by water reuse of an estimated 18 BCM and withdrawing 8.3BCM of shallow groundwater (MWRI, 2010).

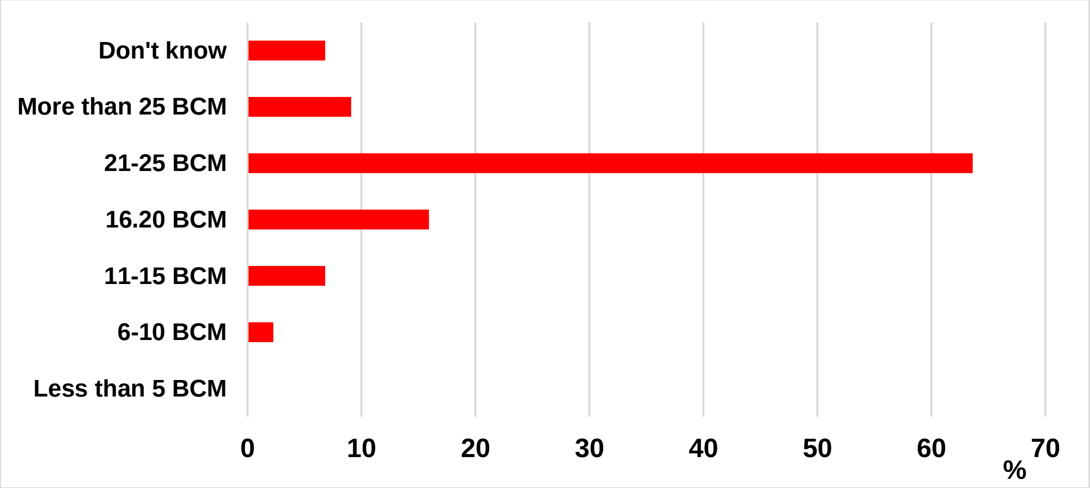


Figure 7.3 Stakeholder expectations of the water gap in 2050.

Respondents considered the main driver of the future water gap would be population growth (68% of respondents), followed by use of traditional irrigation methods with large water losses (55%), significant as agriculture uses about 80%. Of all water in the study area. In addition, 25% of respondents felt inefficient water consumption behaviour by the population would contribute to the water gap in future. Therefore, there should be more incentives and tools in place to increase social awareness about more conservative water consumption, particularly in urban areas. Furthermore, 20% of responses indicated that poor water resources management and water disputes in riparian countries could impact on the water gap. Most of the experts referred to the risk from building hydropower projects in the Nile basin not covered by previous agreements, such as the Grand Ethiopian Renaissance Dam.

Surprisingly, few experts (7%) considered climate change to have much effect on the water gap. These may be due to the experts' view of the minimal contribution of rain in the study area, and an optimistic view of the increase in Nile flow from increased rainfall over the Nile’s upstream. Notably, most experts have confidence in the current water policy to close the water gap, with only 9% attributing the water gap to water policy inefficiency. Those experts provided a de facto evidence for the inefficiency of current water policies that the water deficit has still existed and it is constantly increasing. While the majority of experts commented with respect to the water plan that "there is nothing more to do", many of them emphasized the danger of the state's plans to reclaim more land, placing increased pressure on water resources. Limited water supply was identified as a reason for the gap by 15% of respondents, whilst 11% identified people's lack of awareness as the issue (Figure 7.4). These results on causes of the growing water gap were then used in the Delphi process to inform identification of management responses.

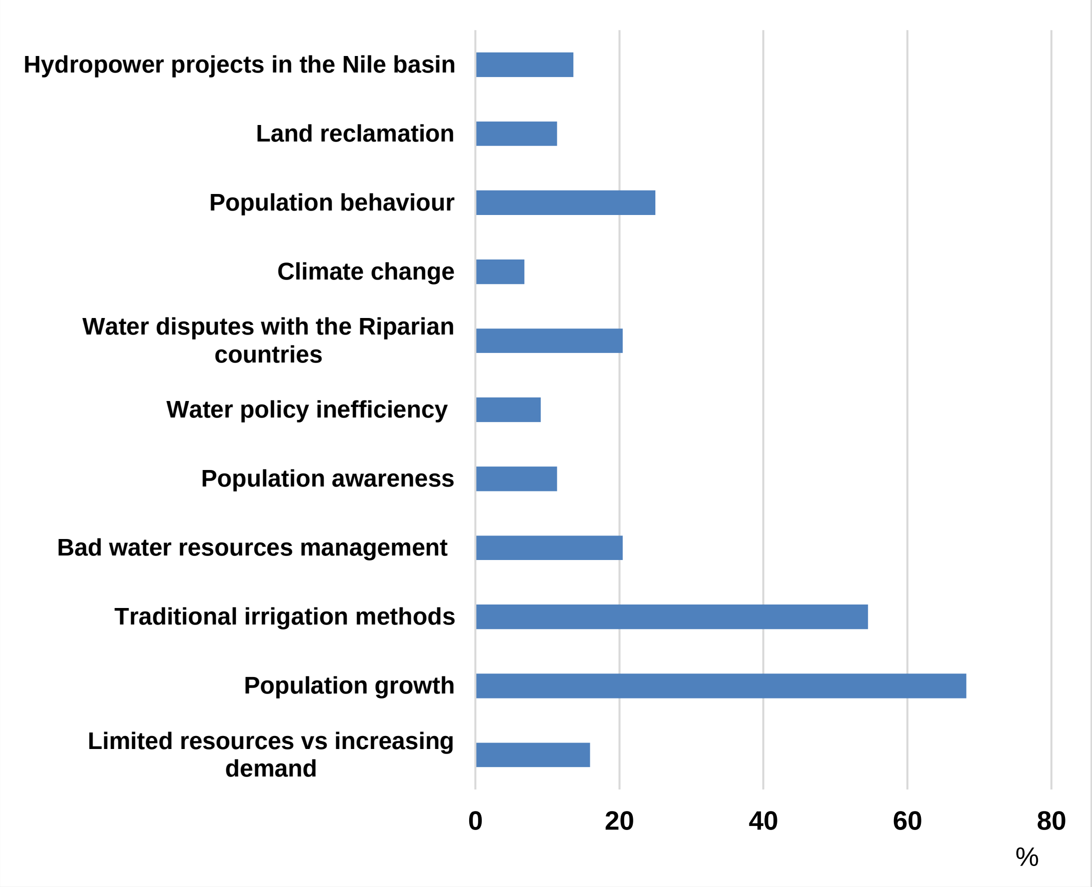


Figure 7.4 Stakeholder opinion on causes of the future water gap.

7.4.1.2 Dealing with Uncertainties in Water Management

Knowledge for dealing with uncertainty in water resources management is inevitably incomplete, and often contentious for policymaking. Figure 7.5 shows stakeholder views on how to address uncertainty in Egypt's water management, although there is a consensus of 61% regarding need for continuous and effective communication amongst stakeholders. The reason for this consensus is due to the formal and centralized decision process in Egypt, where all water policy decisions are taken at very high level, i.e. the President, the Cabinet, and Minister of Water Resources and Irrigation (MWRI, 2005; Barendrecht, 2015). The extent of participation depends on the strategic value of the decision, which has far-reaching implications for other sectors (Luzi, 2010). Furthermore, the experts point out that expert stakeholders are more familiar with uncertainty factors in water resources management than top level decision makers, hence, engagement and communication are critical for policy advice.

Some 55% of respondents indicated a need for more plausible scenarios to better understand the future and the challenges to come, as depending only on optimistic, moderate, and pessimistic views may be insufficient and misleading. Scenarios are the main driving force for setting future water plans, so optimism and pessimism should not be exaggerated and should be clarified by the interviewed experts.

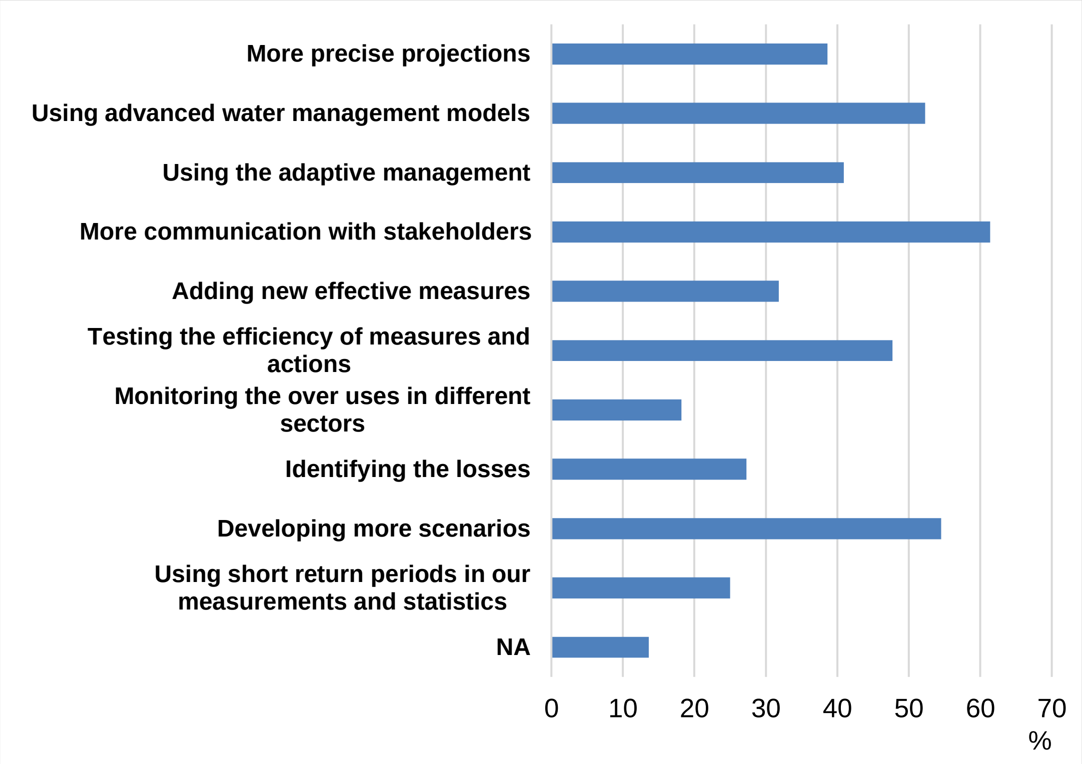


Figure 7.5 Stakeholder views on how to address uncertainty in water management.

About half (52%) of the participants confirmed that using advanced water management models may raise certainty in the outcomes of water resources management. They indicated that The National Water Resources Plan (NWRP) depends on the RIBASIM7 model to plan Egypt's water balance. Barendrecht (2015) reported that RIBASIM7 has some drawbacks, including that it does not include many components and measures, and does not include the socioeconomics consequences.

Slightly fewer (48%) experts felt that testing the efficiency of measures and actions before adoption in the national plan would be a valuable way to deal with uncertainty, and help avoid risk of water shortages and investment on measures that were of limited benefit. Similarly, 41% of responses reported that using adaptive management provides a degree of protection against adverse risks. The experts felt that adaptive management helps to monitor the water system to reduce uncertainty, which gives essential information for management.

The uncertainty problem is often related to the accuracy of projections of future uncertainty factors, and 38% of experts indicated that more accurate projections may be useful in reducing uncertainty in water management. Precise projections provide information about the future that may help in selecting appropriate measures and actions. In addition, 31% of participants felt that searching for new effective measures is a significant way to deal with the unknown future in water resources management. Further, identifying water losses and sources in different sectors is reported by 27% of respondents as necessary to address uncertainty. The experts also stated that determining water losses more accurately may help planners and policymakers to control and manage the annual water balance and rationalize water consumption.

Some 25% of respondents agreed that using shorter data collection intervals in measurement and statistics may be beneficial to better understand uncertainty in some projections, particular the social variables for which projections are limited and tend to ignore uncertainty. Several experts pointed out that the population census is conducted in Egypt once every ten years, and over such a long periods leads to major errors in future forecast. The Central Agency for Public Mobilization and Statistics in 2011 forecast the population of Egypt to be 92.6 million in 2020, while in practice it was 94.7 million people in 2017 and a 100 million in 2020 (CAPMAS, 2011; CAPMAS, 2017a; CAPMAS, 2020).

Finally, 18% of respondents agreed with greater monitoring of water consumption in different sectors to more confidently identify the reasons for uncertainty in water consumption. Participants suggested monitoring using smart meters, and analysing historical data. Only 13% of respondents did not identify any means of reducing uncertainty.

7.4.1.3 Proposed Measures

The process for defining priority water resources management measures was carried out in stages using the Delphi method. In the first round, 10 measures were presented, based on prior literature review, with the request of stakeholders submit further proposed measures. In the second Delphi round, the experts suggested removing some measures, adding others, and changing some names due to ambiguity of terms. For example, they asked for renaming the measure of ‘Political hard work’ with Nile basin countries to ‘Increasing Egypt’s quota from Nile water’. In addition, some experts asked for adding new measures such as reducing discharge into the sea, increasing withdrawal from groundwater, enhancing metering using smart meters, and reducing leakage and losses. By the third and final round, 15 measures resulted (Figure 7.6) that were subject to further evaluation and WEAP modelling.

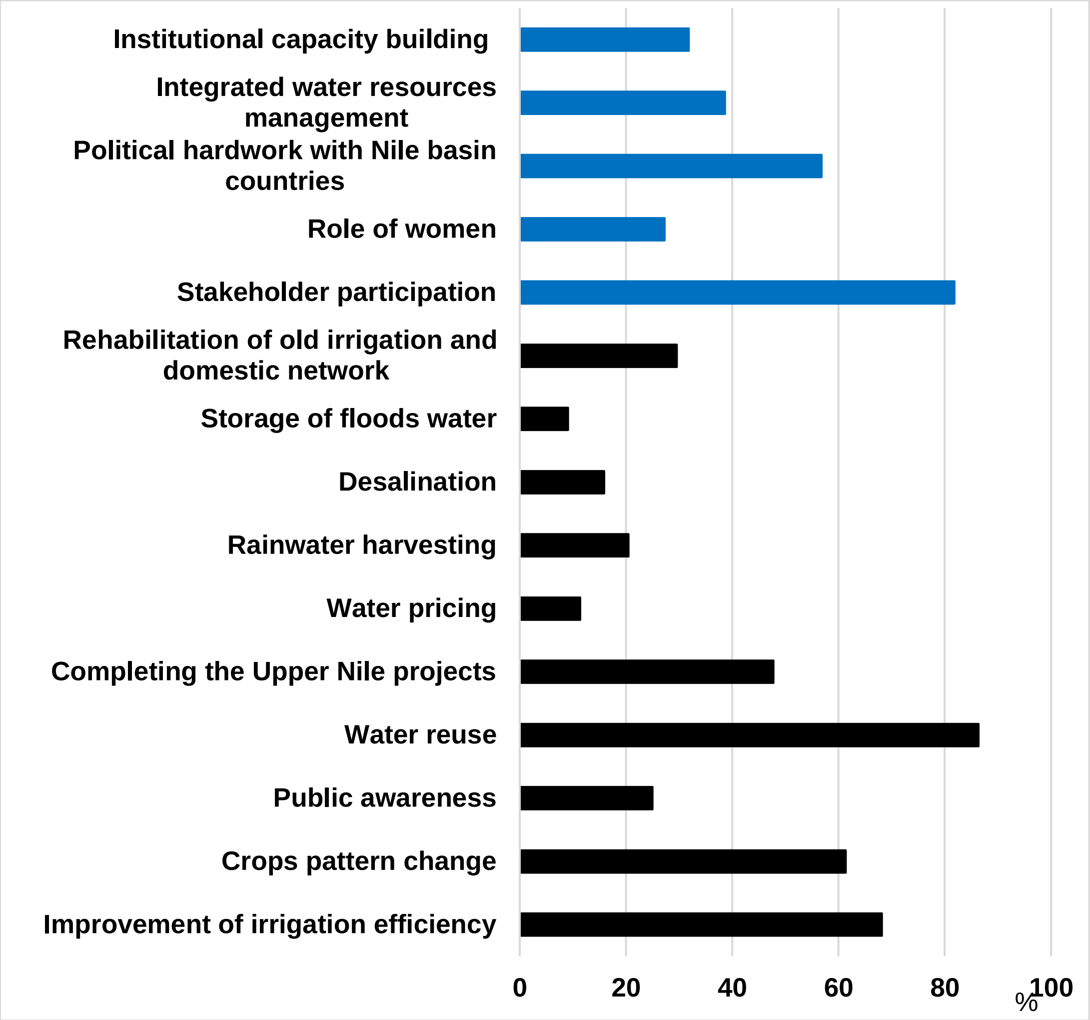


Figure 7.6 The proposed measures for water resources management from the experts' point of view. Measures in black colour proposed by the study and those in blue colour proposed by experts.

A series of observations can be made with respect to the expert’s preferences on water management measures:

- The majority of participants base their opinions on measures in the current National Water Plan, with 86% of participants agreeing with further water reuse as a key measure to bridge the future water gap. According to the 2017 water balance, water reuse from wastewater and agricultural drainage is 13.5 BCM of the total 21 BCM available for reuse.

- 82% of the respondents support involvement of stakeholders as a powerful measure in water management in an administrative environment where water policy decisions are very centralized at a high level.
- Osama et al. (2017) report that low irrigation system efficiency places a significant burden on Egyptian water resources, due to aging primitive irrigation systems as described by El Qausy et al. (2018). Improving efficiency using modern irrigation methods is top of the list of measures for 68% of stakeholders, and has support from several studies (Wichelns, 1999; He et al., 2004; Abdin and Gaafar, 2009; Osman et al., 2016; Multsch et al., 2017). In this study, modern irrigation method is used with meaning of replacing flood irrigation practises with drip, bubble irrigation and mist spraying.
- 61% of respondents agree with changing cropping patterns in the old lands of Egypt to save water, particularly for rice and sugar cane, where use per feddan is 5500 m^3 and 9660 m^3 respectively, compared to 1300 – 3500 m^3 for other crops (MALR, 2012). The participants clarified that the government is struggling to change crop patterns because rice and sugar cane deliver high net returns to farmers and are essential, strategic crops.
- 57% of respondents felt that Egypt should intensify its efforts in political cooperation with Nile Basin countries, to prevent the emergence of further threats affecting the Nile to Egypt, such as the GERD. This measure may at least be able to maintain the current state of water supply. Stakeholders believe that political hard work with Nile basin countries could resolve the complex hydro-political conflicts and allow completion of the Upper Nile projects such as Jonglei canal, Mashar swamps, Bahr El Ghazal swamps in South Sudan country. These projects aim to conserve the water that lost in the swamps of southern Sudan by constructing canals to collect the water and reducing the evaporation (illustrated in Section 7.4.2 and Figure 7.9).
- 48% of the respondents stated that Egypt should complete the Upper Nile projects, especially after the GERD problem arose on the Blue Nile. Many studies assess the feasibility of these projects and the water that can be saved from loss in swamps or to evaporation (Howell et al., 1988; Whittington and McClelland, 1992; Ramadan et al., 2011; Sadek, 2012).

- The key premise of the internationally accepted IWRM approach is that water issues are not considered in isolation (Maestu, 2015), which 39% of participants see as the key means of bridging the water gap. These experts feel that Egypt's IWRM should be holistic involving demographic, land use, political, technical, climatic changes drivers, and change water policies as these all influence water resources.
- The need for IWRM to facilitate coherent distribution of water among all sectors requires building institutional capacity to support integrated national planning (Hamdy et al., 1998). One third (32%) of the experts included institutional capacity building as a proposed measure. They defined institutional capacity residing in organizations, and the development of policies, rules, and managerial performance efficiency in the planning and implementation of water management programmes and projects.
- 29% of respondents argued for rehabilitation of old irrigation and domestic networks, which they felt would increase water conveyance efficiency and the hydraulic performance of canals, reducing water losses. Some recommended the construction of new infrastructure for specific areas, rather than rehabilitation.
- 27% of respondents encouraged support for the role of women as a proposed measure in IWRM, as women act as primary caretakers in Egyptian society and play a major role in domestic water management.
- Engagement of citizens in water issues and raising awareness of water consumption (Seelen et al., 2019) was seen as an absolute necessity. Some 25% of participants indicated this was needed in IWRM to reduce personal water usage and other threats, such as pollution.
- 20% of respondents felt rainwater harvesting was one viable option to increase water supply. Experts pointed to the lack of studies for accurately determining the quantities of rainwater in Egypt, and the crude estimate in water plans of only 1.3 BCM/year. This amount has been constant for decades. In addition, 16% of respondents supported use of further desalination in coastal areas, although the majority opposed this because of the high cost.
- A few respondents (11%) suggested increasing the price of water to reduce consumption. Most experts rejected this proposal noting that prices had been increased more than once in recent years. In addition, the economic situation of citizens does not allow the price of water to be

raised further. However, a rising block tariff is used, in which the water price is 0.65 pounds/ m^3 for the first use block, rising to 3.15 pounds/ m^3 for the fifth and final block, which incentives conservation. Lasheen (2019) has reported that the national policy readjusted the water tariff many times for covering the cost of operation and maintenance to help the water utilities but the policy goal has not been fully achieved. In fact, the situation of utilities has not changed much and covering the cost of operation and maintenance is limited. However, tariff determining is a highly political process by the government and keeping it below the production cost may attribute to the low income of the citizen. Finally, a few (9%) mentioned that storing floodwater in flood years may be helpful but most opposed this, as such flood events are infrequent and the Toshka depression in the western desert is sufficient to capture floodwaters.

7.4.1.4 Uncertainty Assessment Matrix

The uncertainty assessment matrix is a tool for addressing uncertainty associated with the proposed measures and actions for IWRM based on stakeholder participation using the Delphi method-led questionnaires. In the previous step, stakeholders proposed 15 measures, which are now presented in the uncertainty matrix for evaluation using specific criteria.

In the second Delphi round, the experts suggested removing some measures, adding others, and changing some names due to ambiguity of terms. For example, they asked for renaming the measure of ‘Political hard work’ with Nile basin countries to ‘Increasing Egypt’s quota from Nile water’. In addition, some experts asked for adding new measures such as reducing discharge into the sea, increasing withdrawal from groundwater, enhancing metering using smart meters, and reducing leakage and losses.

Experts were asked to evaluate the water management measures based on the nine criteria presented earlier. Number of responses supportive of each measure was determined and measures were arranged (Table 7.3, Figure 7.7) according to the highest score. Many experts prefer to answer only about their specialty. The result of this uncertainty matrix assessment matrix for the selected measures (Table 7.3, Figure 7.7) revealed the following:

- Water reuse and leakage reduction are seen as optimal measures to close the water gap with the highest score of 170 for suitability and 7 for unsuitability side, and with moderate risk and cost. For both measures, stakeholders refer to the reasonable suitability of the ease of implementation and acceptability and ability to solve the water gap problem.

- Changing to modern irrigation came in third with a score of 163 for suitability and 5 for unsuitability, with low risk and high costs. For this measure, stakeholders indicate reasonable suitability and acceptability and its ability to close the water deficit, but there is a difficulty in implementation due to high cost and huge area of old lands, which exceeds 9 million feddans.
- Cropping pattern change was next a score of 160 for suitability and 8 for unsuitability, with reasonable suitability over all metrics taking into consideration the implementation and the state's need for essential strategic crops, of wheat, maize, rice, sugar products and cotton.
- Rainwater harvesting ranked fifth rank with a score of 159 for suitability and 10 for unsuitability, and with moderate cost and low risk. Stakeholder evaluations support its ease of implementation, acceptability and effectiveness but its ability to solve the water gap problem is low due to little rainfall and it only being possible in the winter, which also means it has low public acceptability).
- Rehabilitation of old irrigation and domestic networks is ranked sixth with a score of 158 for suitability and 8 for unsuitability, with high cost and low risk. The suitability of this measure to help in the water gap issue is significant in terms of all evaluation criteria except implementation restrictions due to the high cost.
- Increasing the public awareness to save water ranked seventh with a score of 155 for suitability and zero for unsuitability, and with low cost and zero risk. The suitability of this measure to contribute to solving the water gap issue is very high depending on the evaluation criteria results by participants. This may attribute to the unusual behaviour population in water usage in Egypt.
- Completing the upper Nile projects ranks eighth with a score of 152 for suitability and 71 for unsuitability, with high cost and low risk. This measure has significant unsuitability in terms of implementation restrictions, environmental impacts, and political acceptability in other countries, but is able to contribute effectively to solving the water gap according to the respondent’s assessment.

- Enhancing monitoring (using smart meters) ranks ninth rank with a score of 148 for suitability and 17 for unsuitability, and with high cost and low risk. There is accepted suitability that this measure can conserve water and contribute to solving the shortage issue. There are concerns from a few experts about the political acceptability and feasibility of smart metering.
- Desalination ranks tenth with a score of 144 for suitability and 62 for unsuitability, with high cost and moderate risk. It was opposed due to high cost, thought to lead to political unacceptability.
- Reducing freshwater discharge to the sea ranked eleventh with a score of 135 for suitability and 48 for unsuitability, and with low cost and high risk. Some experts proposed this measure and others rejected it, explaining that freshwater discharge to the sea from the Nile is less than 1 BCM, and Egypt only discharges agricultural drainage that has been reused at least once. In addition, discharge provides important environmental protection of Delta lands from saline intrusion.
- Creating new storage for floods ranked twelfth rank with a score of 122 for suitability and 68 for unsuitability, with moderate cost and low risk. There is a considerable unsuitability with this measure due to the low frequency of floods. High water levels of the Aswan High Dam flow into the Toshka depression in the western desert, which is sufficient to absorb the floodwaters (Chapter 4, Section 4.3.6.3, HADR Operation Rules).
- Increasing withdrawal of groundwater ranked thirteenth rank with a score of 109 for suitability and 58 for unsuitability, with moderate cost and high risk. Groundwater specialists amongst the participants revealed that Egypt is approaching the safe limit of withdrawal from shallow and deep groundwater (7.2 BCM and 2.5 BCM withdrawn respectively in 2017), against corresponding annual safe limits of 8.5 BCM and 4.9 BCM. Therefore, this measure was not considered viable.
- Water-pricing ranked fourteenth rank with a score of 95 for suitability and 78 for unsuitability, and with zero cost and high risk due to the economic situation of citizens. There is unsuitability about implementation restrictions, political acceptability, feasibility, and its effectiveness to solve the water issue in Egypt, especially as the price of water has been raised several times in recent years.

- Finally, experts agreed that increasing Egypt's share of water through political efforts intended to change water agreements is not possible, especially with respect to political issues related to water with the Nile Basin countries, but Egypt can increase its share by completing the Upper Nile projects such as Jonglei canal, Mashar swamps, Bahr El Ghazal swamps in South Sudan country. Therefore, increasing Egypt's share measure ranked last of 15 with a score of 79 for certainty and 50 for uncertainty, with low cost and zero risk.

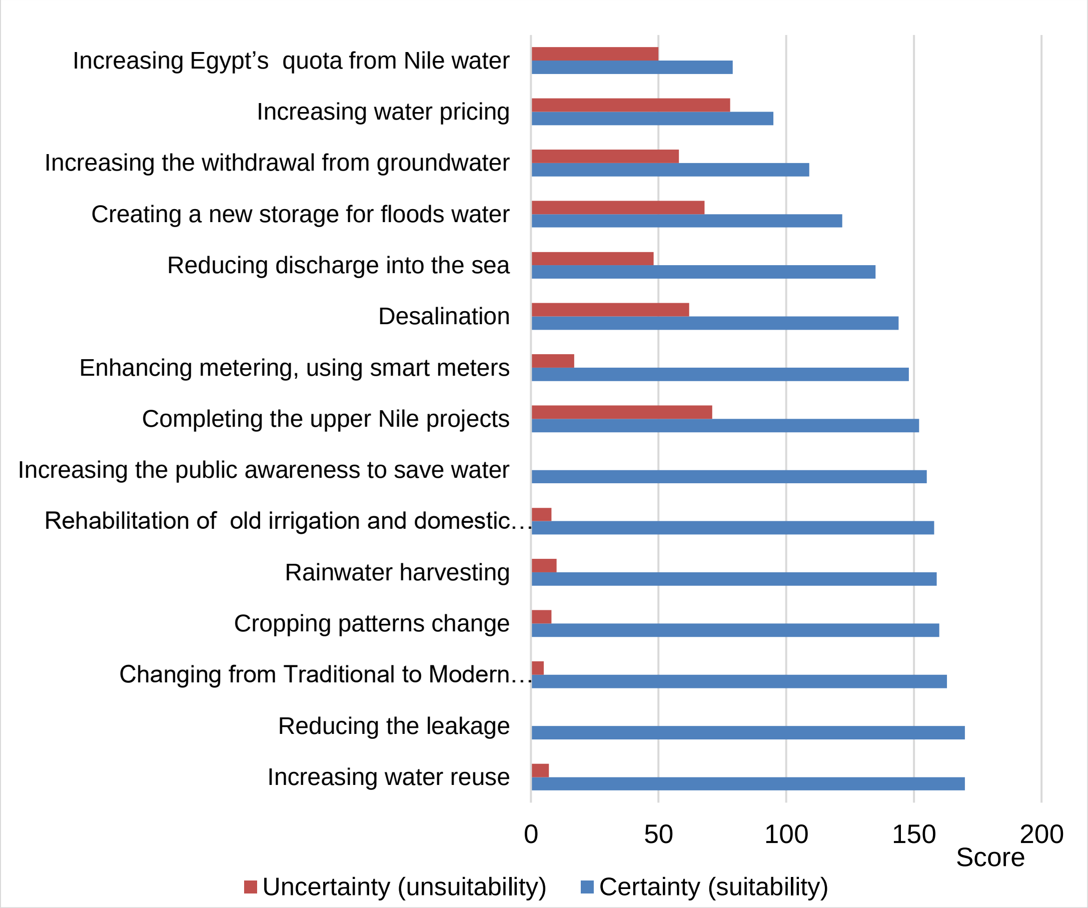
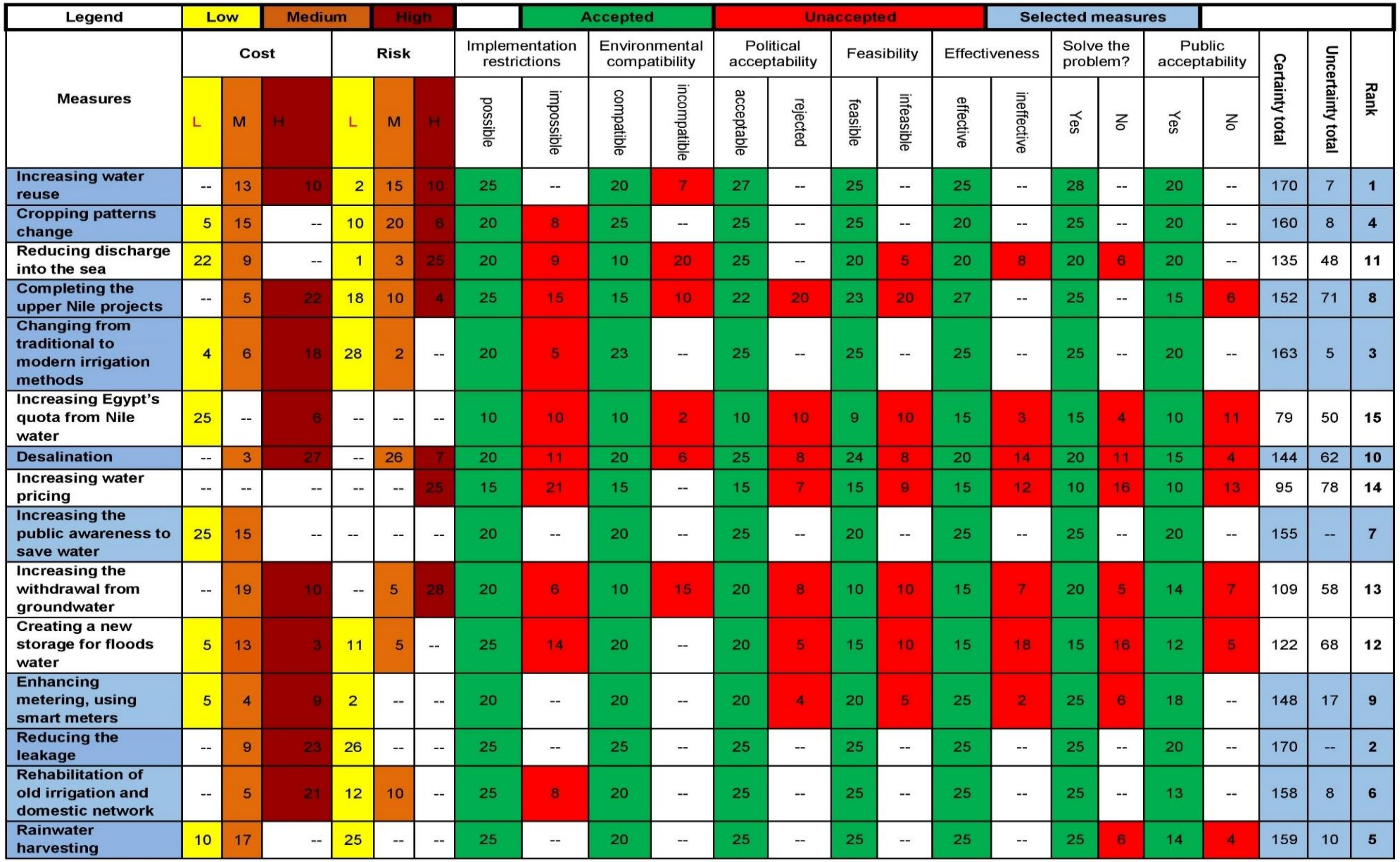


Figure 7.7 Certainty (suitability) and uncertainty (unsuitability) of proposed measures to bridge the water gap.

Table 7.3 Results of uncertainty assessment matrix for the proposed measures.



Legend	Low	Medium	High		Accepted	Unaccepted	Selected measures	

Measures	Cost			Risk			Implementation restrictions		Environmental compatibility		Political acceptability		Feasibility		Effectiveness		Solve the problem?		Public acceptability		Certainty total	Uncertainty total	Rank
	L	M	H	L	M	H	possible	impossible	compatible	incompatible	acceptable	rejected	feasible	infeasible	effective	ineffective	Yes	No	Yes	No			
Increasing water reuse	--	13	10	2	15	10	25	--	20	7	27	--	25	--	25	--	28	--	20	--	170	7	**1**
Cropping patterns change	5	15	--	10	20	6	20	8	25	--	25	--	25	--	20	--	25	--	20	--	160	8	**4**
Reducing discharge into the sea	22	9	--	1	3	25	20	9	10	20	25	--	20	5	20	8	20	6	20	--	135	48	**11**
Completing the upper Nile projects	--	5	22	18	10	4	25	15	15	10	22	20	23	20	27	--	25	--	15	6	152	71	**8**
Changing from traditional to modern irrigation methods	4	6	18	28	2	--	20	5	23	--	25	--	25	--	25	--	25	--	20	--	163	5	**3**
Increasing Egypt's quota from Nile water	25	--	6	--	--	--	10	10	10	2	10	10	9	10	15	3	15	4	10	11	79	50	**15**
Desalination	--	3	27	--	26	7	20	11	20	6	25	8	24	8	20	14	20	11	15	4	144	62	**10**
Increasing water pricing	--	--	--	--	--	25	15	21	15	--	15	7	15	9	15	12	10	16	10	13	95	78	**14**
Increasing the public awareness to save water	25	15	--	--	--	--	20	--	20	--	25	--	20	--	25	--	25	--	20	--	155	--	**7**
Increasing the withdrawal from groundwater	--	19	10	--	5	28	20	6	10	15	20	8	10	10	15	7	20	5	14	7	109	58	**13**
Creating a new storage for floods water	5	13	3	11	5	--	25	14	20	--	20	5	15	10	15	18	15	16	12	5	122	68	**12**
Enhancing metering, using smart meters	5	4	9	2	--	--	20	--	20	--	20	4	20	5	25	2	25	6	18	--	148	17	**9**
Reducing the leakage	--	9	23	26	--	--	25	--	25	--	25	--	25	--	25	--	25	--	20	--	170	--	**2**
Rehabilitation of old irrigation and domestic network	--	5	21	12	10	--	25	8	20	--	25	--	25	--	25	--	25	--	13	--	158	8	**6**
Rainwater harvesting	10	17	--	25	--	--	25	--	20	--	25	--	25	--	25	--	25	6	14	4	159	10	**5**

7.4.2 Integrated Water Resources Management Model

To develop a strategy to close the water gap, ten measures were selected and tested experimentally using the WEAP model to 2050. The measures were selected based on the highest certainty to close the water gap depending on Delphi process and further analysis above. The measures were represented in WEAP as follows:

1. Water reuse is represented in WEAP by increasing the percentages of reuse water from agriculture, domestic, industrial sectors, incrementally.
2. Leakage reduction, change to modern irrigation and rehabilitation of old irrigation and domestic networks, increased public awareness, and enhanced metering are represented by reducing the percentages of water losses for agriculture, domestic, industrial sectors, incrementally.
3. For crop pattern change measure, I selected rice and sugar cane and replaced them with wheat, which is a lower water-consuming crop in Egypt (Figure (7.8). According to CAPMAS (2017b), the agricultural area of rice cropping was 1.35 million feddans in 2016 and each rice feddan consumes approximately 4500 m^3 of water. Thus, the total cultivated area of rice consumes about 6.07 BCM/year of water. Sugarcane has the maximum water ration c. 9,660 m^3/feddan, and a cultivated area of 0.325 million feddans in 2016, thus, the cultivated area of sugar cane consumes about 3.14 BCM of water annually. The sum of both crops was deducted from the total agriculture water consumption in WEAP incrementally.
4. Rainwater harvesting is represented in WEAP by slightly increasing the contribution of rainfall in the water balance.
5. For upper Nile projects, the study used results of previous studies, the Permanent Joint Technical Commission for Nile Waters reports (PJTCNW), and stakeholder participation to estimate the approximate amount of water these projects may deliver. The Jonglei Canal project has been studied by the Egyptian government in 1946 and the construction work began in 1978. The project aimed to reduce the substantial evapotranspiration losses in Bahr El Jabel swamps by connecting the Bahr El Jabel with the Sobat River. 70% of the work had been completed but stopped due to security problems in southern Sudan (Abu-Zeid, 1992; Allen et al., 1994). Mashar Swamps project aims to construct a parallel canal to the Sobat River to avoid the Mashar Swamps. Bahr El Ghazal project has been proposed to conserve the water of Bahr El-Ghazal that

lost in the swamps. The projects (Figure 7.9) could harvest about 18 BCM of wasted Nile water, providing about 9 BCM/year, from the Jonglei Canal (3.5 BCM), Mashar Swamps (2 BCM), and Bahr El Ghazal (3.5 BCM) (PJTCNW, 1961; Howell et al., 1988; Abu-Zeid, 1992; Allen et al., 1994; Allam, 2001; Ahmad, 2008; Allam et al., 2018; El Qausy et al., 2018). The 9 BCM is represented inside the WEAP model by adding it to the HADR incrementally.

6. Desalination is represented in WEAP by increasing it incrementally to reach the appropriate value for reporting it in the proposed policy. This is based on Egypt's expansion desalination capacity due to the construction of the GERD, where in August 2019 the Egyptian government announced its intention to build 39 desalination plants with a capacity of 1.4 million m^3/day.

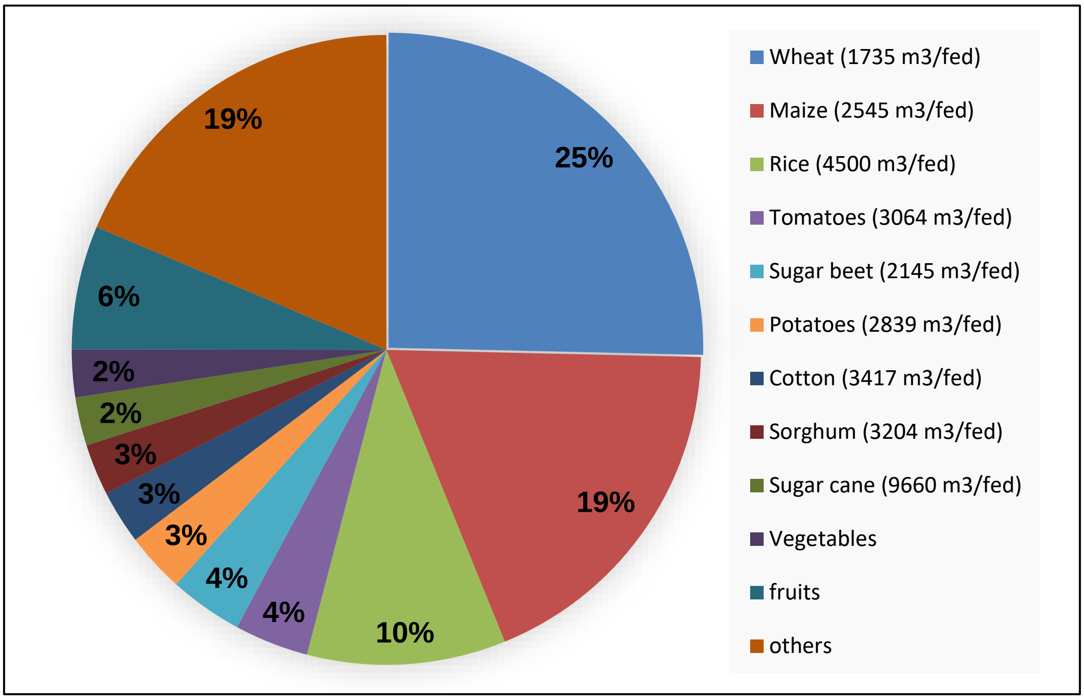


Figure 7.8 Water distribution by crop type in Egypt 2016 (CAPMAS, 2017b).

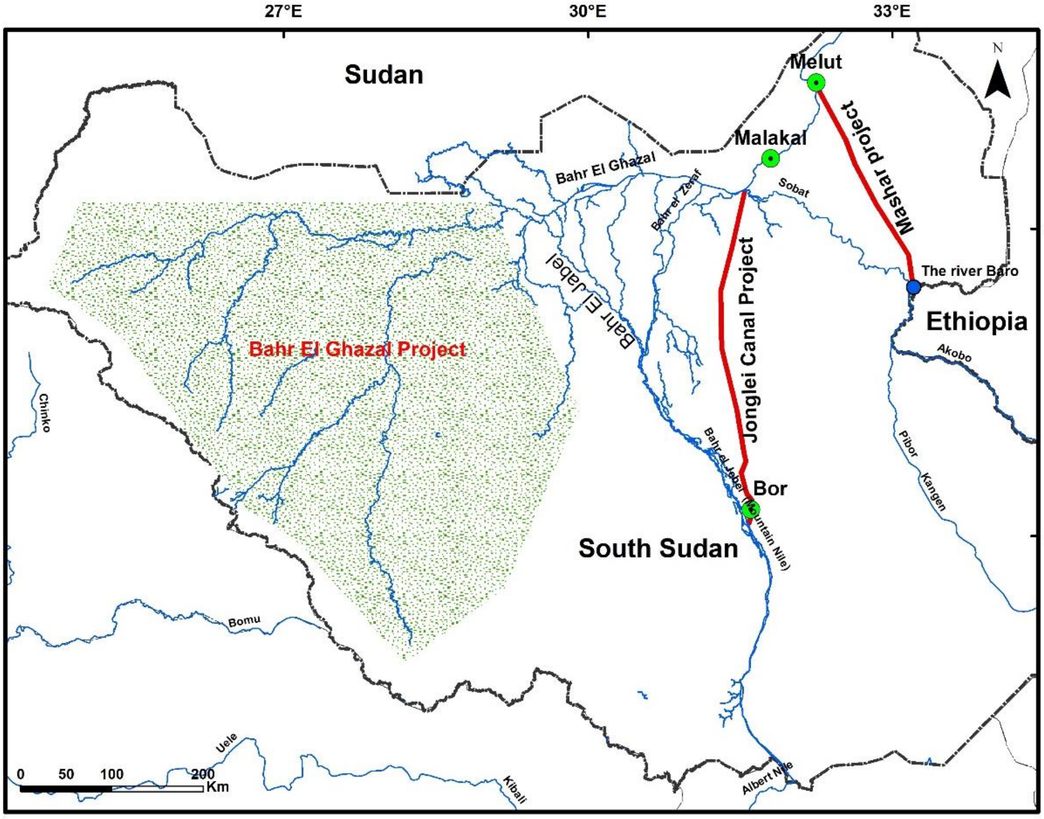


Figure 7.9 Route and location of upper Nile projects.

Figure 7.10 shows the schematic of the IWRM model built in WEAP, representing the relevant water demand and supply components, variables, and proposed measures by nodes and links. The key drivers of demand and supply (Table 7.4) were input to run the model, and values for measures iterated incrementally and repeatedly until finding optimal values were identified to overcome the water deficit. The results show that to bridge the water gap under the worst scenarios to 2050, estimated at 18.09 BCM, Egypt's must integrate management measures from both demand and supply sides.

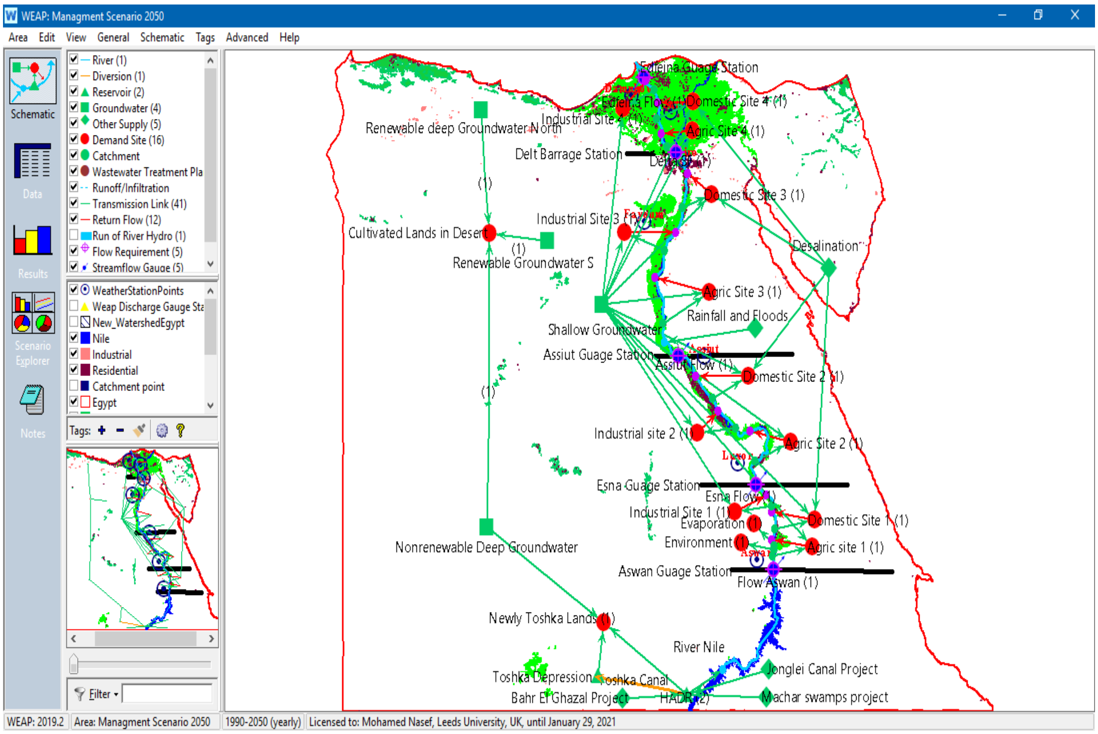


Figure 7.10 WEAP schematic of for the IWRM measures for Egypt.

Table 7.4 Drivers and assumptions in the integrated management water model.

	Key Drivers	**2050**
	Demand	
1	Agricultural area	13.06 Million feddans
2	Annual water consumption per feddan	4800 M^3
3	Population growth	174.7 Million persons
4	Annual water consumption perp capita	95 M^3
5	Industrial expansion	18840 Units
6	Annual water consumption per industrial unit	300000 M^3
7	Environment	1 BCM
8	Evaporation	2.5 BCM
	Supply	
9	Rainfall	1.5 BCM
10	River supply	52 BCM
11	HAD outflow	57.5 BCM
12	Shallow groundwater	8 BCM
13	Deep groundwater	4.7 BCM
14	Desalination	3 BCM
	Increasing water reuse	
15	Reused water rate from agriculture	30%
16	Reused water rate from domestic	20%
17	Reused water rate from industry	20%
	Reducing the losses, leakages, and enhancing the irrigation techniques	
18	Loss rate from agriculture	35%
19	Loss rate from domestic	27%
20	Loss rate from industry	65%
	New water resources from upstream projects	
21	Jonglei Canal	3.5 BCM
22	Mashar Swamps	2 BCM
23	Bahr El Ghazal	3.5 BCM
	Cropping patterns change	
24	Rice and sugar cane	4 BCM

For water demand measures, Egypt should increase the percentage of water reuse to be 30%, 20%, and 20% for agriculture, domestic, industrial sectors respectively instead of the current 19.15%, 11.54%, and 11.54%. Water losses percentages should be reduced to 35%, 27%, and 65% for agriculture, domestic, industrial sectors respectively instead of the current 37%, 29%, and 77.8%. The study assumed that reducing the percentage of water losses in every sector only very slightly would be realistic up to 2050. This slight decrease would be due to policies of reducing the infrastructure leakage, changing to modern irrigation, rehabilitation of old irrigation and domestic network, increasing public awareness, and using smart meters.

Egypt’s policy should also be to alter crop patterns, in particular for rice and sugar cane. Results reveal that changing half the area of rice and sugar cane to wheat is sufficient to save about 4.0 BCM/year.

For water supply, Egypt’s policy should be to enhance rainwater harvesting to collect 1.5 BCM instead of 1.3 BCM. In addition, there is an imperative to complete the Upper Nile projects, as Egypt will need at least 3.39 BCM annually beside its existing share of 55.5 to meet demand. This could be achieved by cooperation and political hard work with the Nile basin countries. Furthermore, the water policy should adopt desalination to reach 3 BCM in 2050 instead of 0.1 BCM currently. It is worth noting that this proposed policy is based on the results of the worst-case scenario and to 2050 only.

7.4.3 Water Balance 2050

Using the results of the WEAP IWRM modelling, a water balance for Egypt in 2050 can be presented (Table 7.5 and Figure 7.11). This indicates that all demands can be met under the proposed policy to 2050.

Demand is likely to be about 105.7 BCM with actual usage about 91.8 BCM. The difference between consumption and demand has diminished, compared to the results of the pessimistic scenario, as a result of controlling water losses. The growth in demand is attributed to accelerated growth in water demand variables in different sectors, including population, agricultural area, and industrial units. Water supply will increase to 105.7 BCM in 2050 as a result of adding new supplies from upper Nile projects, plus some desalination and water reuse.

Considering individual sectors, water demand and consumption in 2050 is estimated at 71.2 BCM and 66.34 BCM for agriculture; 17.8 BCM and 16.24

BCM in the domestic sector, and 13.2 BCM and 5.77 BCM for industry (Table 7.5). Water level in the HADR will decrease dramatically from 2042 (Figure 7.12) due to the continuously increasing demand and steady supply.

Table 7.5 Water balance for Egypt in 2050 under worst case (Pessimistic) scenario plus modelled IWRM strategy.

Water Supply	Quantity BCM/year
Conventional	
River Nile	57.5
Deep underground water	4.7
Underground water in Sinai	0.04
Underground water in North	0.02
Rainfall and floods	1.5
Upper Nile Projects	3.39
Total	**67.1**
Non-conventional	
Desalination	3
Shallow underground water	8
Water reuse	27.56
Total	**105.7**
Water Consumption	
Agriculture	66.34
Domestic	16.24
Industry	5.77
Evaporation	2.5
Environment	1.0
Total	**91.8**
Water Demand	
Agriculture	71.2
Domestic	17.8
Industry	13.2
Evaporation	2.5
Environment	1.0
Total	**105.7**
Water deficit	**38.6**
Water shortage after addition of non-conventional resources	**0.0**

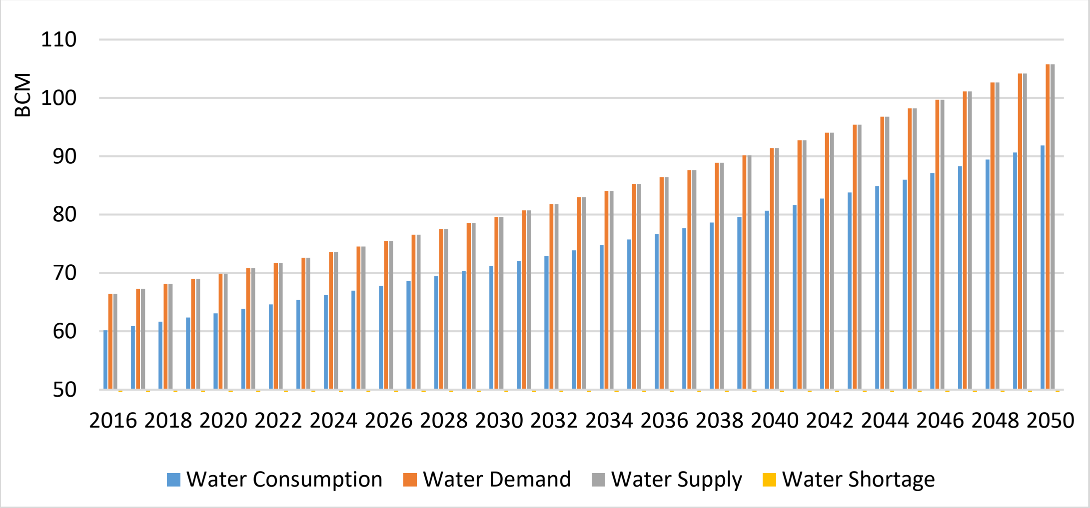


Figure 7.11 Water demand and supply over the period 2016 - 2050 under worst case (Pessimistic) scenario plus modelled IWRM strategy.

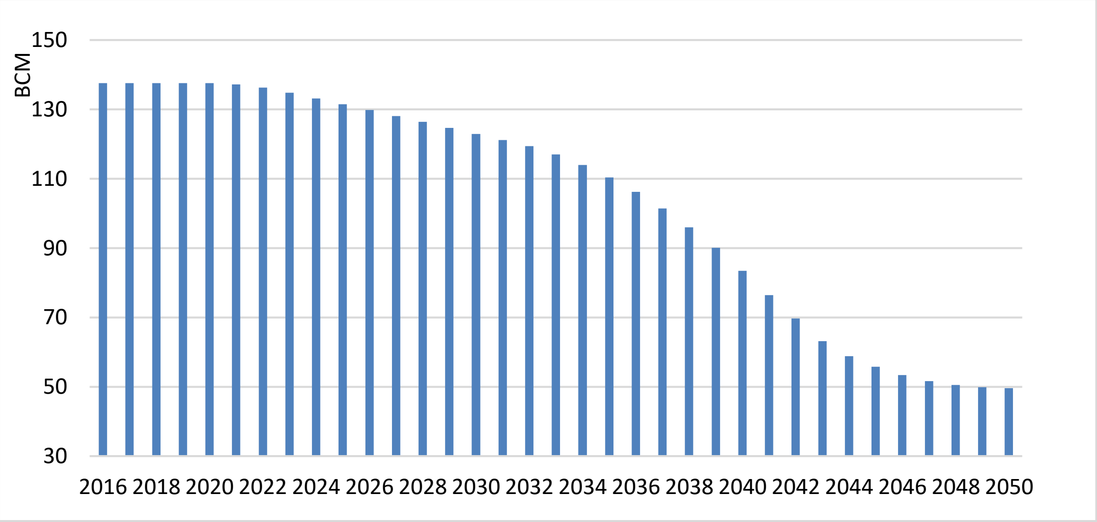


Figure 7.12 HAD Reservoir volume under management to 2050 under worst case (Pessimistic) scenario plus modelled IWRM strategy.

7.5 Conclusion

The study addresses uncertainty and complexity in water management in the context of water stress in Egypt. Water management issues are large-scale, complex, and inextricably related to natural risks, human actions, measures, and values. Complexity arises over time and space with respect to the natural systems (climate, hydrology etc) and the human system including both the use and management of water. This complex system implies high uncertainty and so to bridge the water gap, water resources management requires multidisciplinary coordination of stakeholders.

In this chapter, I have applied a precautionary measures approach based on participation of expert stakeholders, using Delphi method-led questionnaires and integrated WEAP modelling, a powerful and efficient way to address uncertainty and complexity to bridge Egypt’s water gap. It can be argued that this framework provides decision makers and planners with reliable information before they take a decision. I deal with Egypt’s uncertainty and complexity by planning against a worst case pessimistic scenario to support design of policies informed by the need to avert the worst outcomes associated with water scarcity.

This chapter has explored and examined a series of measures that can be used collectively to bridge the water gap in Egypt to 2050. A stakeholder-based approach resulted in 15 measures to explore in overcoming future shortage, with these measures, applied in realistic degrees, able to bridge the water gap in Egypt, even under the worst-case scenario to 2050. There is a variable degree of uncertainty around the proposed measures but this uncertainty was evaluated by expert stakeholders, and measures prioritised for suitability alongside an evaluation of the uncertainty, cost and risk. In order of priority suitable measures were: water reuse and leakage reduction, changing to modern irrigation, changing cropping patterns, and completing upper Nile projects. Monitoring of water consumption in agriculture will save a huge amount of water that can be used in other sectors.

It is clear that any reduction in the available water supply, combined with an anticipated increase in demand, could have dramatic consequences. Therefore, cooperation and understanding with the Nile Basin countries in managing Nile water will benefit all basin countries, where the management of water cannot be regarded as the responsibility of any one nation. In this context of co-operation, engaging with stakeholders and experimental modelling addressing uncertainty and complexity is a great opportunity to achieve IWRM of the wider Nile basin. Uncertainty and complexity will remain part of research, modelling, and future planning effort in water resources. If stakeholders and decision-makers participate over the many opportunities that the future holds, they could strengthen water policy and strategies under uncertainty and complexity reducing the risk of adverse outcomes for all parties.

The methodological decisions in this chapter helped in achieving the purpose of this chapter, where it made addressing the uncertainty in the proposed measures to bridge the water gap flexible and efficient and simplified the complexity in water management. Results of this chapter were more sensitive to the methodological choices. For example, the study adopted a precautionary approach, which uses the WEAP model and Delphi method-led questionnaires based on group communication from stakeholders made the results highly sensitive to the stakeholders' opinion particularly in identifying the optimal measures and robust solutions to water deficit. In addition, testing the proposed measures in the WEAP model added value to the results and made them more reliable. Furthermore, building the water management model based on the worst case "pessimistic scenario" affected the results, where it led to specifying a package of proposed solution, not one measure to bridge the water gap. These methods and choices can be generalized broadly and the results are internally valid and can be used to compare with results of other studies discussing the same issues.

Finally, although the package of proposed measures can overcome the deficit to 2050, there is no room for complacency. The analysis is limited to the period 2016-2050, but it is recommended that current and proposed strategies, policies, and programs be reviewed and renewed to consider the post 2050 period, particularly in light of the long period, often decades, usually involved in implementation of many types of water resource management measures, whether that be infrastructure development requiring substantial investment, or changing water consumption behaviours in people.

Chapter 8
Conclusion and Recommendations

The study was conducted with the aim of dealing with uncertainty and complexity in the development of water demand and supply scenarios in Egypt. It represents a first attempt to do so, and employs the WEAP model, GLUE method, and Delphi technique as research tools to simulate, analyse, and manage water demand and supply. The main research questions covered in this study address uncertainty and complexity in water demand and supply modelling, assessment of the impacts of uncertainty factors on demand and supply, framing of potential futures demand and supply, and thus bridging the water gap under uncertainty and complexity.

Uncertainty in demand and supply is inherent and will remain, but it can be dealt with by reducing it, assessing the effects of uncertain factors, framing potential futures, and so identifying precautionary measures and actions in advance to confront and manage risks. This chapter summarises the main findings of the study and gives recommendations for further improving the prediction of future water demand and supply in Egypt, and closing its future water gap.

8.1 Dealing with Uncertainty and Complexity in Water Demand and Supply

Uncertainty and complexity is inevitable in water demand and supply, and exists in all its aspects (modelling to determine current levels, forecasting future states, and managing demand and supply). In water resource systems, sources of uncertainty include lack of data, systematic errors in data collection, projection factors to predict future supply and demand, natural processes in watersheds, human interventions, used model, model formula, model parameters, and modeller experience. All these elements play a significant role in increasing uncertainty in model outputs, and can be dealt with in three ways:

- Uncertainties in model inputs and variables, model parameters, model structure, and physical system are dealt with using probability distributions using a prediction approach;
- Future uncertainties associated with factors projections, such as climate, socio-economic change, and political change are dealt with by exploring

and assessing their impacts on future water demand and supply to determine the uncertainty range of their risk for each factor individually. A scenarios approach can be used for dealing with future uncertainty by framing the potential futures of water demand and supply.

- Uncertainties related to water resources management are dealt with using a precautionary approach combing the optimal measures in a best fit strategy to tackle the water resources problems. The precautionary approach is based on a participatory, stakeholder-driven mechanism using a communicate-together principle to define critical uncertainties and find optimal measures and robust solutions to water deficit. This approach is implemented alongside WEAP modelling as a simulation model to examine the measures and actions.

Complexities with water demand and supply are numerous and include: selecting the appropriate model, system representation, the large numbers of variables and interrelationships, data availability limitation, identifying spatial and time scale, estimating parameters and their ranges, optimization and computational time, model output explanation, model calibration and reliability, determining appropriate scenario drivers, and assessing the measures and actions to bridge the water gap. The complexity can be dealt with in each case by finding the optimal mean for simplifying the process. Selecting the way of handling the complexity in the system, model or modelling approach is up to the modeller.

8.2 Modelling of Water Demand and Supply

It can be concluded that dealing with uncertainty and complexity in water demand and supply modelling is primarily subject to the modeller’s experience in selecting appropriate tools such as the most suitable model, sensitive parameters, and influential variables, and the designer's mastering of water system components. Uncertainty is inevitable and can be dealt with by reducing it in the model outputs through optimization algorithms based on accurate input data and choosing models with few and sensitive parameters. The findings of the study show that the WEAP model enabled analyses of water demand and supply and simplified the complexities in Egypt's water demand and supply system. Uncertainty and complexity are a knotty problem in water demand and supply modelling; based on the results of the study, there are clear trade-offs between model and system complexity, uncertainty sources, and predictive ability, as representing the multi-variables of a complex system and model’s parameters inherently raises complexity and introduces multiple uncertainties. This may raise/lessen the predictive ability based on the variables and factors involved in running the model. Overall, the rational selection of the model and modeller’s experience can minimize complexity, and an efficient and feasible uncertainty analysis algorithm can limit the uncertainty of simulation results.

Uncertainty in Egyptian Water demand and supply is associated with spatial variation of influencing factors in the study area such as climate, agricultural area, population growth, industrial units, HAD outflow and human interventions, where the extreme annual change in these factors leads to a change of uncertainties in different basin areas. According to the results, the p-factor and the r-factor values were 1 and 0.65 in calibration period (1990-2006) for Aswan station, 0.88 and 0.63 for Esna station, 0.56 and 0.45 for Assiut station, 0.72 and 0.47 for Delta station. For the validation period (2007-2015), the p-factor and the r-factor values were 1 and 0.94 for Aswan station, 0.78 and 1 for Esna station, 0.56 and 0.95 for Assiut station, 0.56 and 0.50 for Delta station. Based on the result of sensitivity analysis, the soil water capacity (SWC), relative storage in lower soil bucket (Z2), and deep conductivity (DC) are the most sensitive parameters and the dominant factors in the hydrological model for the Nile river basin in Egypt. This means that these parameters (SWC, Z2, and DC) play a key role in the simulation of streamflow and uncertainty in the study area.

In spite of the importance of these three parameters, no single parameter makes the model significant but the combination of the model parameters is key. Over the study period 1990 - 2015, annual rainfall volume in the basin varies widely from one year to another (3.9–5.1 BCM). Egypt reports only 1.5 BCM as an estimated approximate value (NWRP, 2005; MWRI, 2012). More rainfall data and stations are needed for more accurate rainfall volume results. In addition, the result of evapotranspiration using Soil Moisture Method in WEAP varies between 360–460 MCM. It can be observed that the change in annual evapotranspiration is unstable and is in line with the variability in annual rainfall. Furthermore, the results of surface runoff present only the water that reaches the stream channel due to rainfall. The surface runoff differs between 2.0–3.24 MCM and tends to decrease as a result of low rainfall in the catchment area. This means that the contribution of rainfall in the water supply system may lessen in the future.

It is concluded that all of the demands for all sites are continuously increasing during the entire simulation period 1990-2015. The rapidly growing demand in

Egypt is a response to an increasing agricultural area, population, and industrial production. The supply side is fluctuating due to the variation of reservoir withdrawal, groundwater, and rainfall variability yearly. At supply lows, periodic water shortage occurs. In 2015, modelled and reported water demand was 80.2, and 80.4 BCM respectively, while modelled and reported supply were 63.8, and 59.0 BCM respectively. The modelled and reported supply varies due to the difference in the withdrawal from the High Aswan Dam reservoir and estimation of rainfall. This difference between water demand and supply leads to deficit (unmet demand), estimated at 16.4 BCM in 2015.

The model shows that demand increase varies spatially, according to population density, agricultural area and industrial units. The highest demand sites are in Assiut-Delta and Delta divisions, estimated to be 31.87% for each division from the total demand in the whole basin. The water demand for the divisions of Esna-Assiut and Aswan-Esna is estimated at 27.3% and 8.9% respectively. The agricultural sector shows the highest demand in each area, about 80% of supply, followed by domestic and industrial sectors of about 13% and 7% respectively. Furthermore, water supply in the study area varies from one year to another according to the flooding year, rainfall variation, and groundwater exploitation. In 2015, the Nile provided 85.63% of the total supply in the study area including rainfall. Groundwater provides 14.36% of water with shallow and deep groundwater accounting for 10.81%, and 3.55% respectively. Desalination is insignificant at 0.1 BCM in 2015. It is interesting to note that groundwater consumption is increasing continually to overcome the deficit.

These continuous differences and complexities in water demand and supply factors contribute to model uncertainty due to errors in their input data. Nevertheless, the model results show that Egypt faces severe water scarcity, with the deficit increasing and unstable over the simulation period, estimated at 16.4 BCM in 2015. The deficit varies spatially; for instance, the maximal water shortage is in Assiut-Delta and Delta divisions, estimated at 32.07% for each division from the total water shortfall in the study area. The water deficit for the divisions of Esna-Assiut and Aswan-Esna is estimated at 27.4% and 8.5% respectively. The driver of deficit also varies in each sector; agriculture has the highest scarcity demand at 79.75%, with the domestic sector at 13.3%, and industrial sector at 6.9%. This is due to the different size of activities for each sector in each geographic division, where the greater the size of the sector, the higher demand, so leading to a widening water deficit.

Uncertainties in supply and demand were categorized based on the source of uncertainty and the method used to dealing with it. The uncertainties considered were: hydrological modelling uncertainty, cognitive uncertainty, future uncertainty, unexpected events' uncertainty, and managerial uncertainty (Table 8.1). In addition, the study involved a lot of complexity, which had to be broken down too. The study thus presents a classification of complexity in modelling of water supply and demand based on a defined set of criteria. These deal with the degree of complexity in each criterion by finding the optimal mean for simplifying the process. Selecting the way of handling the complexity in system or model is up to the modeller.

Table 8.1 Summary of uncertainty types, sources, predictability, and handling method in water demand and supply.

Type	**Source**	**Predictability**	**Handling method**
Hydrological modelling uncertainty	Input data, Model structure, Model parameters Modeller's experience	Predictable	Sensitivity and uncertainty analysis
Cognitive uncertainty	Modeller's experience and skills in modelling Lack of understanding the system	Predictable	Modeller's capabilities development Study the system well and investigating field visits
Future uncertainty	Projections of future factors Changes in the system components and variables	Predictable	Running the model with different probabilities Scenarios analysis
Unexpected events' uncertainty	Unknown sources	Unpredictable	Precautionary approach
Managerial uncertainty	Water policies and plans	Predictable	Precautionary approach

Using the WEAP hydrological model with fewer parameters and understandable structure made dealing with uncertainty in the hydrological modelling of the study area simpler, reducing complexity, whilst achieving acceptable results. In addition the familiarity of the modeller with the hydrological system play an important role in system representation and calibration and so model performance. In accordance with the analysis and results above, the WEAP model has the ability to represent different hydrologic situations. In a sense, this provides a confidence that the future water demand and supply prediction can be accurately projected based on future factors. In addition, the GLUE methodology proved appropriate to deal with uncertainty in the system by quantifying uncertainty in input data error and model structure based on the parameters uncertainty.

8.3 The Impact of Future Uncertainty Factors on Water Demand and Supply

This study built a WEAP hydrological model to assess the impacts of uncertainty factors on Egypt’s future water deficit (2016–2050). The uncertainty factors include climate change over Egypt, climate variability in the Nile basin, Grand Ethiopian Renaissance Dam impacts, population growth, and land use change. Assessment of the impacts of future uncertainty factors is important in planning Egypt's water resources and to wider stakeholders, taking into account the time dimension of socio-economic conditions, climate change projections, and political and development changes in Nile basin countries. In addition, the methodology of using the exploratory approach and simulation model WEAP to deal with uncertainty and complexity of these factors’ impacts served as a useful tool to simulate the complex water system and assess the impact of different uncertainty factors on demand and supply. Moreover, this methodology also allows the water planner and manager to identify and select the most appropriate policy and measure for overcoming water demand and supply constraints.

The impacts of uncertainty factors on Egypt’s water demand and supply were varied. I conclude, first, that for climate change impacts over Egyptian inlands, the results show that the climate models that best represent the future in the study area are GISS_E2_H p1, MIROC5, FIO_ESM, and ACCESS1-0 respectively. The results of projections data analysis of four CMIP5 models to determine the uncertainty range for each model show a significant change in temperature and rainfall for the period 2016-2050 for the two RCPs 4.5 and 8.5. The mean temperature change for the period 2016-2050 for the four models will likely be in the range of 0.9 to -1.7 °C. In contrast, the rainfall change for the period 2016-2050 for the four models presents high uncertainty in the future, where the change tends to decrease and will likely be in the range -1.6 to -8.9 mm. All models recorded a decrease in the rainfall amount over the period 2016-2050. The uncertainty range of rainfall volume will likely be 2.8 – 5 BCM over the period 2016 – 2050 in comparison to 3.9 – 5.1 BCM for the period of 1990-2015. This change tends to decrease rainfall in the region by 0.1 to 1.1 BCM in 2050. The results show that the impact of climate change on water supply in the study area over the period 2016 – 2050 will likely be in the range -0.52 to -0.57 BCM depending on the climate models results. This means that climate change has a limited impact on water supply in the study area, largely because the bulk of Egypt's water comes from outside its national boundaries (i.e. from upper Nile countries).

Next, I consider the risk of climate variability over the Nile's upstream (i.e. non-Egypt upper Nile) on Egypt's supply from which I concluded that, depending on the regression, sensitivity analysis and water year method, a high uncertainty range in the rainfall over the Nile basin leads to high uncertainty in water reaching Egypt at Dongola station. The variation range is estimated to be ± 95 mm from the average rainfall over the White Nile, ± 160 mm from average over the Blue Nile, and ± 30 mm from average over the Atbara River, thus the uncertainty range in water reaching Egypt will likely be ± 27 BCM of average at Dongola station. This high uncertainty's range is due to the high variability in rainfall over the upper Nile basin, resulting in high uncertainty in the water reaching Egypt. This uncertainty was handled by assessing risk to the Egyptian water system using the water year method in the WEAP model.

The result of the climate variability impact assessment (using the water year method in the WEAP model, and assuming that water demand is steady in each case at 85 BCM) on the water system in the study area, 2016 – 2050, was as follows. For the different years' sequence, total water supply for during the period will likely vary in the range 69.8– 80.2 BCM, and the gap between demand and supply will likely be in the range 5.0–15.5 BCM. For the very wet years sequence, total water supply will likely vary in the range 80.1 – 80.4 BCM, with the water gap in the range 4.9- 5.2 BCM. For the wet year's sequence, water supply will vary in the range 74.7–74.9 BCM, with a water gap in the range 10.3 – 10.6 BCM. For the normal year's sequence, total water supply will vary in the range 71.2 – 71.5 BCM and the water gap will likely be in the range 13.8 – 14.1 BCM. The HADR volume will decrease to be between 84.2 – 89.8 BCM. If the climate in the Nile basin tends to be dry, the situation will get worse. The results confirm that water shortage will increase to vary between 24.5 – 26.8 BCM due to the reduction in water supply of between

58.5 – 60.7 BCM, from 2016 – 2050. This will cause a serious impact on Egypt and may stop the HAD turbines, as the volume will reach 36 BCM and the HAD dead level is 31.6 BCM. In the worst case very dry years sequence there is an emphatic risk to Egypt, due to a dramatic change in supply in the range 43.9 – 56.4 BCM. This will cause an enormous water gap of 28.9 – 41.4 BCM even after exhausting all the HADR water to the dead limit. The probability of a very dry years sequence is very low as this needs a dramatic change in the climate of the Nile basin over a short time.

Egypt will experience significant increase in population (from the current 100 Million) to 2050 to reach 145.6, 159.9, 174.7, or 154.0 Million people according to the low, medium, and high variants of the UN projection, and CAPMAS projection, respectively. This population growth poses a serious risk through elevated water demand. There is a critical increase in demand to 2050 under the respective projections above, estimated at 91.3, 93.0, 94.7, and 92.7 BCM. This is a dramatic increase in demand; about 9 BCM a year by 2050, with uncertainty range ± 3.4 BCM. The water deficit due to this population growth will increase to 19.74, 21.4, 23.14, and 21.2 BCM in 2050 (under above respective projections) assuming water withdrawal from the HAD of 58 BCM and annual water consumption per capita of 87.6 m^3.

The land-use change assessment on Egypt's demand used a forecast analysis that adopted Exponential Triple Smoothing (ETS) to extract the low, medium, and high probabilities of agriculture and industry sector growth, based on historical data. The agricultural area will likely increase to 9.5, 11.3, and 13.06 Million feddans in 2050 over low, medium, and high range respectively. This is attributed to Egypt's ambitious program of land reclamation to bridge the food gap. Industrial growth has high uncertainty because of inaccurate information on the number of industrial units, as many industrial units are not registered with the ministry and operate in secret. According to the ETS projections, industrial units are estimated at 9 457, 14 149, and 18 840 units by 2050 over low, medium, and high ranges. The impact of land-use change (combining agriculture, industry, and population factors) on the Egyptian water system poses a high risk, as Egypt faces a major increase in demand to 2050, estimated at 95.5 BCM, 113.5 BCM, and 131.9 BCM under low, medium, and high ranges respectively, with uncertainty range of ± 36.4 BCM. Agriculture has the largest share of demand as a result of land-use change, where irrigation consumes the bulk of the available water supplies. Water shortage resulting from land-use change will increase to 2050 to be 23.9 BCM, 41.96 BCM, and 60.23 BCM over low, medium, high ranges respectively. These results assume current conditions, where water withdrawal from the HAD is constant at 58 BCM, water consumption per capita is 87.6 m^3, water consumption per feddan is 4700 m^3, and water consumption rate for industrial unit is 200 000 m^3. If the high projection occurs, Egypt cannot bridge the water gap from 2030, which will reach 30 BCM by 2050.

Analysis also revealed the risk to Egypt posed by the Grand Ethiopian Renaissance Dam (GERD). If the GERD reservoir fills quickly, over three years, Egypt will face a disastrous water deficit ranging from 16.2 to 56.8 BCM depending on climate variability in the Nile basin (very wet to very dry years). The highest water shortage of 56.8 BCM in the third year of filling occurs in the case of a sequence of very dry and dry years. In this case, Egypt cannot handle this gap by any means, because the HADR volume falls into the inactive zone, at 31.6 BCM. Even in the very wet years' sequence, the deficit will be 16.2 BCM, although Egypt can manage this deficit as the HADR volume will be high at 137 BCM. If the reservoir fills over seven years, the gap will likely be in the range 16.2– 43 BCM and the reservoir volume will range from 92.8 to 240.4 BCM with very wet to very dry climate conditions in the Nile basin. From 2023, Egypt cannot manage shortages under a dry and very dry years' sequence. The water gap will increase dramatically to 43.0 BCM in 2023 if the very dry sequence occurs. In 2024, the water gap is estimated to be 43.0 and 34.0 BCM for very dry and dry years respectively. For the sequence of normal, wet and very wet years, the situation will be better and Egypt can overcome the deficit. The water gap is still a problem with the GERD reservoir filling over ten years, under a very dry years' sequence, where the deficit will increase to 38 BCM in 2023. The range in water gap with ten years filling will be 16 -39 BCM. It can be concluded that the impact of GERD on supply to Egypt will be catastrophic if Egypt experiences a drought period (dry or very dry years). Filling the GERD reservoir over ten years is considered by this study as more appropriate than the three or seven years, particularly in the event of droughts, so as to provide Egypt with necessary water security. However, the risk of the GERD relates not only to the filling duration but also to Ethiopia's policy on water discharge after the filling period. This adds further uncertainty for downstream countries and raises the spectre of transboundary conflict. Therefore, the study assumes that the water volume reaching Egypt is only that already enshrined in international agreement (55.5 BCM), and WEAP is run to quantify the risk of this policy on water supply to Egypt. In this case, the High Dam in Egypt will cease to be effective, as there will be no surplus water to store, and the annual water gap will be about 21.6 BCM.

8.4 Framing Future Water Demand and Supply

To identify the potential future of Egypt's water demand and supply, six scenarios were developed using the WEAP model, and applied for the period 2016 – 2050. The results show that Egypt must develop new policy aims to increase water consumption efficiency and seek alternative water resources to bridge the forecast deficit.

The BAU scenario indicated that annual demand will increase significantly to 115.0 BCM in 2050 due to growth in agriculture, population, and industry, with actual water consumption (demand minus losses) likely to be 83.15 BCM. Water supply will grow to 106.15 BCM in 2050 due to the increased water reuse as a result of higher demand. Even though the water supply is increasing, it will not meet all demands, and there will be a water gap of 8.9 BCM in 2050. Agriculture demand is 74.8 BCM with 58.8 BCM consumption in 2050. Due to population growth, consumption and demand in the domestic sector are likely to reach 17.3 BCM and 21.62 BCM respectively in 2050. The industrial sector may witness a reasonable increase in consumption estimated at 3.88 BCM in 2050, and a strong rise in demand to 15.49 BCM; this difference is due to the huge loss rate, due to the absence of advanced technology use and existence of many industrial units that operate without a government license or monitoring.

Under the Critical Scenario, water usage and demand increase to 75.4 BCM and 94.1 BCM in 2050 respectively. Egypt will withdraw only its 55.5 BCM share through the high dam, where the inflow to Egypt at Dongola station is assumed to be 52 BCM due to the dry climate upstream. This will lead to an expansion in rainwater harvesting and groundwater exploitation. As a result of the water gap, Egypt uses desalination and expansion of water reuse to close the water gap. Agriculture remains the largest consumer of water between by sector due to the huge agricultural area in Egypt, which reach 11.3 million feddans in 2050 under this scenario. Industrial water consumption and demand increase more than in the domestic sector in this scenario, where the industrial consumption and demand reach 5.76 BCM and 16.47 BCM in 2050 respectively. Domestic water consumption and demand is estimated at 13.6 BCM and 15.91 BCM in 2050 respectively.

Under the Optimistic Scenario, demand is likely to decrease to about 76.01 BCM with consumption at 63.52 BCM in 2050. In 2050, agriculture will consume 45.59 BCM, with demand at 55.58 BCM; industry may use about

2.82 BCM and water requirement may be 4.51 BCM, and domestic usage will be 12.01 BCM with demand at 12.81 BCM. The water shortage gap is likely to be zero (0 BCM).

Under the Balanced Scenario, there is a modest increase in consumption and demand, which reach 74.88 BCM and 92.07 BCM respectively. Agricultural lands, population census, and industrial units are at 11.3 million feddans, 159.9 million people, and 14 149 units respectively in 2050, based on their projected growth rates. Resulting water consumption and demand are estimated at 53.65 BCM and 63.44 BCM for agriculture; 14.02 BCM and 14.98 BCM for the domestic sector and 4.01 BCM and 10.45 BCM for industry by 2050. Supply is estimated at 92.07 BCM, where the drivers of supply are assumed to be balanced. The water shortage can be bridged.

Under the Pessimistic Scenario, demand is likely to increase sharply to about 116.74 BCM and consumption will be about 91.85 BCM in 2050. Water supply will be 98.65 BCM in 2050. This difference between demand and supply appear in 2029 and lead to a huge water deficit, estimated at 18.09 BCM by 2050. The agricultural land and industrial units will comprise 13.06 million feddans and 18840 units respectively in 2050 based on projected growth rates, to meet the needs of a population estimated at 174.7 million people by 2050. Huge demand and consumption results for each sector, estimated at 77.02 BCM and 66.34 BCM for agriculture; 17.40 BCM and 16.24 BCM in the domestic sector, and 18.82 BCM and 5.77 BCM for industry by 2050.

Under the Hybrid Scenario, water usage and demand rise slightly to above the current situation, to 71.42 BCM and 83.52 BCM respectively by 2050, but all demands can be met. Water supply increases relative to the current situation to 83.52 BCM due to expansion in water reuse. The water deficit will be easily overcome, although the outflow from the High Dam will be only 54 BCM. Agricultural land, population and industrial units will grow to 10.83 million feddans, 160 million people, and 15 387 industrial units respectively by 2050. This will lead to a manageable demand and consumption for each sector, very close to the current levels. Water usages and requirements will be 51.04 BCM and 58 BCM for agriculture; 13.24 BCM and 14.55 BCM for the domestic sector, and 4.04 BCM and 7.87 BCM for industry by 2050.

According to the coefficient of variation (CV), the results indicate that uncertainty range is modest with standard deviation values in the range of 4.4 to 13.4 BCM for the six scenarios. The Optimistic, Hybrid, and Balanced scenarios have CV values of 0.06, 0.08, and 0.09, respectively. This uncertainty increases slightly to 0.11 and 0.10 for the demand and supply sides respectively in the BAU scenario. Similarity, the uncertainty for the Critical scenario is by 0.11 for both demand and supply. The Pessimistic scenario has a remarkable level of uncertainty shown by the CV value of 0.14 and 0.10 for demand and supply respectively. The uncertainty increase in the Pessimistic scenario and the difference in uncertainty for the other scenarios is attributed to variation in the growth of agriculture, population, industry, and supply variables. It is noted that the uncertainty grows because of the widening gap between supply and demand, and that uncertainty of demand increase is raised compared to that of water supply, especially under the Pessimistic and BAU scenarios, due to the relative stability of supply.

Complexity in developing water demand and supply scenarios was addressed by selecting the appropriate model, system representation, data availability limitation, determining the scenarios drivers, and identifying an appropriate spatial and temporal scale. The WEAP model offers sophisticated and flexible tools to develop scenarios explore options for the future, where implications of various probabilities and policies can be evaluated. Even though the water system in Egypt is very complex due to the large spatial scale and variety of variables in demand and supply, WEAP performed well to simulate the system. In addition, data availability is a complex problem in modelling in general, and in developing scenarios in particular, so the data often controls determines model selection, temporal and spatial scales, definition of scenarios drivers, as well as processes for determining future probabilities for scenarios drivers.

The advantage of WEAP is that it can run in different time frames; daily, monthly, or yearly, offering tools to handle complexity associated with limited data. Running WEAP with an annual timeframe greatly reduced the complexity of the modelling, but the time step was nevertheless entirely consistent with the strategic, long term nature of the analysis.

8.5 Integrated Water Demand and Supply Management

Measures to bridge Egypt’s water gap were identified, and their uncertainty in bridging the gap evaluated, using Delphi method-led questionnaires with Egyptian water experts, and representation of the measures in WEAP modelling under the Pessimistic scenario. I used the Pessimistic ‘worst case’ scenario to develop this precautionary analysis; given the significance of adverse impacts to Egypt should a water deficit occur. This proved to be a powerful and efficient way of dealing with the uncertainty and complexity associated with Egypt's water gap.

Water resources management adds further complexity and uncertainty due to the variety of measures available, the extent to which they can be represented in assessment (e.g. scaling may be data constrained) and due to differing subjective judgement on the feasibility and acceptability of measures. Management measures vary in feasibility, implementation restrictions, cost, risk, environmental compatibility, effectiveness, ability to solve the fundamental problem (in our case, to eliminate the water deficit), the extent to which they are promotable (public acceptability), and political acceptability. These attributes are important in appraisal and selection of measures, but all add further uncertainty. In Egypt, there is considerable uncertainty and complexity around measures proposed to bridge the water gap. Therefore the stakeholder-based approach using Delphi method-led questionnaires was used to derive a list of options, which were then subject to subjective uncertainty appraisal using the criteria above, followed by application in the WEAP model (under varying extent and intensity of application, within realistic bounds) to close the water gap. In order of most to least feasible, these were considered the measures needed to avoid a future water deficit in Egypt:

- Increased water reuse to be 27.5 BCM per year,
- Increased leakage reduction to be 35% for agriculture, 27% for domestic, and 65% for industry,
- Change to modern irrigation methods such as drip, bubble irrigation and mist spraying instead of surface irrigation,
- Change of cropping pattern to lower water intensity crops. changing the half area of rice and sugar cane with wheat is sufficient to some extent to save water about 4 BCM/year,
- Rainwater harvesting system to collect 1.5 BCM/year instead of 1.3 BCM/year,
- Rehabilitation of old irrigation and domestic network,
- Increasing public awareness to save water,
- Completing the upper Nile water supply projects to provide with 3.4 BCM/year,
- Enhancing metering (smart meters),
- More desalination to reach 3 BCM/year,
- Reducing discharge of fresh water into the sea,
- Creating new storage for flood water,

- Increased withdrawal of underground water to reach 4.7 BCM/year from deep underground water in the desert and 8.0 BCM/year from shallow underground water in the Delta and Nile valley,
- Increased water-pricing slightly with respect to recovery of to cover the cost of operation and maintenance,
- Increasing Egypt's share of Nile water to be 57.5 BCM/year instead of 55.5 BCM/year.

It is also worth pointing out that the proposed solution is not one measure, but a package of them. In addition, there are flexibility and trade-off in this solution related to implementing the proposed measures, for example, the planner and decision makers could reduce the leakage more, then they would not need to convert much rice/sugar areas to wheat. Another example is that increasing the water supplies from the upper Nile project could reduce the needs for more desalinated water quantities. These measures can bridge the water gap in Egypt even under the worst-case scenarios to 2050. Water reuse and leakage reduction offer greatest certainty in ability to bridge the water gap, followed by implementing modern irrigation methods, substitution of water intensive crops, and completing the upper Nile water supply projects. Better monitoring and management of water in agriculture, the largest user of water in Egypt, will raise water security for other sectors.

8.6 Recommendations, Limitations of the Study, and Future Work

The study provided valuable knowledge about dealing with uncertainty and complexity of water demand and supply in Egypt and its potential future and management of the water gap in Egypt. The main recommendations stemming from the study are presented here.

8.6.1 Recommendations for Dealing with Uncertainty and Complexity in Water Demand and Supply in Egypt

The study provided a method to deal with uncertainty and complexity in water demand and supply assessment in Egypt for establishing a primary understanding of the basin hydrology (Chapter 4). The hydrological system in Egypt is complex and includes many uncertain factors such as the Nile River supply, climate change, population growth, land use change, water consumption rate, human interventions and development in the riparian countries. Therefore, dealing with this system needs an appropriate models and tools to simplify the complexities and addressed the uncertainties. This study recommends the WEAP model and GLUE algorithm as powerful tools to simulate the water demand and supply and limit uncertainty and complexity.

The amount of released water from the HAD is not always 55.5 BCM/year as reported in many research and by Ministry of Water, as the released amount depends on the needs of the demand sites, the high floods, and the water volume in HADR. To avoid uncertainty in input data and obtaining accurate results with related to water supply and deficit, The study recommends using the actual outflow from HAD, which is different from year to year other according to the flooding and water level in the HADR. In addition, there is a need for a comprehensive and adequate model of rainwater volumes in Egypt, as this is ignored by many researchers who rely on estimates provided by the Egyptian Ministry of Water.

More accurate data for demand and supply variable is required, where Egypt needs to set up the time frame of demand and supply data monthly rather than annually to give more accurate model simulation. For example, Egypt needs to determine accurately the agricultural area and number of industrial units in light of the many projects announced that are delivered only partially or not at all. For example, the New Toshka lands agricultural project in the south and Al Salam Canal project in Sinai Peninsula (Chapter 1, Section 1.3 and Figure 1.1). Furthermore, the industrial sector data is uncertain and there is a need to be more accurate, where many industrial units work in secret without a license and are not registered in the database of the ministry of water or ministry of industry. The study recommends a comprehensive and accurate survey to identify the number of industrial and industrial units and the quantities of water withdrawal for each unit separately.

The study recommends supporting studies of uncertainty and complexity applied for Egypt’s water demand and supply in order to obtain more accurate results, as within the scope of my knowledge there are no studies that dealt with the uncertainty and complexity of the hydrological system inside Egypt.

8.6.2 Recommendations for the Future Water Demand and Supply in Egypt

The study presented a framework for assessing the impacts of uncertainty factors on Egypt’s water deficit, water demand, and supply over the period 2016 – 2050 (Chapter 5). The results support water policy makers by shaping and quantifying the risk produced by these uncertainty factors. Recommendations can be drawn from this context to mitigate consequences of these uncertain factors on Egypt's water demand and supply as follows.

There is a need for more studies of climate change impacts over Egypt using more climatic models to identify the future of climate over Egypt accurately. Uncertainty about climate variability over the Nile’s upstream sources affects the flow of Nile water into Egypt, which in turn affects its main reservoir in Nasser Lake, as it influences the ministry's policy on the amount of water that must be released from the reservoir through the gates of the Aswan High Dam. Therefore, the study recommends monitoring the climate variability over the Nile's upstream and preparing precise climatic studies using the sophisticated climatic models, where the large amount of freshwater is coming from outside Egypt.

In addition, the study recommends developing more accurate projections for population growth, where Egypt’s population increase rapidly and the previous projections were not precise. Egypt should seek to find solutions through awareness to curb the doubling of the population as Egypt will face an increasing demand drastically on water resources in the near future.

There is great uncertainty and complexity around the impact of the GERD on Egypt. There should be an advanced agreement about the rules of filling the GERD reservoir and operating rules for periods of drought that include measures to mitigate drought in downstream countries. The study recommends that the GERD should be filled during wet and very-wet years only to avoid affecting the downstream countries. In addition, Egypt should be looking for more rational water management and increase water consumption efficiency during the storage period and many studies should be undertaken to confirm or deny the risk.

The study recommends the need for clear and confirmed data for the state’s plan in land reclamation and industrial development, as the observed data constituted a major obstacle in drawing out future projections for agricultural areas and industrial units.

The study detected the potential future of Egypt's water demand and supply by developing six scenarios for the period 2016 - 2050 using the WEAP model (Chapter 6). The study recommends that attention should be drawn to optimizing water resource use where water resources available may not meet the future need. Also, the need to reduce water losses in the agricultural, domestic and industrial sector due to the distribution losses, network leakage, unmetered water consumption in public parks and buildings, and clandestine connections...etc.

Egypt should take into consideration that current water resource exploitation cannot be relied on to satisfy expected increased future demand. Any reduction in the available water, combined with this increase in demand, will have dramatic consequences.

8.6.3 Recommendations for Water Management and Policy Makers

The study dealt with uncertainty and complexity in water management in the context of water stress in Egypt by planning against a worst case pessimistic scenario to support planners and policy makers in Egypt to avert the worst outcomes associated with water scarcity (Chapter 7). The study recommends considering the results of this study that allow the water planner and manager to identify and select the most appropriate policy and measure for overcoming the water demand and supply constraints. The study recommends 15 proposed measures to overcome the water gap in Egypt (Figure 7.7). These measures distinguished by flexibility and trade-off in implementation to close the water gap. The study recommends the priority of suitable measures as follow: water reuse and leakage reduction, changing to modern irrigation, changing cropping patterns, and completing upper Nile projects.

The need to reduce water losses in demand sectors is essential to conserve the water. The study recommends replacing the traditional irrigation method with modern methods such as drip, bubble irrigation and mist spraying. In addition, it recommends changing the half area of rice and sugar cane with wheat to save water about 4.0 BCM/year.

According to the hydrological modelling in Chapter 4, the study recommends that Egypt can harvest more than 1.3 BCM from rainwater to include in its water balance; more accurate studies are required to determine the quantity.

The study recommends the necessity of completing the upper Nile projects due to the rapid increased demand and developments in riparian countries. Although developments in riparian countries including Ethiopia and Sudan may reduce water supply to Egypt, these countries could also increase supply to Egypt through upper Nile projects, by conserving water lost in swamps. Therefore, cooperation and mutual understanding with the Nile Basin countries are very important to conserve river water resources.

In spite of the efficiency of the proposed measures in this study, the study recommends that Egypt should renew its water policy and management to be able to overcome the water shortage after 2050 in case the pessimistic scenario arises. In addressing the water deficit, uncertainty in Egypt's water demand and supply should not obstruct policymakers and water planners from reconsider and reassess the existing policies.

The study recommends developing a holistic approach in managing water resources by participating the experts and stakeholders to support the planner and policy maker. In addition, the study supports the WEAP model and Delphi technique as an efficient framework in the integrated water resources management.

8.6.4 The Limitations of the Study, Reflections and Opportunities for Future Works

While this thesis has, it is hoped, generated valuable knowledge and insight on dealing with uncertainty and complexity in Egypt's water demand and supply, additional surveys are needed to increase the accuracy of the analysis and to validate the results obtained. These results are of interest to policymakers and planners through the integrated management of water resources, as a model of good governance of management.

The research has some limitations that can be drawn as follow. In the field of modelling, selecting the appropriate model to simulate the Egyptian complex system and use it as hydrological and planning model was not an easy task at all. Several models were tried on the study area before choosing the WEAP model to apply in this study.

During collecting data and applying the questionnaire, some organisations refused to cooperate with the researcher, leading to the limitation of data. In addition, there were difficulties in obtaining detailed data, as there is a lack of data about the water demand and supply such as water consumption coefficients by sector are aggregate and demand data are available in annual time step only. Therefore, if this data becomes available in the future, it will give more accurate results.

The limitations of data availability and the nature of the study area as a downstream country affected the methodological choices, for example, selecting an appropriate model that can represent and simulate the hydrological system. Consequently, choosing an appropriate method to address the uncertainty and it can be operated with the selected model. In addition, the lack of previous hydrological studies on the study area led to using the PEST tool for initial estimation of the parameters ranges before conducting the sensitivity analysis and uncertainty analysis. Furthermore, the nature of the hydrological basin forced me to identify the impacts of climate change over Egyptian lands using the climate models data and use the water year methods to detect the effects of climate variability over the Nile’s upstream basin on Egypt's water supply. Further, the limitations of knowledge about the used measures in Egypt's water policy led to adopting the precautionary approach, which uses the WEAP model and Delphi method-led questionnaires based on group communication from stakeholders to identify the uncertainty about the proposed measures and select the optimal measures and robust solutions to water deficit.

In Egypt, water policy decisions are making and implementing in an environment dominated by central government entities that follow a strict routine in giving information such as Ministry of Water and the Ministry of Agriculture, so dealing with these entities was not an easy task at all. In addition, In Egypt, government institutions having the upper hand in managing and allocating the water resources. These institutions have a hierarchical way of organizing work, so it was hard to convince the experts to participate in the questionnaire without permission of the head of institution. This hindered the study to apply a larger number of the questionnaire and consumed more time. Therefore, conducting such studies with participation of a larger number of governmental and non-governmental stakeholders -namely citizens and the private sector- may add other measures and give more accurate results.

The investigation of uncertainty and complexity of water demand and supply in Egypt has underlined some new avenues for future research. In the field of uncertainty and complexity, more focus on the model structure and parameters and its effects on increasing/decreasing the uncertainty and complexity. Therefore, the researcher has future intentions to incorporate a comparative study between the performance of WEAP model and other hydrological and management models. In addition, more focus on the modeller’s role in modelling process, estimate uncertainty and simplify complexity. Furthermore, comparing the results of this study based on annual data with results of study based on monthly data will be useful to understand the role of data time step in increase/decrease uncertainty.

In the field of water management and implementation, the researcher would like to extend the boundaries of the study to include non-state stakeholders to give more focus on the role of them in water policy. Also, the researcher would like to address the uncertainty and complexity of water security and management in the face of pandemics such as COVID-19.

To conclude, it remains to be seen how the water demand, supply, and deficit in Egypt will look like in the years to come in light of the results of this study. Nonetheless, one may predict an increase in water demand against limited supply. It is my belief that this calls for the measures proposed in this study and full implementation of the principles of rational and integrated management, particularly the participatory decision-making.

List of References

Abbas, M. H., 2010. Water projects in Ethiopia and its implications for the future of the Nile waters, the prospects for cooperation and integration among the Nile Basin countries, Opportunities and Challenges*. The Institute of African Research and Studies, Cairo University*, pp. 151-291.

Abbas, M. H., 2011. Great Ethiopian Renaissance Dam (Millennium Dam) and influence in Egypt and northern Sudan, and the future of Egypt's relations with Nile Basin countries*. The Institute of African Research and Studies, Cairo University*.

Abbaspour, K.C., 2015. SWAT calibration and uncertainty programs—a user manual. *Swiss Federal Institute of Aquatic Science and Technology: Eawag, Switzerland*.

Abbaspour, K.C., Johnson, C.A. and Van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. *Vadose Zone Journal*, *3*(4), pp.1340-1352.

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S.R.I.N.I.V.A.S.A.N.B., Srinivasan, R., Yang, H. and Kløve, B., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology*, *524*, pp.733-752.

Abdelhaleem, F.S. and Helal, E.Y., 2015. Impacts of Grand Ethiopian Renaissance Dam on different water usages in upper Egypt. Br. J. Appl. Sci. Technol, 8(5), pp.461-483.

Abdel-Latif, M.M. and Yacoub, M., 2011. Effect of change of discharges at Dongola station due to sedimentation on the water losses from Nasser Lake. *Nile Basin Water Science & Engineering Journal*, *4*(1), pp.86-98.

Abdel-Satar, A.M., Ali, M.H. and Goher, M.E., 2017. Indices of water quality and metal pollution of Nile River, Egypt. The Egyptian Journal of Aquatic Research, 43(1), pp.21-29.

Abdel-Shafy, H. and Aly, R., 2002. Water issue in Egypt: Resources, pollution and protection endeavors. Navigation, 49(3.1), pp.4-6.

Abdel-Shafy, H.I., El-Saharty, A.A., Regelsberger, M. and Platzer, C., 2010. Rainwater in Egypt: quantity, distribution and harvesting. *Mediterranean Marine Science*, *11*(2), pp.245-258.

Abdin, A.E. and Gaafar, I., 2009. Rational water consumption in Egypt. *Technological perspectives for rational use of water resources in the Mediterranean region*, *88*, pp.11-27.

Abrishamchi, A., Alizadeh, H., Tajrishy, M. and Abrishamchi, A., 2007. Water resources management scenario analysis in Karkheh River

Basin, Iran, using WEAP model. *Hydrological Science and Technology*, *23*(1/4), p.1.

Abu-Zeid M., 1991. Water Resources Assessment for Egypt, Ministry of water resources and irrigation. Egypt.

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

Abu-Zeid, M., Rady, M.A., Le Moigne, G., Barghouti, S. and Feder, G., 1992. Water resources management and policies in Egypt. *Country experiences with water resources management: economic, technical sand environmental issues. World Bank, Technical paper*, (175).

Adly, E. and Ahmed, T., 2009. Water and food security in the river Nile Basin: perspectives of the government and NGOs in Egypt. In *Facing Global Environmental Change* (pp. 641-649). Springer, Berlin, Heidelberg.

Agrawala, S., Moehner, A., El Raey, M., Conway, D., Van Aalst, M., Hagenstad, M. and Smith, J., 2004. Development and climate change in Egypt: focus on coastal resources and the Nile. *Organisation for Economic Co-operation and Development*, *1*, pp.1-68.

Ahmad, A.M., 2008. Post-Jonglei planning in southern Sudan: combining environment with development. *Environment and urbanization*, *20*(2), pp.575-586.

Ahmad, M., 2000. Water pricing and markets in the Near East: policy issues and options. *Water policy*, *2*(3), pp.229-242.

Ako, A.A., Eyong, G.E.T. and Nkeng, G.E., 2010. Water resources management and integrated water resources management (IWRM) in Cameroon. *Water Resources Management*, *24*(5), pp.871-888.

Alazzy, A.A., Lü, H. and Zhu, Y., 2015. Assessing the uncertainty of the Xinanjiang rainfall-runoff model: effect of the likelihood function choice on the GLUE method. *Journal of Hydrologic Engineering*, *20*(10), p.04015016.

Alcamo, J., Flörke, M., and Märker, M., 2007. Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrological Sciences Journal,52(2), 247–275.

Allam, M.M., Bekhit, H., Elzawahry, A.M. and Allam, M.N., 2018. Jonglei Canal Project Under Potential Developments in the Upper Nile States. *Journal of Water Management Modeling*.

Allam, M.N. and Allam, G.I., 2007. Water resources in Egypt: future challeges and opportunities. *Water International*, *32*(2), pp.205-218.

Allam, M.N., 2001. Water and agricultural land in Egypt: past, present and future. *Academic Library, Cairo*. (In Arabic)

Allen, J.W., Allan, J.A. and Howell, P.P. 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.

Al-Omari, A., Al-Quraan, S., Al-Salihi, A. and Abdulla, F., 2009. A water management support system for Amman Zarqa Basin in Jordan. *Water resources management*, *23*(15), p.3165.

Amin, A., Iqbal, J., Asghar, A. and Ribbe, L., 2018. Analysis of current and future water demands in the Upper Indus Basin under IPCC climate and socio-economic scenarios using a hydro-economic WEAP model. *Water*, *10*(5), p.537.

Antunes, Ricardo, and Vicente Gonzalez. "A Production Model for Construction: A Theoretical Framework." Buildings 5.1 (2015): 209-28.

Anwar, M.R., Li Liu, D., Macadam, I. and Kelly, G., 2013. Adapting agriculture to climate change: a review. *Theoretical and applied climatology*, *113*(1-2), pp.225-245.

Apel, H., Thieken, A.H., Merz, B. and Blöschl, G., 2004. Flood risk assessment and associated uncertainty. *Natural Hazards and Earth System Sciences*, *4*(2), pp.295-308.

Argent, R.M., 2004. An overview of model integration for environmental applications—components, frameworks and semantics. *Environmental Modelling & Software*, *19*(3), pp.219-234.

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W. and Kannan, N., 2012. SWAT: Model use, calibration, and validation. Transactions of the ASABE, 55(4), pp.1491-1508.

Asghar, A., Iqbal, J., Amin, A. and Ribbe, L., 2019. Integrated hydrological modeling for assessment of water demand and supply under socio-economic and IPCC climate change scenarios using WEAP in Central Indus Basin. *Journal of Water Supply: Research and Technology—AQUA*, *68*(2), pp.136-148.

Aspinall, W.P. and Cooke, R.M., 2013. Quantifying scientific uncertainty from expert judgement elicitation, in. *Risk and uncertainty assessment for natural hazards*, p.64.

Atkinson, R., Crawford, L. and Ward, S., 2006. Fundamental uncertainties in projects and the scope of project management. *International journal of project management*, *24*(8), pp.687-698.

Atkinson, S.E., Woods, R.A. and Sivapalan, M., 2002. Climate and landscape controls on water balance model complexity over changing timescales. *Water Resources Research*, *38*(12), pp.50-1.

Attaher, S.M., Medany, M.A. and Abou-Hadid, A.F., 2009. Possible adaptation measures of agriculture sector in the Nile Delta to climate change impacts. *Advances in Science and Research*, *3*, p.123.

Attia, B.B., 2018. Securing Water resources for Egypt: a major challenge for policy planners. In *Unconventional Water Resources and Agriculture in Egypt* (pp. 485-506). Springer, Cham.

Ayyub, B.M. and Chao, R.U., 1997. Uncertainty modeling in civil engineering with structural and reliability applications. *Uncertainty modeling and analysis in civil engineering*, pp.1-8.

Ayyub, B.M., Gupta, M.M. and Kanal, L.N. eds., 1992. *Analysis and management of uncertainty: theory and applications* (Vol. 13). North-Holland.

Azari, A. and Asadi, M., 2017. Investigating the capabilities of the NSGA-II multi-objective algorithm in automatic calibration of the WEAP model for simulating Jareh Dam and network system. *Journal of Applied Research in Water and Wastewater*, *4*(1), pp.305-313.

Babuscia, A. and Cheung, K.M., 2014. An approach to perform expert elicitation for engineering design risk analysis: methodology and experimental results. *Journal of the Royal Statistical Society. Series A (Statistics in Society)*, pp.475-497.

Baccarini, D., 1996. The concept of project complexity—a review. *International journal of project management*, *14*(4), pp.201-204.

Bamber, J.L., Oppenheimer, M., Kopp, R.E., Aspinall, W.P. and Cooke, R.M., 2019. Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences*, *116*(23), pp.11195-11200.

Bárcena, J.F., Camus, P., García, A. and Álvarez, C., 2015. Selecting model scenarios of real hydrodynamic forcings on mesotidal and macrotidal estuaries influenced by river discharges using K-means clustering. *Environmental Modelling & Software*, *68*, pp.70-82.

Barendrecht, M.H., 2015. Bridging the Information Gap between Scientists and Decision Makers in the Eastern Nile. *TU Delft, Delft University of Technology*.

Bark, R.H., Peeters, L.J.M., Lester, R.E., Pollino, C.A., Crossman, N.D. and Kandulu, J.M., 2013. Understanding the sources of uncertainty to reduce the risks of undesirable outcomes in large-scale freshwater ecosystem restoration projects: An example from the Murray–Darling Basin, Australia. *Environmental science & policy*, *33*, pp.97-108.

Barnes, J., 2016. Uncertainty in the signal: modelling Egypt's water futures. *Journal of the Royal Anthropological Institute*, *22*(S1), pp.46-66.

Basco-Carrera, L., Warren, A., van Beek, E., Jonoski, A. and Giardino, A., 2017. Collaborative modelling or participatory modelling? A framework for water resources management. *Environmental Modelling & Software*, *91*, pp.95-110.

Bates, B.C. and Campbell, E.P., 2001. A Markov chain Monte Carlo scheme for parameter estimation and inference in conceptual rainfall-runoff modeling. *Water resources research*, *37*(4), pp.937-947.

Beard, M. K., B. P. Buttenfield, and S. B. Clapham. 1991. NCGIA Research Initiative 7: Visualization of spatial data quality. Technical Paper 91-26, National Center for Geographic Information and Analysis. 59pp.

Beh, E.H., Maier, H.R. and Dandy, G.C., 2015. Adaptive, multiobjective optimal sequencing approach for urban water supply augmentation under deep uncertainty. *Water Resources Research*, *51*(3), pp.1529-1551.

Bernstein, P., Against the Gods: The Remarkable story of risk, John Wiley & Sons, Inc., New York, NY, 1998.

Beven, K. and Binley, A., 1992. The future of distributed models: model calibration and uncertainty prediction. *Hydrological processes*, *6*(3), pp.279-298.

Beven, K. and Freer, J., 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *Journal of hydrology*, *249*(1-4), pp.11-29.

Beven, K. and Smith, P., 2015. Concepts of information content and likelihood in parameter calibration for hydrological simulation models. *Journal of Hydrologic Engineering*, *20*(1), p.A4014010.

Beven, K. and Young, P., 2003. Comment on "Bayesian recursive parameter estimation for hydrologic models" by M. Thiemann, M. Trosset, H. Gupta, and S. Sorooshian. WRR, 39(5), p.1116.

Beven, K., 2005. On the concept of model structural error. *Water Science and Technology*, *52*(6), pp.167-175.

Beven, K., 2006. A manifesto for the equifinality thesis. *Journal of hydrology*, *320*(1-2), pp.18-36.

Beven, K., 2016. Facets of uncertainty: epistemic uncertainty, non-stationarity, likelihood, hypothesis testing, and communication. *Hydrological Sciences Journal*, *61*(9), pp.1652-1665.

Beven, K.J. and Young, P., 2013. A guide to good practice in modeling semantics for authors and referees. Water Resources Research, 49 (8), 5092–5098. doi:10.1002/wrcr.20393

Beven, K.J., 2018. On hypothesis testing in hydrology: Why falsification of models is still a really good idea. *Wiley Interdisciplinary Reviews: Water*, *5*(3), p.e1278.

Beven, K.J., Leedal, D.T. and McCarthy, S., 2014. Framework for assessing uncertainty in fluvial flood risk mapping, CIRIA report C721/2014.

Bharati, L., Smakhtin, V.U. and Anand, B.K., 2009. Modeling water supply and demand scenarios: the Godavari–Krishna inter-basin transfer, India. *Water Policy*, *11*(S1), pp.140-153.

Blanken, J., 2012. Mainstreaming of MDGF Projects (FAO Component) and provision of tools for strategic decisions for the adaptation to Climate Change in the Egyptian agricultural sector. Final mission report - UNJP/EGY/022/SPA, Climate Change Risk Management Program.

Booker, J.M. and Ross, T.J., 2011. An evolution of uncertainty assessment and quantification. *Scientia Iranica*, *18*(3), pp.669-676.

Brady, T. and Davies, A., 2010. From hero to hubris–Reconsidering the project management of Heathrow’s Terminal 5. *International Journal of Project Management*, *28*(2), pp.151-157.

Brodlie, Ken, Rodolfo AllendesÂ Osorio, and Adriano Lopes. "A Review of Uncertainty in Data Visualization." Expanding the Frontiers of Visual Analytics and Visualization (2012): 81-109.

Busch, P., Heinonen, T. and Lahti, P., 2007. Heisenberg's uncertainty principle. *Physics Reports*, *452*(6), pp.155-176.

Butts, M.B., Payne, J.T., Kristensen, M. and Madsen, H., 2004. An evaluation of the impact of model structure on hydrological modelling uncertainty for streamflow simulation. *Journal of hydrology*, *298*(1-4), pp.242-266.

Camerer, C. and Weber, M., 1992. Recent developments in modeling preferences: Uncertainty and ambiguity. *Journal of risk and uncertainty*, *5*(4), pp.325-370.

CAPMAS 2001->2015. Annual Bulletin drinking water and sanitation statistics. Cairo, Egypt.

CAPMAS 2006. The central agency for public mobilisation and statistics. Final Results of 2006 Population Census. Cairo, Egypt. (In Arabic)

CAPMAS 2017a. Census of Population, Housing, and Establishments 2017. Central Agency for Public Mobilization and Statistics. Cairo, Egypt. (In Arabic)

CAPMAS 2017b. The central agency for public mobilisation and statistics. In: Annual Bulletin of Water Resources and Irrigation. Cairo, Egypt. (In Arabic)

CAPMAS 2020. https://www.capmas.gov.eg/HomePage.aspx at 26/7/2018

CAPMAS, 2015. Annual Industrial Statistics (Public / Private Sector) for the Whole Republic. Cairo, Egypt.

CAPMAS, 2016. Population statistics 2016. Central Agency for Public Mobilization and Statistics. Cairo, Egypt.

CAPMAS, 2018. Population statistics 2016. Central Agency for Public Mobilization and Statistics. Cairo, Egypt.

Carlos D. Correa, Yu-Hsuan Chan, and Kwan-Liu Ma. A framework for uncertainty-aware visual analytics. In Proceedings of IEEE Symposium on Visual Analytics Science and Technology VAST 09, 2009.

Carpi, A. and Egger, A.E., 2008. Data: Uncertainty, Error, and Confidence. *Visionlearning*, (3).

Carter, T.R., Jones, R.N., Lu, X., Bhadwal, S., Conde, C., Mearns, L.O., O'Neill, B.C., MDA, R. and Zurek, M.B., 2007. New assessment methods and the characterization of future conditions. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

CCA, U., 2001. United Nation's Common Country Assessment-Egypt. *Cairo, Egypt*.

Chen, J., Brissette, F.P., Poulin, A. and Leconte, R., 2011. Overall uncertainty study of the hydrological impacts of climate change for a Canadian watershed. *Water Resources Research*, *47*(12).

Chung, E.S., Won, K., Kim, Y. and Lee, H., 2014. Water resource vulnerability characteristics by district's population size in a changing climate using subjective and objective weights. *Sustainability*, *6*(9), pp.6141-6157.

Chung, G., Lansey, K. and Bayraksan, G., 2009. Reliable water supply system design under uncertainty. Environmental Modelling & Software, 24(4), pp.449-462.

Clark, W.C. Sustainability science: A room of its own. Proc. Natl. Acad. Sci. USA 2007, 104, 1737–1738.

Colson, A.R. and Cooke, R.M., 2018. Expert elicitation: using the classical model to validate experts' judgments. *Review of Environmental Economics and Policy*, *12*(1), pp.113-132.

Conway, D., 1996. The impacts of climate variability and future climate change in the Nile Basin on water resources in Egypt. International Journal of Water Resources Development, 12(3), pp.277-296.

Cosgrove, W.J. and Loucks, D.P., 2015. Water management: Current and future challenges and research directions. *Water Resources Research*, *51*(6), pp.4823-4839.

Crosetto, M. and Tarantola, S., 2001. Uncertainty and sensitivity analysis: tools for GIS-based model implementation. *International Journal of Geographical Information Science*, *15*(5), pp.415-437.

Custer, R.L., Scarcella, J.A. and Stewart, B.R., 1999. The Modified Delphi Technique-A Rotational Modification. *Journal of Career and Technical Education*, *15*(2).

Custovic, E., 2015. Engineering management: Old story, new demands. *IEEE engineering management review*, *43*(2), pp.21-23.

Darwish, R., Abd El-Maksoud, S. and El-Shibini, F., 1998. Economical and Environmental Aspects of Re-use of Drainage Water. *Arab Water'98*, pp.26-28.

De Carvalho, B.E., Marques, R.C. and Netto, O.C., 2017. Delphi technique as a consultation method in regulatory impact assessment (RIA)–the Portuguese water sector. *Water Policy*, *19*(3), pp.423-439.

De Loe, R.C., 1995. Exploring complex policy questions using the policy Delphi: A multi-round, interactive survey method. *Applied Geography*, *15*(1), pp.53-68.

DEPA, 2002. Water Prices in CEE and CIS Countries; A Toolkit for Assessing Willingness to Pay, Affordability and Political Acceptability. Danish Environmental Protection Agency,Ministry of the Environment.

Dequech, D., 2000. Fundamental uncertainty and ambiguity. *Eastern Economic Journal*, *26*(1), pp.41-60.

De-ren, L.I., 2006. Some Thoughts on Spatial Data Uncertainty in GIS [J]. *Journal of Zhengzhou Institute of Surveying and Mapping*, *6*.

Desai, P., 2002. *Methods beyond interviewing in qualitative market research* (Vol. 3). Sage.

Dessai, S. and Hulme, M., 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. *Global environmental change*, *17*(1), pp.59-72.

Dessai, S. and van der Sluijs, J., 2011. Modelling climate change impacts for adaptation assessments. *Simplicity, complexity and modelling. Wiley, Chichester*, pp.83-102.

Dessai, S., Browne, A. and Harou, J.J., 2013. Introduction to the special issue on “adaptation and resilience of water systems to an uncertain changing climate”. *Water Resources Management*, *27*(4), pp.943-948.

Di Baldassarre, G., Brandimarte, L. and Beven, K., 2016. The seventh facet of uncertainty: wrong assumptions, unknowns and surprises in the dynamics of human–water systems. *Hydrological Sciences Journal*, *61*(9), pp.1748-1758.

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

Dictionary, B., 2018. Business dictionary. *Retrieved April*, *17*, 2018.

http://www.businessdictionary.com/definition/complexity-factor.html

Djuma, H., Bruggeman, A., Eliades, M. and Lange, M.A., 2016. Non-conventional water resources research in semi-arid countries of the Middle East. *Desalination and Water Treatment*, *57*(5), pp.2290-2303.

DoPs., 2015. *Agreement on Declaration of Principles between the Arab Republic of Egypt, the Federal Democratic Republic of Ethiopia and the Republic of the Sudan on the Grand Ethiopian Renaissance Dam Project (GERDP)*. 23 March 2015. Khartoum, Sudan. https://www.internationalwaterlaw.org/documents/regionaldocs/Final_Nile_Agreement_23_March_2015.pdf [Accessed 21 August 2020].

Droubi, A., Al-Sibai, M., Abdallah, A., Zahra, S., Obeissi, M., Wolfer, J., Huber, M., Hennings, V. and Schelkes, K., 2008. A Decision Support System (DSS) for Water Resources Management,–Design and Results from a Pilot Study in Syria. In *Climatic changes and water resources in the Middle East and North Africa* (pp. 199-225). Springer, Berlin, Heidelberg.

Duan, Q., Sorooshian, S. and Gupta, V., 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. *Water resources research*, *28*(4), pp.1015-1031.

Dudley, N.J. and Hearn, A.B., 1993. Systems modeling to integrate river valley water supply and irrigation decision making under uncertainty. Agricultural systems, 42(1-2), pp.3-23.

Dungan, J.L., Gao, D. and Pang, A.T., 2002. Definitions of Uncertainty. *white paper,* ftp://128.114.47.74/pub/reinas/papers/white.pdf

Dwivedi, A., Mishra, D. and Kalra, P.K., 2006. Handling uncertainties-using probability theory to possibility theory. *Mag IIT Kanpur*, *7*(3), pp.1-12.

Edmonds, B., 1999. Syntactic measures of complexity (Doctoral dissertation, University of Manchester).

Eid, H. and Saleh, M., 1992. Modeling of Climate Change Impacts on Egyptian Agriculture. A report prepared for the University of Colorado at Boulder.

Eid, H.M., El-Marsafawy, S.M. and Ouda, S.A., 2007. Assessing the economic impacts of climate change on agriculture in Egypt: a Ricardian approach.

Eid, Helmy M., 1997. Support for the National Action Plan of Egypt: Assessment of Strategy and Policy Measures for Adaptation to Climate Change in Egyptian Agriculture. Final Report. Giza: Soils, Water and Environment Research Institute (SWERI), Ministry of Agriculture.

El Bastawesy, M., Gabr, S. and Mohamed, I., 2015. Assessment of hydrological changes in the Nile River due to the construction of Renaissance Dam in Ethiopia. The Egyptian Journal of Remote Sensing and Space Science, 18(1), pp.65-75.

El Qausy, D., Shideed, K., Oweis, T. and Karrou, M., 2018. Role of current policies and institutions Egypt in improving irrigated agriculture. International Center for Agricultural Research in the Dry Areas (ICARDA).

Elkassar, G.M., 2008. Monitoring and Evaluation of Improved Irrigation Delivery System in W/10 Command Area–Egypt. Science Water Journal-NWRC-December.

El-Raey, M., Dewidar, K.R. and El-Hattab, M., 1999. Adaptation to the impacts of sea level rise in Egypt. *Mitigation and Adaptation Strategies for Global Change*, *4*(3-4), pp.343-361.

Elsaeed, G., 2012. Effects of climate change on Egypt's water supply. In National Security and Human Health Implications of Climate Change (pp. 337-347). Springer Netherlands.

Elsayed, H., Djordjević, S., Savić, D.A., 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, 146(11), p.04020085.

Elshamy, M., Baldassarre, G.D. and Griensven, A.V., 2013. Characterizing climate model uncertainty using an informal Bayesian framework: application to the River Nile. *Journal of Hydrologic Engineering*, *18*(5), pp.582-589.

Elshamy, M.E., 2008. Assessing the hydrological performance of the Nile Forecast System in long term simulations. *Nile Water Science & Engineering Magazine*, *1*, pp.22-36.

Elshamy, M.E., Sayed, M.A. and Badawy, B., 2009a. Impacts of climate change on the Nile flows at Dongola using statistical downscaled GCM scenarios. *Nile Basin Water Engineering Scientific Magazine*, *2*, pp.1-14.

Elshamy, M.E., Seierstad, I.A. and Sorteberg, A., 2009b. Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. *Hydrol. Earth Syst. Sci*, *13*, pp.551-565.

Erlenkotter, D., Sethi, S. and Okada, N., 1989. Planning for surprise: Water resources development under demand and supply uncertainty I. The general model. Management science, 35(2), pp.149-163.

Falkenmark, M., Lundqvist, J. and Widstrand, C., 1989, November. Macro-scale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development. In *Natural resources forum* (Vol. 13, No. 4, pp. 258-267). Oxford, UK: Blackwell Publishing Ltd.

Faramarzi, M., Abbaspour, K.C., Vaghefi, S.A., Farzaneh, M.R., Zehnder, A.J., Srinivasan, R. and Yang, H., 2013. Modeling impacts of climate change on freshwater availability in Africa. Journal of Hydrology, 480, pp.85-101.

Farmer, D., Sivapalan, M. and Jothityangkoon, C., 2003. Climate, soil, and vegetation controls upon the variability of water balance in temperate and semiarid landscapes: Downward approach to water balance analysis. *Water Resources Research*, *39*(2).

Feil, B., Kucherenko, S. and Shah, N., 2009, September. Comparison of Monte Carlo and quasi Monte Carlo sampling methods in high dimensional model representation. In *2009 first international conference on advances in system simulation* (pp. 12-17). IEEE.

Fenemor, A., 2014. Managing technical communication and information risks during collaborative catchment limit-setting processes. *Landcare Research Contract Report LC1881 prepared for Environment Canterbury*.

Fernando, H.J.S., Klaić, Z.B. and McCulley, J.L. eds., 2012. *National security and human health implications of climate change*. Springer Science & Business Media.

Fischlin, A., Midgley, G.F., Price, J.T., Leemans, R., Gopal, B., Turley, C., Rounsevell, M.D.A., Dube, O.P., Tarazona, J. and Velichko, A.A., 2007. Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC fourth assessment report: climate change.

Foley, A.M., 2010. Uncertainty in regional climate modelling: A review. *Progress in Physical Geography*, *34*(5), pp.647-670.

Frey, H.C., 1992. Quantitative analysis of uncertainty and variability in environmental policy making. *Fellowship Program for Environmental Science and Engineering, American Association for the Advancement of Science, Washington, DC*.

Gado, T.A. and El-Agha, D.E., 2019. Feasibility of rainwater harvesting for sustainable water management in urban areas of Egypt. *Environmental Science and Pollution Research*, pp.1-14.

Gal, G., Makler-Pick, V. and Shachar, N., 2014. Dealing with uncertainty in ecosystem model scenarios: application of the single-model ensemble approach. *Environmental modelling & software*, *61*, pp.360-370.

Geertman, S. and Stillwell, J., 2003. Planning support systems: an introduction. In *Planning support systems in practice* (pp. 3-22). Springer, Berlin, Heidelberg.

Geraldi, J., Maylor, H. and Williams, T., 2011. Now, let's make it really complex (complicated). *International journal of operations & production management*.

Geraldi, J.G. and Adlbrecht, G., 2007. On faith, fact, and interaction in projects. *Project Management Journal*, *38*(1), pp.32-43.

Gharib, S., 2004. *Modeling the Irrigation system in Egypt* (Doctoral dissertation, Ph. D. thesis). University of Bergen, Norway.

Gleckler, P.J., Taylor, K.E. and Doutriaux, C., 2008. Performance metrics for climate models. *Journal of Geophysical Research: Atmospheres*, *113*(D6).

Gleick, P.H., 1991. The vulnerability of runoff in the Nile Basin to climatic changes. *Environmental Professional*, *13*(1), pp.66-73.

Gomez, K.A. and Gomez, A.A., 1984. Statistical procedures for agricultural research. John Wiley & Sons.

Gong, Y., Shen, Z., Hong, Q., Liu, R. and Liao, Q., 2011. Parameter uncertainty analysis in watershed total phosphorus modeling using the GLUE methodology. *Agriculture, ecosystems & environment*, *142*(3-4), pp.246-255.

Goodchild, M., B. Buttenfield, and J. Wood. 1994. On introduction to visualizing data validity. In H. Hearnshaw and D. Unwin, editors, Visualization in Geographical Information Systems, pages 141–149. Wiley.

Goossens, L.H.J. and Cooke, R.M., 2001. Expert judgement elicitation in risk assessment. In *Assessment and management of environmental risks* (pp. 411-426). Springer, Dordrecht.

Grassberger, P., 1989. Problems in quantifying self4organized complexity. *Helv. Phys. Acta*, *62*, p.4984511.

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S. and Wada, Y., 2018. Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability*, *1*(9), pp.486-494.

Groves, D.G., 2005. *New methods for identifying robust long-term water resources management strategies for California*. Ph.D. thesis. The Pardee RAND Graduate School.

Guieysse, B., Béchet, Q. and Shilton, A., 2013. Variability and uncertainty in water demand and water footprint assessments of fresh algae cultivation based on case studies from five climatic regions. Bioresource technology, 128, pp.317-323.

Hackanson, L. and Peters, R.H., 1995. Predictive limnology: methods for predictive modeling. *SPB Academic Pub., Amsterdam*, pp.1-464.

Hadded, R., Nouiri, I., Alshihabi, O., Maßmann, J., Huber, M., Laghouane, A., Yahiaoui, H. and Tarhouni, J., 2013. A decision support system to manage the groundwater of the zeuss koutine aquifer using the WEAP-MODFLOW framework. Water resources management, 27(7), pp.1981-2000.

Hamdy, A., Abu-Zeid, M. and Lacirignola, C., 1998. Institutional capacity building for water sector development. *Water International*, *23*(3), pp.126-133.

Hamlat, A., Errih, M. and Guidoum, A., 2013. Simulation of water resources management scenarios in western Algeria watersheds using WEAP model. *Arabian Journal of Geosciences*, *6*(7), pp.2225-2236.

Hamza, W. and Mason, S., 2004, November. Water availability and food security challenges in Egypt. In *Proceedings International Forum on*

Food Security Under Water Scarcity in the Middle East: Problems and Solutions. Como, Italy (pp. 24-27).

Hao, L., Sun, G., Liu, Y. and Qian, H., 2015. Integrated modeling of water supply and demand under management options and climate change scenarios in Chifeng City, China. *JAWRA Journal of the American Water Resources Association*, *51*(3), pp.655-671.

Harrison, S. and Stainforth, D., 2009. Predicting climate change: Lessons from reductionism, emergence, and the past. *Eos, Transactions American Geophysical Union*, *90*(13), pp.111-112.

Hassan, A.F. and Willems, P., 2005. Analysis of the return periods of low flow Hazards in Egypt and Sudan. In *CD-ROM Proceedings International Conference of UNESCO Flanders FIT FRIEND/Nile Project-Towards a better cooperation* (p. 11).

Hassan, D., Rais, M.N., Ahmed, W., Bano, R., Burian, S.J., Ijaz, M.W. and Bhatti, F.A., 2019. Future water demand modeling using water evaluation and planning: a case study of the Indus Basin in Pakistan. *Sustainable Water Resources Management*, *5*(4), pp.1903-1915.

Hassing, J., Ipsen, N., Clausen, T.J., Larsen, H. and Lindgaard-Jørgensen, P., 2009. Integrated water resources management (IWRM) in action. *World Water Assessment Programme (WWAP), DHI Water Policy and UNEP-DHI Centre for Water and Environment, Paris*.

Hayes, K., Regan, H.M., Burgman, M.A., Devlin, R.H., Kapuscinski, A.R. and Dambacher, J.M., 2006, September. Methods to address uncertainty in ecological risk assessment of Genetically Modified Organisms. In *Conference Proceedings for 9th International Symposium on the Biosafety of Genetically Modified Organisms* (pp. 28-31).

He, L., Tyner, W.E. and Siam, G., 2004. *Improving irrigation water allocation efficiency using alternative policy options in Egypt* (No. 377-2016-20722).

Heal, G. and Millner, A., 2014. Uncertainty and decision making in climate change economics. Rev. Environ. *Econ. Policy*, *8*(1), pp.120-137.

Hejazi, M., Edmonds, J., Chaturvedi, V., Davies, E. and Eom, J., 2013. Scenarios of global municipal water-use demand projections over the 21st century. Hydrological Sciences Journal, 58(3), pp.519-538.

Helal, M., 2020. *So Close, Yet So Far: An Account Of The Negotiations On The Grand Ethiopian Renaissance Dam (Part II)*. [online] Opinio Juris. Available at: http://opiniojuris.org/2020/05/04/so-close-yet-so-far-an-account-of-the-negotiations-on-the-grand-ethiopian-renaissance-dam-part-ii/ [Accessed 21 August 2020].

Her, Y. and Chaubey, I., 2015. Impact of the numbers of observations and calibration parameters on equifinality, model performance, and output and parameter uncertainty. *Hydrological Processes*, *29*(19), pp.4220-4237.

Hereher, M.E., 2009. Inventory of agricultural land area of Egypt using MODIS data. *Egypt J Remote Sens Space Sci*, *12*, pp.179-184.

Hill, L.J., Sparks, R.S.J. and Rougier, J.C., 2013. Risk assessment and uncertainty in natural hazards. *Risk and uncertainty assessment for natural hazards, edited by: Rougier, JC, Sparks, RS J., and Hill, LJ*, pp.1-18.

Holtanová, E., Mikšovský, J., Kalvová, J., Pišoft, P. and Motl, M., 2012. Performance of ENSEMBLES regional climate models over Central Europe using various metrics. *Theoretical and applied climatology*, *108*(3-4), pp.463-470.

Hong, S., Heo, J. and Vonderohe, A.P., 2013. Simulation-based approach for uncertainty assessment: Integrating GPS and GIS. *Transportation Research Part C: Emerging Technologies*, *36*, pp.125-137.

Honti, M., Scheidegger, A. and Stamm, C., 2014. The importance of hydrological uncertainty assessment methods in climate change impact studies. *Hydrol. Earth Syst. Sci*, *18*(8), pp.3301-3317.

Hoogduin, L., 2016. Decision Making in a Complex and Uncertain World. Retrived on 22/06/2018

https://www.futurelearn.com/courses/complexity-and-uncertainty

Howell, P., Lock, M. and Cobb, S., 1988. The Jonglei Canal: impact and opportunity. *Cambridge studies in applied ecology and resource management.*

Hsu, C.C. and Sandford, B.A., 2007. The Delphi technique: making sense of consensus. *Practical Assessment, Research, and Evaluation*, *12*(1), p.10.

Hunsaker CT, Goodchild MF, Friedl MA, Case TJ (2001) Spatial uncertainty in ecology: implications for remote sensing and GIS applications. Springer, New York.

Hunter, G.J., 1999. Managing uncertainty in GIS. *Geographical information systems*, *2*, pp.633-641.

International Panel of experts (IPoE) on Grand Ethiopian Renaissance Dam Project (GERDP), Final Report, Addis Ababa , Ethiopia, May, 31 st ; 2013. Available :

https://www.internationalrivers.org/sites/default/files/attached-files/international_panel_of_experts_for_ethiopian_renaissance_dam-_final_report_1.pdf

IPCC, 2007: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jajarmizadeh, M., Harun, S., Abdullah, R. and Salarpour, M., 2012. Using soil and water assessment tool for flow simulation and assessment of sensitive parameters applying SUFI-2 algorithm. *Caspian Journal of Applied Sciences Research*, *2*(1), pp.37-47.

Jakeman, A.J. and Hornberger, G.M., 1993. How much complexity is warranted in a rainfall-runoff model?. *Water resources research*, *29*(8), pp.2637-2649.

Jin, X., Xu, C.Y., Zhang, Q. and Singh, V.P., 2010. Parameter and modeling uncertainty simulated by GLUE and a formal Bayesian method for a conceptual hydrological model. *Journal of Hydrology*, *383*(3-4), pp.147-155.

Jones, R.N., 2012. Applying scenarios to complex issues: Australia 2050. *Negotiating Our Future: Living scenarios for Australia to 2050*, *2*, pp.173-190.

Jury, W.A. and Vaux, H.J., 2007. The emerging global water crisis: managing scarcity and conflict between water consumptionrs. Advances in Agronomy , 95, 1–76.

Kanta, L. and Zechman, E., 2014. Complex adaptive systems framework to assess supply-side and demand-side management for urban water resources. *Journal of Water Resources Planning and Management*, *140*(1), pp.75-85.

Karajeh, F., Oweis, T. and Swelam, A., 2013. *Water and Agriculture in Egypt* (No. 253822). International Center for Agricultural Research in the Dry Areas (ICARDA).

Kase, K. and Cantón, C.G., 2013. Judgement-Making in the Face of Contingency. In Towards Organizational Knowledge (pp. 306-349). Palgrave Macmillan UK.

Kern-Isberner, G. and Lukasiewicz, T., 2017. Many facets of reasoning under uncertainty, inconsistency, vagueness, and preferences: A brief survey. *KI-Künstliche Intelligenz*, *31*(1), pp.9-13.

Khoi, D.N. and Thom, V.T., 2015. Parameter uncertainty analysis for simulating streamflow in a river catchment of Vietnam. *Global ecology and conservation*, *4*, pp.538-548.

Khosravi, F. and Jha-Thakur, U., 2019. Managing uncertainties through scenario analysis in strategic environmental assessment. *Journal of Environmental Planning and Management*, *62*(6), pp.979-1000.

Khu, S.T. and Werner, M.G., 2003. Reduction of Monte-Carlo simulation runs for uncertainty estimation in hydrological modelling. *Hydrology and Earth System Sciences*, *7*(5), pp.680-692.

Kiefer, Jack C., Charles Yoe, John M. Clayton, and Jamie C. Leonard, 2016. Uncertainty in Long-term Water Demand Forecasts: A Primer on Concepts and Review of Water Industry Practices. Denver, CO: Water Research Foundation.

Kim, D.E., Jung, Y., Park, M.J., Yoon, J.Y., Kim, S.D. and Choi, M.H., 2011. Vulnerability analysis of water resources considering climate change. *Journal of Wetlands Research*, *13*(1), pp.25-33.

Kirchner, J.W., 2006. Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. *Water Resources Research*, *42*(3).

Klein, B., Meissner, D., Kobialka, H.U. and Reggiani, P., 2016. Predictive uncertainty estimation of hydrological multi-model ensembles using pair-copula construction. *Water*, *8*(4), p.125.

Klir, G. and M. Wierman. 1999. Uncertainty-Based Information: Elements of Generalized Information Theory, 2nd edition. Physica-Verlag. 168pp.

Klir, G.J., 2006. Uncertainty and information. *Foundations of Generalized Information Theory*. John Wiley & Sons, Inc.

Knight, F.H., 1921. Risk, uncertainty and profit. New York: Houghton-Mifflin Co. (reprinted University of Chicago Press, 1971).

Kok, K. and van Delden, H., 2009. Combining two approaches of integrated scenario development to combat desertification in the Guadalentin watershed, Spain. *Environment and Planning B: Planning and Design*, *36*(1), pp.49-66.

Kok, K., van Vliet, M., Bärlund, I., Dubel, A. and Sendzimir, J., 2011. Combining participative backcasting and exploratory scenario development: experiences from the SCENES project. *Technological Forecasting and Social Change*, *78*(5), pp.835-851.

Koutsoyiannis, D., 2010. HESS opinions: “A random walk on water”. Hydrology and Earth System Sciences, 14 (3), 585–601. doi:10.5194/hess-14-585-2010

Kouvelis, P. and Milner, J.M., 2002. Supply chain capacity and outsourcing decisions: the dynamic interplay of demand and supply uncertainty. IIE transactions, 34(8), pp.717-728.

Kuczera, G. and Parent, E., 1998. Monte Carlo assessment of parameter uncertainty in conceptual catchment models: the Metropolis algorithm. *Journal of hydrology*, *211*(1-4), pp.69-85.

Kundzewicz, Z.W., Krysanova, V., Benestad, R.E., Hov, Ø., Piniewski, M. and Otto, I.M., 2018. Uncertainty in climate change impacts on water resources. *Environmental Science & Policy*, *79*, pp.1-8.

Lahham, N., Saleh, M. and Sabry, S.S., 2011. Egypt’s Water Security–Future Vision 2030 Using Delphi Method. *Eur. Foresight Platf. Br*, (252).

Lan, F., Lin, W.H. and Lansey, K., 2015. Scenario-based robust optimization of a water supply system under risk of facility failure. *Environmental Modelling & Software*, *67*, pp.160-172.

Larson, K.L., White, D.D., Gober, P. and Wutich, A., 2015. Decision-making under uncertainty for water sustainability and urban climate change adaptation. Sustainability, 7(11), pp.14761-14784.

Lasheen, W., 2019. *Explaining water governance in Egypt: actors, mechanisms and challenges* (Doctoral dissertation, University of Exeter).

Le Page, M., Berjamy, B., Fakir, Y., Bourgin, F., Jarlan, L., Abourida, A., Benrhanem, M., Jacob, G., Huber, M., Sghrer, F. and Simonneaux, V., 2012. An integrated DSS for groundwater management based on remote sensing. The case of a semi-arid aquifer in Morocco. *Water resources management*, *26*(11), pp.3209-3230.

Leichenko, R., 2011. Climate change and urban resilience. *Current opinion in environmental sustainability*, *3*(3), pp.164-168.

Leonard, B. ed., 2009. GAO Cost estimating and assessment guide: best practices for developing and managing capital program costs. DIANE Publishing.

Leong, W.K. and Lai, S.H., 2017, June. Application of water evaluation and planning model for integrated water resources management: Case study of Langat River basin, Malaysia. In *Series: Materials Science and Engineering 210. IOP Conf. Series: Materials Science and Engineering* (Vol. 210).

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*(20-27), pp.779-786.

Li, X., Zhao, Y., Shi, C., Sha, J., Wang, Z.L. and Wang, Y., 2015. Application of Water Evaluation and Planning (WEAP) model for water resources management strategy estimation in coastal Binhai New Area, China. *Ocean & Coastal Management*, *106*, pp.97-109.

Li, Y., Chen, J. and Feng, L., 2012. Dealing with uncertainty: A survey of theories and practices. *IEEE Transactions on Knowledge and Data Engineering*, *25*(11), pp.2463-2482.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J. and Ostrom, E., 2007. Complexity of coupled human and natural systems. *science*, *317*(5844), pp.1513-1516.

Liu, Y. and Gupta, H.V., 2007. Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework. Water resources research, 43(7).

Lubchenco, J., 1998. Entering the century of the environment: a new social contract for science. *Science*, *279*(5350), pp.491-497.

Luce, R.D. and Raiffa, H., 1989. *Games and decisions: Introduction and critical survey*. Courier Corporation.

Ludwig, R., May, I., Turcotte, R., Vescovi, L., Braun, M., Cyr, J.F., Fortin, L.G., Chaumont, D., Biner, S., Chartier, I. and Caya, D., 2009. The role of hydrological model complexity and uncertainty in climate change impact assessment. *Advances in Geosciences*, *21*, p.63.

Luft, J., und Harry Ingham. 1955. The Johari window, a graphic model of interpersonal awareness. *Proceedings of the western training laboratory in group development. Los Angeles: UCLA*.

Luzi, S., 2010. Driving forces and patterns of water policy making in Egypt. *Water Policy*, *12*(1), pp.92-113.

Mabera, F., Dlamini, K. and Makamase, M., 2020. Spotlight on Africa: Mapping Geopolitical Trends for Quarter One 2020. *The Institute for Global Dialogue*. Pretoria, South Africa.

Mach, K.J., Mastrandrea, M.D., Freeman, P.T. and Field, C.B., 2017. Unleashing expert judgment in assessment. *Global Environmental Change*, *44*, pp.1-14.

Maestu, J., 2015. A 10 Year Story: The Water For Life Decade 2005-2015 and Beyond. *United Nations Office*.

Maier, H.R., Guillaume, J.H., van Delden, H., Riddell, G.A., Haasnoot, M. and Kwakkel, J.H., 2016. An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together?. *Environmental Modelling & Software*, *81*, pp.154-164.

MALR E. 2012. Annual bulletin of indicators of agricultural statistics. The ministry of agriculture and land reclamation.

Manca, A., Sechi, G.M., Sulis, A. and Zuddas, P., 2006. Scenario analysis in water resources management under data uncertainty. In *Summit on Environmental Modelling and Software*. IEMSS.

Mantovan, P. and Todini, E., 2006. Hydrological forecasting uncertainty assessment: incoherence of the GLUE methodology. Journal of Hydrology, 330, 368–381. doi:10.1016/j.jhydrol.2006.04.046

Marshall, L., Nott, D. and Sharma, A., 2004. A comparative study of Markov chain Monte Carlo methods for conceptual rainfall-runoff modeling. *Water Resources Research*, *40*(2).

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R. and Plattner, G.K., 2010. Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties. Intergovernmental Panel on Climate Change (IPCC).

McIntosh, B.S., Seaton, R.A. and Jeffrey, P., 2007. Tools to think with? Towards understanding the use of computer-based support tools in policy relevant research. *Environmental Modelling & Software*, *22*(5), pp.640-648.

McManus, H. and Hastings, D., 2006. A framework for understanding uncertainty and its mitigation and exploitation in complex systems. *IEEE Engineering Management Review*, *34*(3), pp.81-81.

McMillan, H.K., Westerberg, I.K. and Krueger, T., 2018. Hydrological data uncertainty and its implications. *Wiley Interdisciplinary Reviews: Water*, *5*(6), p.e1319.

Means, E.D., Patrick, R., Ospina, L. and West, N., 2005. Scenario planning: A tool to manage future water utility uncertainty. *Journal-American Water Works Association*, *97*(10), pp.68-75.

Mehan, S., Neupane, R.P. and Kumar, S., 2017. Coupling of SUFI 2 and SWAT for Improving the Simulation of Streamflow in an Agricultural Watershed of South Dakota. *Hydrol. Curr. Res*, *8*(3).

Melchers, R.E. and Beck, A.T., 1999. *Structural reliability analysis and prediction*. John wiley & sons.

Metwalli, N., 2010. Climate Change Risk Management Program (CCRMP)-Egypt. Mid Term Review, UNDP/MDG.

Middelkoop, H., Van Asselt, M.B., Van't Klooster, S.A., Van Deursen, W.P., Kwadijk, J.C. and Buiteveld, H., 2004. Perspectives on flood management in the Rhine and Meuse rivers. *River research and applications*, *20*(3), pp.327-342.

Mirzaei, M., Huang, Y.F., El-Shafie, A. and Shatirah, A., 2015. Application of the generalized likelihood uncertainty estimation (GLUE) approach for assessing uncertainty in hydrological models: a review. *Stochastic environmental research and risk assessment*, *29*(5), pp.1265-1273.

Moellering, H. 1988. The proposed standard for digital cartographic data: report of the digital cartographic data standards task force. The American Cartographer 15.

Moghazy, H.M., Saleh, O.K. and El Azim, N.A., 2013. Hydraulic analysis of El Mahmoudia canal. WIT Transactions on Ecology and the Environment, 178, pp.41-52.

Mohie El Din, M.O. and Moussa, A.M., 2016. Water management in Egypt for facing the future challenges. Journal of advanced research, 7(3), pp.403-412.

Montanari, A. and Koutsoyiannis, D., 2012. A blueprint for process-based modeling of uncertain hydrological systems. Water Resources Research, 48, W09555. doi:10.1029/ 2011WR011412

Montanari, A., 2005. Large sample behaviors of the generalized likelihood uncertainty estimation (GLUE) in assessing the uncertainty of rainfall-runoff simulations. *Water resources research*, *41*(8).

Montanari, A., 2007. What do we mean by ‘uncertainty’? The need for a consistent wording about uncertainty assessment in hydrology. Hydrological Processes, 21, 841–845. doi:10.1002/hyp.6623

Morgan, M.G., 2014. Use (and abuse) of expert elicitation in support of decision making for public policy. *Proceedings of the National academy of Sciences*, *111*(20), pp.7176-7184.

Morgan, M.G., Henrion, M. and Small, M., 1990. *Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis*. Cambridge university press.

Moss, R. H. and S. H. Schneider, 2000: “Uncertainties in the IPCC TAR: recommendation to lead authors for more consistent assessment and reporting,” in R. Pachauri, T. Taniguchi, and K. Tanaka (eds.), Third Assessment Report: Cross Cutting Issues Guidance Papers (Geneva: World Meteorological Organisation), pp. 33–51.

Mowrer, H. T. and R. Congalton, editors. 2000. Quantifying Spatial Uncertainty in Natural Resources: Theory and Applications for GIS and Remote Sensing. Ann Arbor Press.

Muala, E., Mohamed, Y.A., Duan, Z. and van der Zaag, P., 2014. Estimation of reservoir discharges from Lake Nasser and Roseires Reservoir in the Nile Basin using satellite altimetry and imagery data. Remote Sensing, 6(8), pp.7522-7545.

Mugatsia, E.A., 2010. Simulation and scenario analysis of water resources management in Perkerra catchment using WEAP model. *Master’s Thesis, Department of Civil and Structural Engineering, School of Engineering, Moi University, Kenya,(December)*.

Mukheibir, P. and Mitchell, C., 2014. Decision-making under future uncertainty: developing adaptive urban water strategies. *International Journal of Water*, *8*(4), pp.435-447.

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*, *2014*.

Multsch, S., Elshamy, M.E., Batarseh, S., Seid, A.H., Frede, H.G. and Breuer, L., 2017. Improving irrigation efficiency will be insufficient to meet future water demand in the Nile Basin. *Journal of Hydrology: Regional Studies*, *12*, pp.315-330.

Mutikanga, H.E., Sharma, S.K. and Vairavamoorthy, K., 2011. Multi-criteria decision analysis: a strategic planning tool for water loss management. *Water resources management*, *25*(14), p.3947.

MWRI 2010. Water Resources Development and Management Strategy in Egypt – 2050. Ministry of Water Resources and Irrigation, Cairo, Egypt. (in Arabic)

MWRI, 2005. National Water Resources Plan 2017. Water for the Future, National Water Resources Plan 2017.Available online: http://extwprlegs1.fao.org/docs/pdf/egy147082.pdf (accessed on 23 June 2016).

MWRI, 2014. Ministry of Water Resources and Irrigation. Water Scarcity in Egypt; February 2014. [accessed July 18, 2016], https://www.mwri.gov.eg/.

MWRI, 2017. Egypt and Water: Facts and numbers. Unpublished Report

MWRI, 2018. Egypt and Water: Facts and numbers. Unpublished Report

MWRI., 1997. The Egyptian Water Strategy Till 2017, Planning Sector - Ministry of Water Resources and Irrigation, Cairo, Egypt

Nasef, M.A.A., 2012. Using GIS and statistical methods to detect the multi-decadal variability for temperature trends on Egypt: 1960-2000. Geographia Technica, 15(1), pp.46-60.

Nearing, G.S., Tian, Y., Gupta, H.V., Clark, M.P., Harrison, K.W. and Weijs, S.V., 2016. A philosophical basis for hydrological uncertainty. *Hydrological Sciences Journal*, *61*(9), pp.1666-1678.

Newham, L.T.H., Jakeman, A.J. and Letcher, R.A., 2007. Stakeholder participation in modelling for integrated catchment assessment and management: an Australian case study. *International Journal of River Basin Management*, *5*(2), pp.79-91.

Ng, T.L., Eheart, J.W. and Cai, X.M., 2010. Comparative calibration of a complex hydrologic model by stochastic methods GLUE and PEST. *Transactions of the ASABE*, *53*(6), pp.1773-1786.

Nofal, E.R., Fekry, A.M. and El-Didy, S.M., 2014. Adaptation to the impact of sea level rise in the Nile Delta coastal zone, Egypt. *Journal of American Science*, *10*(9), pp.1-7.

Nour El-Din, M., 2013. Proposed Climate Change Adaptation Strategy for the Ministry of Water Resources & Irrigation in Egypt. Prepared for UNESCO-Cairo Office.

NSACC., 2011. Egypt’s National Strategy for Adaptation to Climate Change and Disaster Risk Reduction. Egyptian Cabinet / Information and Decision Support Center / UNDP.

NWRP., 2005. National Water Resources Plan, Facing the Challenge. Ministry of Water Resources and Irrigation Integrated Water Resources Management Plan for 2017.

Oberkampf, W., DeLand, S., Rutherford, B., Diegert, K. and Alvin, K., 1999. A new methodology for the estimation of total uncertainty in computational simulation. In *40th Structures, Structural Dynamics, and Materials Conference and Exhibit* (p. 1612).

Oberkampf, W., Helton, J. and Sentz, K., 2001, April. Mathematical representation of uncertainty. In *19th AIAA applied aerodynamics conference* (p. 1645).

O'Hagan, A., Buck, C.E., Daneshkhah, A., Eiser, J.R., Garthwaite, P.H., Jenkinson, D.J., Oakley, J.E. and Rakow, T., 2006. *Uncertain judgements: eliciting experts' probabilities*. John Wiley & Sons.

Okungu, J., Adeyemo, J. and Otieno, F., 2017. Scenario Analysis of Water Supply and Demand Using WEAP Model: A Case of Yala Catchment, Kenya. *American Journal of Water Resources*, *5*(4), pp.125-131.

Omar, M.M., 2013. Evaluation of actions for better water supply and demand management in Fayoum, Egypt using RIBASIM. *Water Science*, *27*(54), pp.78-90.

Oppenheimer, M., Little, C.M. and Cooke, R.M., 2016. Expert judgement and uncertainty quantification for climate change. *Nature climate change*, *6*(5), pp.445-451.

Orr, S., Cartwright, A. and Tickner, D., 2009. Understanding Water Risks: A Primer on the Consequences of Water Scarcity for Government and Business. WWF Water Security Series 4. *World Wildlife Fund UK: Godalming*.

Orth, R., Staudinger, M., Seneviratne, S.I., Seibert, J. and Zappa, M., 2015. Does model performance improve with complexity? A case study with three hydrological models. *Journal of Hydrology*, 523, pp.147-159.

Osama, S., Elkholy, M. and Kansoh, R.M., 2017. Optimization of the cropping pattern in Egypt. *Alexandria Engineering Journal*, *56*(4), pp.557-566.

Osman, R., Ferrari, E. and McDonald, S., 2016. Water scarcity and irrigation efficiency in Egypt. *Water Economics and Policy*, *2*(04), p.1650009.

Pallottino, S., Sechi, G.M. and Zuddas, P., 2005. A DSS for water resources management under uncertainty by scenario analysis. *Environmental Modelling & Software*, *20*(8), pp.1031-1042.

Pang, A., 2001, September. Visualizing uncertainty in geo-spatial data. In Proceedings of the Workshop on the Intersections between Geospatial Information and Information Technology (pp. 1-14). Arlington, VA: National Research Council.

Pappenberger, F. and Beven, K.J., 2006. Ignorance is bliss: Or seven reasons not to use uncertainty analysis. *Water resources research*, *42*(5).

Pappenberger, F., Harvey, H., Beven, K., Hall, J. and Meadowcroft, I., 2006. Decision tree for choosing an uncertainty analysis methodology: a wiki experimenthttp://www. floodrisknet. org. uk/methodshttp://www. floodrisk. net. *Hydrological processes*, *20*(17), pp.3793-3798.

Parry, M., Parry, M.L., Canziani, O., Palutikof, J., Van der Linden, P. and Hanson, C. eds., 2007. *Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC* (Vol. 4). Cambridge University Press.

Peat, F.D., 2002. *From certainty to uncertainty: The story of science and ideas in the twentieth century*. Joseph Henry Press.

Perez, J., Menendez, M., Mendez, F.J. and Losada, I.J., 2014. Evaluating the performance of CMIP3 and CMIP5 global climate models over the north-east Atlantic region. *Climate dynamics*, *43*(9-10), pp.2663-2680.

Perminova, O., Gustafsson, M. and Wikström, K., 2008. Defining uncertainty in projects–a new perspective. *International journal of project management*, *26*(1), pp.73-79.

Perrin, C., Michel, C. and Andréassian, V., 2001. Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments. *Journal of hydrology*, 242(3-4), pp.275-301.

Peterson, G.D., Beard Jr, T.D., Beisner, B.E., Bennett, E.M., Carpenter, S.R., Cumming, G.S., Dent, C.L. and Havlicek, T.D., 2003. Assessing future ecosystem services: a case study of the Northern Highlands Lake District, Wisconsin. *Conservation Ecology*, *7*(3).

Pierce, D.W., Barnett, T.P., Santer, B.D. and Gleckler, P.J., 2009. Selecting global climate models for regional climate change studies. *Proceedings of the National Academy of Sciences*, *106*(21), pp.8441-8446.

PJTCNW 1968 -> 2015. Annual Permanent Joint Technical Commission for Nile Waters report (PJTCNW). Ministry of Water Resources and Irrigation library. Egypt. In Arabic.

Postel, S.L., 2000. Entering an era of water scarcity: the challenges ahead. Ecological Applications , 10, 941–948.

Prudhomme, C. and Davies, H., 2009. Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part 2: future climate. *Climatic Change*, *93*(1-2), pp.197-222.

Quan, Z., Teng, J., Sun, W., Cheng, T. and Zhang, J., 2015. Evaluation of the HYMOD model for rainfall–runoff simulation using the GLUE method. *Proceedings of the International Association of Hydrological Sciences*, *368*, pp.180-185.

Qureshi, S.M. and Kang, C., 2015. Analysing the organizational factors of project complexity using structural equation modelling. *International Journal of Project Management*, *33*(1), pp.165-176.

Raccoon, L.B.S., 1995. The complexity gap. *ACM SIGSOFT Software Engineering Notes*, *20*(3), pp.37-44.

Radwan, L., 1998. Water management in the Egyptian Delta: Problems of wastage and inefficiency. *Geographical Journal*, pp.129-138.

Ramadan SM, Negm AM, Smanny M, Helmy AHM. 2013. Environmental Impacts of Great Ethiopian Renaissance Dam on the Egyptian Water Resources Management and Security. The 23rd International

Conference On: Environmental Protection is a Must 11–13 May, Alexandria, Egypt.

Ramadan, S.M., Negm, A.M. and Owais, T.M., 2011. Effect of new upper Nile projects on the integrated management of the basin: Review and methodology. In *Fifteenth International Water Technology Conference, IWTC-15*.

Rayan, M.A. and Djebedjian, B., 2000. Egypt's water demand, supply and management policies. In workshop and training course, Mediterranean Cooperation for Water Desalination Policies in Perspective of a Sustainable Development, Paris.

Refsgaard, J.C., van der Sluijs, J.P., Højberg, A.L. and Vanrolleghem, P.A., 2007. Uncertainty in the environmental modelling process–a framework and guidance. *Environmental modelling & software*, *22*(11), pp.1543-1556.

Regan, H.M., Colyvan, M. and Burgman, M.A., 2002. A taxonomy and treatment of uncertainty for ecology and conservation biology. *Ecological applications*, *12*(2), pp.618-628.

Rekolainen, S., Kämäri, J., Hiltunen, M. and Saloranta, T.M., 2003. A conceptual framework for identifying the need and role of models in the implementation of the Water Framework Directive. *International Journal of River Basin Management*, *1*(4), pp.347-352.

Resnik, M.D., 1987. *Choices: An introduction to decision theory*. U of Minnesota Press.

RIGW 2011. Adaptation to the impact of sea level rise in the Nile Delta Coastal zone, Egypt. 2nd progress report, Research Institute for groundwater, Ministry of Water Resources and Irrigation – Egypt.

Rijsberman, F.R., 2006. Water scarcity: fact or fiction?. Agricultural water management, 80(1), pp.5-22.

Rumsfeld, D., 2002. Defense. gov Transcript: DoD News Briefing-Secretary Rumsfeld and Gen. *Myers, February*, *12*, pp.11-30. Retrieved on 15/08/2020 from:

https://archive.defense.gov/Transcripts/Transcript.aspx?TranscriptID=2636

Sadek, N., 2012. The effect of upper nile projects implementation on water management strategy. In *Twenty Six Arab Engineering Conference on" Water Resources in Arab Countries", Jeddah, Saudi Arabia*.

Safavi, H.R., Golmohammadi, M.H. and Sandoval-Solis, S., 2016. Scenario analysis for integrated water resources planning and management under uncertainty in the Zayandehrud river basin. *Journal of hydrology*, *539*, pp.625-639.

Saleth, R.M. and Dinar, A., 1999. Water challenge and institutional response: a cross-country perspective. World Bank policy research working paper no: 2045, World Bank, Washington. *DC: World Bank*.

Sallam, O.M., El Shewy, M.A. and Dawoud, M.A., 2014. New reclamation mega projects and increasing the pressure on water system in the Nile Valley and Delta in Egypt. In *Proceedings of WSTA 11th Gulf Water Conference* (pp. 37-48).

Salsburg, D., 2001. *The lady tasting tea: How statistics revolutionized science in the twentieth century*. Macmillan.

Santer, B.D., Taylor, K.E., Gleckler, P.J., Bonfils, C., Barnett, T.P., Pierce, D.W., Wigley, T.M.L., Mears, C., Wentz, F.J., Brüggemann, W. and Gillett, N.P., 2009. Incorporating model quality information in climate change detection and attribution studies. *Proceedings of the National Academy of Sciences*, *106*(35), pp.14778-14783.

Sato, I., and Altamirano, J.C. 2019. Uncertainty, Scenario Analysis, and Long-Term Strategies: State of Play and a Way Forward. Working Paper. Washington, DC: World Resources Institute. Available online at

https://files.wri.org/s3fs-public/uncertainty-scenario-analysis-long-term-strategies.pdf

Saunders, F.C., Gale, A.W. and Sherry, A.H., 2015. Conceptualising uncertainty in safety-critical projects: A practitioner perspective. *International Journal of Project Management*, *33*(2), pp.467-478.

Savenije, H.H., Hoekstra, A.Y. and van der Zaag, P., 2014. Evolving water science in the Anthropocene. *Hydrology and Earth System Sciences*, *18*(1), p.319.

Sayed, M. A.Aty & Nour El-Din, M.M., 2002. Adaptation of Water Policy in Egypt to Mitigate Climate Change Effects. Stockholm Water Symposium, Stockholm.

Schneider, S.H. and Kuntz-Duriseti, K., 2002. Uncertainty and climate change policy. Climate change policy: a survey, 8201.

Scott, C.A., Bailey, C.J., Marra, R.P., Woods, G.J., Ormerod, K.J. and Lansey, K., 2012. Scenario planning to address critical uncertainties for robust and resilient water–wastewater infrastructures under conditions of water scarcity and rapid development. *Water*, *4*(4), pp.848-868.

Seelen, L.M., Flaim, G., Jennings, E. and Domis, L.N.D.S., 2019. Saving water for the future: Public awareness of water usage and water quality. *Journal of environmental management*, *242*, pp.246-257.

Seifollahi-Aghmiuni, S., Haddad, O.B., Omid, M.H. and Mariño, M.A., 2011, March. Long-term efficiency of water networks with demand uncertainty. In Proceedings of the Institution of Civil Engineers-Water Management (Vol. 164, No. 3, pp. 147-159). Thomas Telford Ltd.

Shapiro, A., 2003. Monte Carlo sampling methods. *Handbooks in operations research and management science*, *10*, pp.353-425.

Shen, Y., Oki, T., Kanae, S., Hanasaki, N., Utsumi, N. and Kiguchi, M., 2014. Projection of future world water resources under SRES scenarios: an integrated assessment. Hydrological Sciences Journal, 59(10), pp.1775-1793.

Shen, Y., Oki, T., Utsumi, N., Kanae, S. and Hanasaki, N., 2008. Projection of future world water resources under SRES scenarios: water withdrawal/Projection des ressources en eau mondiales futures selon les scénarios du RSSE: prélèvement d'eau. Hydrological Sciences Journal, 53(1), pp.11-33.

Shen, Z.Y., Chen, L., Chen, T. and Di Baldassarre, G., 2012. Analysis of parameter uncertainty in hydrological and sediment modeling using GLUE method: a case study of SWAT model applied to Three Gorges Reservoir Region, China. *Hydrology & Earth System Sciences*, *16*(1).

Shrestha, D.L. and Solomatine, D.P., 2008. Data-driven approaches for estimating uncertainty in rainfall-runoff modelling. *International Journal of River Basin Management*, *6*(2), pp.109-122.

Shrestha, D.L., 2009. *Uncertainty analysis in rainfall-runoff modelling: Application of machine learning techniques*. IHE Delft Institute for Water Education.

Shrestha, D.L., Kayastha, N. and Solomatine, D.P., 2009. A novel approach to parameter uncertainty analysis of hydrological models using neural networks. *Hydrology and Earth System Sciences*, *13*(7), p.1235.

Sieber, J. and Purkey, D., 2015. Weap: water evaluation And planning system. User guide. *Somerville, MA: Stockholm Environment Institute, US Center*

. https://www.weap21.org/downloads/WEAP_User_Guide.pdf

Singh, A., Hauffpauir, R., Mishra, S., Lavenue, M. and Valocchi, A., 2010. Analyzing uncertainty and risk in the management of water resources for the Texas water development board. In *World Environmental and Water Resources Congress 2010: Challenges of Change* (pp. 4740-4743).

Sinharay, S., 2004. Experiences with Markov chain Monte Carlo convergence assessment in two psychometric examples. *Journal of Educational and Behavioral Statistics*, *29*(4), pp.461-488.

Stedinger, J.R., Vogel, R.M., Lee, S.U. and Batchelder, R., 2008. Appraisal of the generalized likelihood uncertainty estimation (GLUE) method. *Water resources research*, *44*(12).

Strzepek, K.M., Onyeji, S.C., Saleh, M. and Yates, D., 1994. An Assessment of Integrated Climate Change Impact on Egypt. IIASA Working Paper. IIASA, Laxenburg, Austria.

Sun, M., Zhang, X., Huo, Z., Feng, S., Huang, G. and Mao, X., 2016. Uncertainty and sensitivity assessments of an agricultural–hydrological model (RZWQM2) using the GLUE method. *Journal of hydrology*, *534*, pp.19-30.

Swain, A., 2011. Challenges for water sharing in the Nile basin: changing geo-politics and changing climate. *Hydrological Sciences Journal*, *56*(4), pp.687-702.

Taghvaye Salimi, E., Nohegar, A., Malekian, A., Hosseini, M. and Holisaz, A., 2016. Runoff simulation using SWAT model and SUFI-2 algorithm (Case study: Shafaroud watershed, Guilan Province, Iran). *Caspian Journal of Environmental Sciences*, *14*(1), pp.69-80.

Tannert, C., Elvers, H.D. and Jandrig, B., 2007. The ethics of uncertainty: In the light of possible dangers, research becomes a moral duty. *EMBO reports*, *8*(10), pp.892-896.

Tantoh, H.B. and Simatele, D., 2018. Complexity and uncertainty in water resource governance in Northwest Cameroon: Reconnoitring the challenges and potential of community-based water resource management. *Land use policy*, *75*, pp.237-251.

Taylor, B. N. and C. E. Kuyatt. 1993. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. Technical report, National Institute of Standards and Technology Technical Note 1297, Gaithersburg, MD.

Taylor, J.G. and Ryder, S.D., 2003. Use of the Delphi Method in Resolving Complex Water Resources Issues 1. *JAWRA Journal of the American Water Resources Association*, *39*(1), pp.183-189.

Tebaldi, C. and Sansó, B., 2009. Joint projections of temperature and precipitation change from multiple climate models: a hierarchical Bayesian approach. *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, *172*(1), pp.83-106.

Tesfa, B., 2013. Benefit of Grand Ethiopian Renaissance Dam Project (GERDP) for Sudan and Egypt. Discussion Paper. EIPSA Communicating Article: Energy, Water, Environment & Economic. Available online at: http://eprints.hud.ac.uk/id/eprint/19305/

Thangaratinam, S. and Redman, C.W., 2005. The delphi technique. *The obstetrician & gynaecologist*, *7*(2), pp.120-125.

The Egyptian Environmental Affairs Agency (EEAA): Egypt Second National Communication Report, May 2010.

Thissen, W., Kwakkel, J., Mens, M., van der Sluijs, J., Stemberger, S., Wardekker, A. and Wildschut, D., 2017. Dealing with uncertainties in fresh water supply: experiences in the Netherlands. *Water resources management*, *31*(2), pp.703-725.

Thunnissen, D.P., 2003. Uncertainty classification for the design and development of complex systems. In *3rd annual predictive methods conference* (pp. 1-16). CA: Newport Beach.

Tonn, B., 1991. Research policy and review 34: The development of ideas of uncertainty representation. *Environment and Planning A*, *23*(6), pp.783-812.

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*, pp.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), pp.4719-4734.

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, pp.122-142.

UN CCA., 2005. United Nations Common Country Assessment 2005, Embracing the Spirit of the Millennium Declaration, Cairo, Egypt.

United Nations, 2019. Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019, Online Edition. Rev. 1.*

https://population.un.org/wpp/Download/Files/1_Indicators%20(Standard)/EXCEL_FILES/1_Population/WPP2019_POP_F01_1_TOTAL_POPULATION_BOTH_SEXES.xlsx [Accessed 21 August 2020].

Uusitalo, L., Lehikoinen, A., Helle, I. and Myrberg, K., 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. *Environmental Modelling & Software*, *63*, pp.24-31.

Van Delden, H., Kirkby, M.J. and Hahn, B.M., 2009. Towards a modelling framework for integrated assessment in arid and semi-arid regions. In *International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation* (pp. 3563-3569). Leeds.

Van Delden, H., Luja, P. and Engelen, G., 2007. Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management. *Environmental Modelling & Software*, *22*(2), pp.223-238.

Van Delden, H., Seppelt, R., White, R. and Jakeman, A.J., 2011. A methodology for the design and development of integrated models for policy support. *Environmental Modelling & Software*, *26*(3), pp.266-279.

van Griensven, A. and Meixner, T., 2006. Methods to quantify and identify the sources of uncertainty for river basin water quality models. *Water Science and Technology*, *53*(1), pp.51-59.

Vidal, L.A., Marle, F. and Bocquet, J.C., 2011. Measuring project complexity using the Analytic Hierarchy Process. *International Journal of Project Management*, *29*(6), pp.718-727.

Viola, F., Noto, L.V., Cannarozzo, M. and La Loggia, G., 2009. Daily streamflow prediction with uncertainty in ephemeral catchments using the GLUE methodology. *Physics and Chemistry of the Earth, Parts A/B/C*, *34*(10-12), pp.701-706.

Volk, M., Hirschfeld, J., Dehnhardt, A., Schmidt, G., Bohn, C., Liersch, S. and Gassman, P.W., 2008. Integrated ecological-economic modelling of water pollution abatement management options in the Upper Ems River Basin. *Ecological Economics*, *66*(1), pp.66-76.

Wagener, T., Boyle, D.P., Lees, M.J., Wheater, H.S., Gupta, H.V. and Sorooshian, S., 2001. A framework for development and application of hydrological models.

Ward, S. and Chapman, C., 2003. Transforming project risk management into project uncertainty management. *International journal of project management*, *21*(2), pp.97-105.

Ward, S., Scott Borden, D., Kabo-Bah, A., Fatawu, A.N. and Mwinkom, X.F., 2019. Water resources data, models and decisions: international expert opinion on knowledge management for an uncertain but resilient future. *Journal of Hydroinformatics*, *21*(1), pp.32-44.

Wardekker, J.A., de Jong, A. and van der Sluijs, J.P., 2010. *Expert elicitation on uncertainty, climate change and human health*. Copernicus Institute.

Webler, T., Levine, D., Rakel, H. and Renn, O., 1991. A novel approach to reducing uncertainty: the group Delphi. *Technological forecasting and social change*, *39*(3), pp.253-263.

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*, *41*(4), pp.611-634.

Whittington, D. and McClelland, E., 1992. Opportunities for regional and international cooperation in the Nile basin. *Water International*, *17*(3), pp.144-154.

Whittington, D., Waterbury, J. and Jeuland, M., 2014. The Grand Renaissance Dam and prospects for cooperation on the Eastern Nile. Water Policy, 16(4), pp.595-608.

WHO. 2003. Water Sanitation and Health.

Website:http://www.who.int/water_sanitation_health/hygiene/en/.

Wichelns, D., 1999. Economic efficiency and irrigation water policy with an example from Egypt. *International Journal of Water Resources Development*, *15*(4), pp.543-560.

Widakuswara, P., 2020. *No Deal From US-Brokered Nile Dam Talks*. [online] Voice of America. Available at: https://www.voanews.com/africa/no-deal-us-brokered-nile-dam-talks [Accessed 21 August 2020].

Wilby, R.L. and Dessai, S., 2010. Robust adaptation to climate change. *Weather*, *65*(7), pp.180-185.

Williams, T.M., 1999. The need for new paradigms for complex projects. *International journal of project management*, *17*(5), pp.269-273.

Wilson, I. and Ralston, W., 2006. Scenario planning handbook: Developing strategies in uncertain times. *South-Western Educational, Belmont, CA*, *272*.

Wolters, W., Smit, R., Nour El-Din, M., Sayed Ahmed, E., Froebrich, J. and Ritzema, H., 2016. Issues and Challenges in Spatial and Temporal Water Allocation in the Nile Delta. Sustainability, 8(4), p.383.

Wu, H., Chen, B. and Li, P., 2013. Comparison of Sequential Uncertainty Fitting Algorithm (SUFI-2) and Parameter Solution (ParaSol) Method for Analyzing Uncertainties in Distributed Hydrological Modeling–A Case Study. *GEN*, *309*, p.1.

WWAP (World Water Assessment Programme)., 2012. The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk. Paris, UNESCO.

Yager, R.R., 1992. Decision making under Dempster-Shafer uncertainties. *International Journal of General System*, *20*(3), pp.233-245.

Yakoub, N.G., 1997, March. Management of Municipal and Industrial Water in Egypt through 2017. In *Second International Water Technology Conference* (pp. 569-582).

Yang, H. and Zehnder, A.J., 2005. The south-north water transfer project in China: An analysis of water demand uncertainty and environmental objectives in decision making. Water International, 30(3), pp.339-349.

Yang, J., Reichert, P., Abbaspour, K.C., Xia, J. and Yang, H., 2008. Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China. *Journal of Hydrology*, *358*(1-2), pp.1-23.

Yang, L., Bai, X., Zheng Khanna, N., Yi, S., Hu, Y., Deng, J., Gao, H., Tuo, L., Xiang, S. and Zhou, N., 2018. Water evaluation and planning (WEAP) model application for exploring the water deficit at catchment level in Beijing. *DESALINATION AND WATER TREATMENT*, 118, pp.12-25.

Yates DN, Strzepek KM (1998a) Assessment of integrated climate change impacts on the agricultural economy of Egypt. Clim Change 38:261–287.

Yates DN, Strzepek KM (1998b) Modeling the Nile basin under climatic change. J Hydrol Eng 3:98–108.

Yates, D., Sieber, J., Purkey, D. and Huber-Lee, A., 2005. WEAP21—A demand-, priority-, and preference-driven water planning model: part 1: model characteristics. *Water International*, *30*(4), pp.487-500.

Zaghloul, S.S., Pacini, N., Schwaiger, K. and de Villeneuve, P.H., 2011. Towards a Lake Nasser management plan: results of a pilot test on integrated water resources management. In *Proceedings of the Fifteenth International Water Technology Conference*.

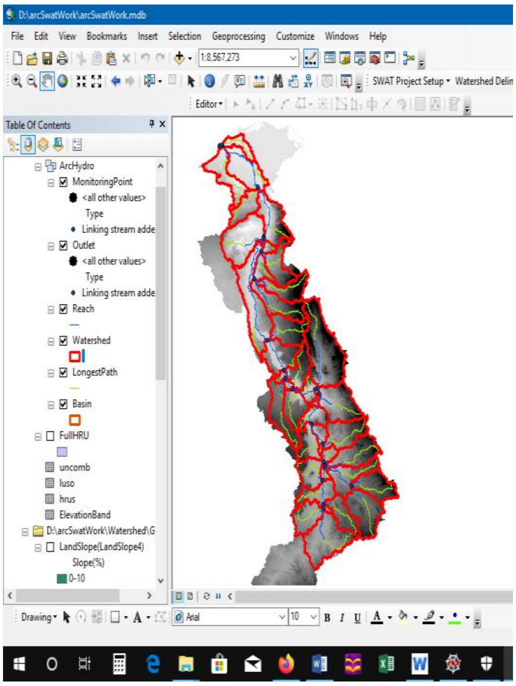
Zerkaoui, L., Benslimane, M. and Hamimed, A., 2018. Planning and systematic management of water resources by the WEAP model, case of the Mabtouh watershed (northwestern Algeria). *Arabian Journal of Geosciences*, *11*(24), p.779.

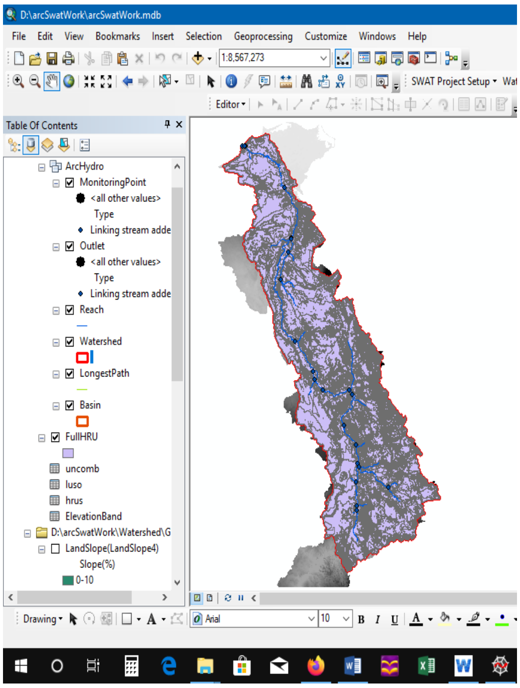
Zheng, Y. and Han, F., 2016. Markov Chain Monte Carlo (MCMC) uncertainty analysis for watershed water quality modeling and management. *Stochastic environmental research and risk assessment*, *30*(1), pp.293-308.

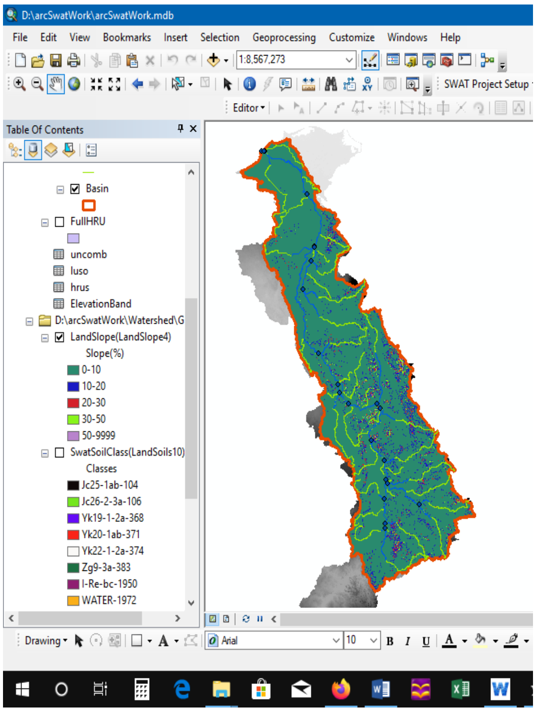
Zhu, Z., Bai, H., Xu, H. and Zhu, T., 2011. An inquiry into the potential of scenario analysis for dealing with uncertainty in strategic environmental assessment in China. *Environmental impact assessment review*, *31*(6), pp.538-548.

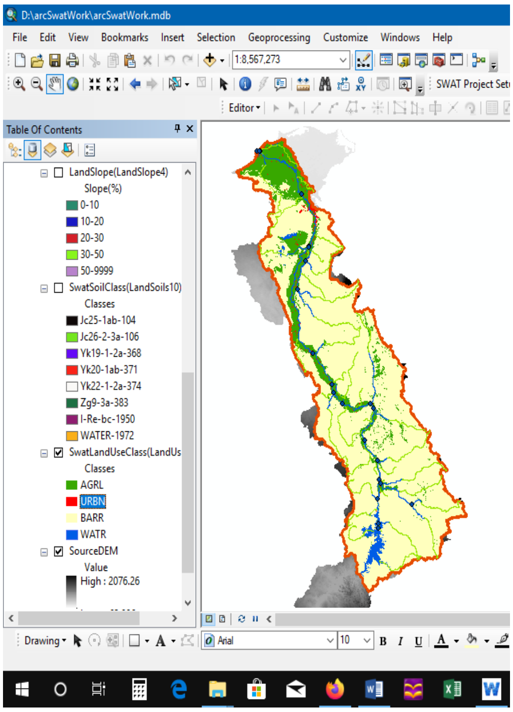
Appendices

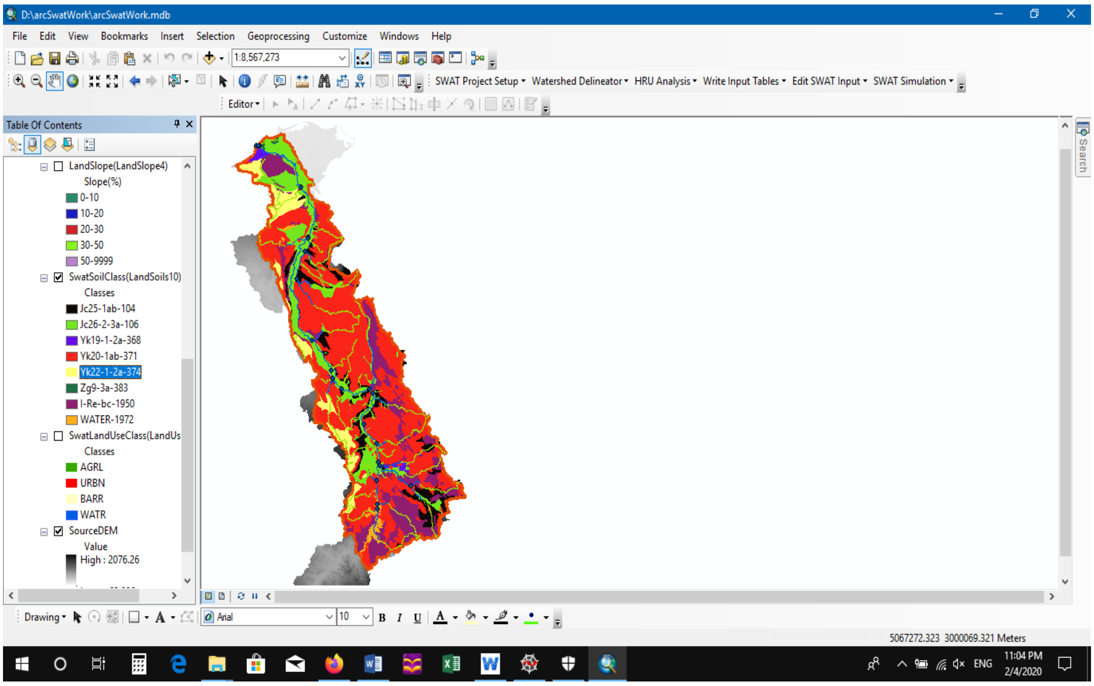
Appendix 1: Applying the SWAT Model to the Study Area to Examine its Suitability for this Study.

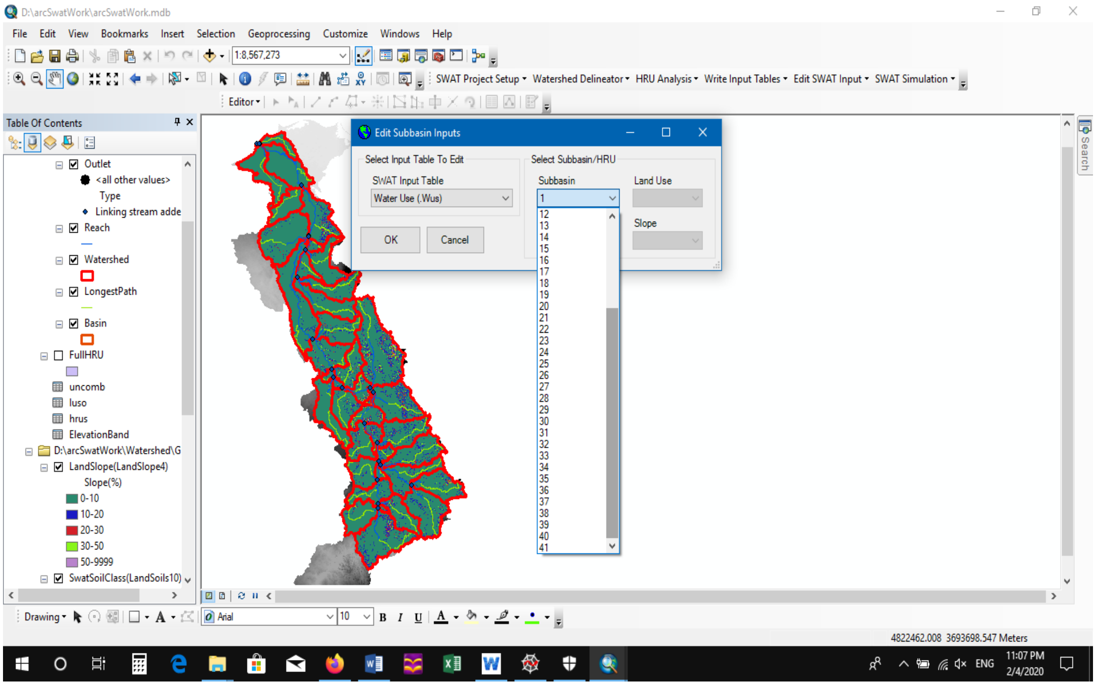












SWAT Input Table: Water Use (.Wus)

Subbasin: 1

- Stopping at this point because SWAT model divides the basin to 41 subbasin and need the water consumption data for 41 subbasin. These data are not available and this is not the actual processes in the catchment area in Egypt. In addition, SWAT model is developed for the rainy areas. Therefore, it does not fit the arid or semi-arid areas or the complex and controlled system like Egypt.

Appendix 2: Python Code for Automating the WEAP Model

```
# -*- coding: utf-8 -*-
"""
Spyder Editor

This is an Automate WEAP model script file.
"""
import win32com.client
import time

def run(name):
    """ This runs the scenario with the given parameters and writes a result
    to a file with the given filename.
    Parameter:
        filename the name of the file
    """
    s = w.Scenario(scenario)
    print(s.FirstYear)
    print(s.LastYear)
    if (w.IsCalculatingInteractively == False):
        print("Initializing Interactive Calculations")
        w.InitializeInteractiveCalculations
    for i in range(s.FirstYear, s.LastYear):
        print("Calculating year", i)
        s.CalculateNextTimeStep
        while (w.IsCalculating == True):
            time.sleep(2)
        #for ts in range(1, w.NumTimeSteps):
        #    print("Calculating time step", ts, "out of", w.NumTimeSteps)
        #    s.CalculateNextTimeStep
        #    while (s.IsCalculating == True):
        #        time.sleep(2)
    s.FinalizeInteractiveCalculations
    w.FinalizeInteractiveCalculations
    #print(step)
    #w.Activate
```

```
    #Activate the StreamFlow branch
    w.ExportResults("E:\\test\\test"+ str(name) +".csv")

def v_list(b):
    """ Print a variable count and list of variables for the branch b.
    Parameters:
        b branch
    """
    vs = b.Variables
    vc = vs.Count
    print("------------------------")
    print("Variable Count for branch", "\"" + b.Name + "\"", vc - 1)
    for i in range(1, vc):
        print(vs(i).Name)
    print("------------------------")

def b_list(b):
    """List branches in branch b.
    Parameters:
        b branch
    """
    print("------------------------")
    c = b.Children
    n = c.count
    print("There are", n - 1, "Children in branch", "\"" + b.Name + "\"")
    for i in range(1, n):
        print(c(i).Name)
    print("------------------------")

"""
w=win32com.client.Dispatch("Excel.Application")
w.Workbooks.Add()
w.Cells(1,1).Value= "Hello"
"""
w=win32com.client.Dispatch("WEAP.WEAPApplication")

print("w.Status", w.Status)
print("w.ActiveArea", w.ActiveArea)
```

```
print(w.Areas.Count)

#name = "Weaping River Basin"
name = "EGYPT WATER MANG 2018"

# Activate the area
if w.Areas.Exists(name):
    w.Areas(name).Open()

# Find out where the WEAP for the basin is stored
print(w.Areas(name).Directory)

# Create a new test scenario unless it already exists
scenario = "Test"
if w.Scenarios.Exists(scenario) == False:
    w.Scenarios.Add(scenario, "Reference")

""" Exploring branches
branch = "Supply and Resources"
print(branch)
sar = w.Branch(branch)
v_list(sar)
b_list(sar)
# River
c = sar.Children
r = c(1)
v_list(r)
b_list(r)
branch = branch + "\\" + r.Name
print(branch)
w.Branch(branch)
# River Nile
c = r.Children
rn = c(2)
v_list(rn)
b_list(rn)
branch = branch + "\\" + rn.Name
print(branch)
w.Branch(branch)
```

```
# Streamflow Gauges
c = rn.Children
sg = c(9)
v_list(sg)
b_list(sg)
branch = branch + "\\" + sg.Name
print(branch)
w.Branch(branch)
"""

def set_demand_sites_and_catchments_branch():
    branch = "Demand Sites and Catchments" #15
    #branch = "\Catchments" #No such bracnh name do not use
    #branch = "\Hydrology" #2
    #branch = "\Supply and Resources" #7
    print(branch)
    return w.Branch(branch)

def set_soil_water_capacity_branch():
    ds = set_demand_sites_and_catchments_branch()
    branch = ds.Name
    v_list(ds)
    b_list(ds)
    # Activate the agriculture branch of the elevation branch of the Egypt Nile
    # branch of the Demand Sites and Catchments branch
    c = ds.Children
    # Egypt Nile
    en = c(5)
    v_list(en)
    b_list(en)
    branch = branch + "\\" + en.Name
    print(branch)
    w.Branch(branch)
    # Elevation
    c = en.Children
    e = c(1)
    v_list(e)
    b_list(e)
    branch = branch + "\\" + e.Name
```

```
    print(branch)
    w.Branch(branch)
    # Agriculture
    c = e.Children
    a = c(2)
    v_list(a)
    b_list(a)
    branch = branch + "\\" + a.Name
    print(branch)
    return w.Branch(branch)

def set_soil_water_capacity(swcv):
    branch = set_soil_water_capacity_branch()
    swc = branch.Variables.Item(6)
    print(swc.Name)
    print(swc.Value)
    swc.Expression = swcv
    print(swc.Value)

# Vary soil water capacity from 0 to 5, every 0.1
for swcv in range(0, 5, 0.1):
    # Set Soil Water Capacity 6
    set_soil_water_capacity(swcv)
    run(swcv)

w.visible=1

def set_deep_water_capacity(dwcv):
    branch = set_deep_water_capacity_branch()
    dwc = branch.Variables.Item(7)
    print(dwc.Name)
    print(dwc.Value)
    dwc.Expression = dwcv
    print(dwc.Value)

# Vary deep water capacity from 10000 to 20000, every 10
for dwcv in range(10000, 20000, 10):
    # Set Deep Water Capacity 7
    set_deep_water_capacity(dwcv)
```

```
    run(dwcv)

w.visible=2

def set_root_zone_conductivity(rzcv):
    branch = set_root_zone_conductivity_branch()
    rzc = branch.Variables.Item(8)
    print(rzc.Name)
    print(rzc.Value)
    rzc.Expression = rzcv
    print(rzc.Value)

# Vary root zone conductivity from 0 to 100, every 1
for rzcv in range(0, 100, 1):
    # Set Root Zone Cconductivity 8
    set_root_zone_conductivity(rzcv)
    run(rzcv)

w.visible=3

def set_deep_conductivity(dcv):
    branch = set_deep_conductivity_branch()
    dc = branch.Variables.Item(9)
    print(dc.Name)
    print(dc.Value)
    dc.Expression = dcv
    print(dc.Value)

# Vary deep conductivity from 10 to 30, every 1
for dcv in range(10, 30, 1):
    # Set Deep Conductivity 9
    set_deep_conductivity(dcv)
    run(dcv)

w.visible=4

def runoff_resistance_factor(rrf):
    branch = set_runoff_ resistance_factor_branch()
    rrf = branch.Variables.Item(10)
```

```
    print(rrf.Name)
    print(rrf.Value)
    rrf.Expression = rrf
    print(rrf.Value)

# Vary runoff resistance factor from 0 to 5, every 0.1
for rrf in range(0, 5, 0.1):
    # Set runoff resistance factor 10
    set_Runoff_ Resistance_Factor(rrf)
    run(rrf)

w.visible=5

def preferred_flow_direction(rrf):
    branch = set_ preferred_flow_direction_branch()
    pfd = branch.Variables.Item(11)
    print(pfd.Name)
    print(pfd.Value)
    pfd.Expression = pfd
    print(pfd.Value)

# Vary runoff preferred flow direction from 0 to 1, every 0.05
for pfd in range(0, 1, 0.05):
    # Set Preferred Flow Direction 11
    set_ preferred_flow_direction (pfd)
    run(pfd)

w.visible=6

def relative_storage_upper(rsu):
    branch = set_ relative_storage_upper _branch()
    rsu = branch.Variables.Item(12)
    print(rsu.Name)
    print(rsu.Value)
    rsu.Expression = rsu
    print(rsu.Value)

# Vary relative storage upper from 0 to 100, every 1
for rsu in range(0, 100, 1):
```

```
    # Set Relative Storage Upper 12
    set_ relative_storage_upper (rsu)
    run(rsu)

w.visible=7

def relative_storage_lower(rsl):
    branch = set_ relative_storage_lower _branch()
    rsl = branch.Variables.Item(13)
    print(rsl.Name)
    print(rsl.Value)
    rsu.Expression = rsl
    print(rsl.Value)

# Vary relative storage lower from 0 to 100, every 1
for rsl in range(0, 100, 1):
    # Set Relative Storage Lower 13
    set_ relative_storage_lower (rsl)
    run(rsl)

w.visible=8
```

Appendix 3: the Questionnaire Questions Guide

Questionnaire

Project title: Complexity and uncertainty in development of water demand and supply scenarios: a case study of Egypt.

Name: Mohamed Nasef
PhD Candidate at University of Leeds and Assistant Lecturer at
University of Minia

July 2017

Participant: **Code: ...**

- ☐ Ministry of Housing, Utilities and New Communities
- ☐ Ministry of Water Resources and Irrigation
- ☐ Ministry of Local Development
- ☐ University professors specialized in water resources
- ☐ Ministry of health and population
- ☐ Ministry Of Industry
- ☐ Ministry of agriculture and Land Reclamation
- ☐ Egyptian Environmental Affairs Agency
- ☐ National Water Research Centre

1- **What is your role in the institution?**
2- **What is your expertise relevant to water sector?**
3- **How do you see the water gap in the past and how it might change in the future in Egypt?**
4- **In your point of view, what are the causes of water gap in Egypt?**
5- **What is your assessment for the current plan to close the water gap in Egypt?**
6- **What measures are included on supply and demand sides?**

7- How can address the uncertainty in water management?

- Developing more scenarios
- Identifying the losses
- Monitoring the over uses in different sectors
- Testing the efficiency of measures and actions
- Using the adaptive management
- Using advanced water management models
- Using short return periods in our measurements and statistics
- Adding new effective measures
- More communication with stakeholders
- Using the adaptive management
- Using advanced water management models
- More precise projections
- NA
- ………………………………………………………………………………… …………………………………………………………………………………

8- **How uncertainty is addressed in current plan?**
9- **Is uncertainty explicitly addressed for each measure or for the package of measures?**
10-**How a growing gap could be closed?**
11- **What are the supply sides considered important and why?**
12- **What are the demand sides considered important and why?**
13-**What are other measures considered important and why?**
14 - **Do you agree on the plan of the Ministry to close the water gap?**

☐ Yes
☐ No
☐ Do not Know

Comments if applicable……………………………………………………………

15 - Do you anticipate the ministry plan will go into effect?

- ☐ Yes
- ☐ No
- ☐ Do not Know

Comments if applicable………………………………………………………………

16- Are there other measures not cited below?

- Water reuse
- Completing the Upper Nile projects
- Water pricing
- Rainwater harvesting
- Desalination
- Improvement of irrigation efficiency
- Crops pattern change
- Public awareness
- Storage of floods water
- Rehabilitation of old irrigation and domestic network
- Stakeholder participation
- Role of women
- Political hardwork with Nile basin countries
- Integrated water resources management
- Institutional capacity building
- ……………………………………………………………………………
- ……………………………………………………………………………
  …………………………………………………………………………..

17- Why these measures are not unaware and unworkable?

18- Have these measures been evaluated?

- ☐ Yes
- ☐ No
- ☐ Do not Know

Comments if applicable --

19- How is the current plan evaluated?

20- Do you expect water demand to exceed available supply in 2050?

- ☐ Yes
- ☐ No
- ☐ Do not Know

Comments if applicable……………………………………………………………

21- What is the magnitude of the expected difference in BCM in 2050?

- ☐ Less than 5 BCM
- ☐ 6 – 10 BCM
- ☐ 11 – 15 BCM
- ☐ 16 – 20 BCM
- ☐ 21 – 25 BCM
- ☐ More than 25 BCM
- ☐ Do not Know

Comments if applicable……………………………………………………………………

22- What is the most reason that will increase the water deficiency?

- ☐ Traditional irrigation methods
- ☐ Limited resources vs increasing demand
- ☐ Population growth
- ☐ Climate change
- ☐ Bad water resources management
- ☐ Population awareness
- ☐ Water policy inefficiency
- ☐ Water disputes with the riparian countries
- ☐ Population behaviour
- ☐ Land reclamation
- ☐ Hydropower projects in Nile basin
- ☐ Other --

Comments if applicable…………………………………………………………………………

23- Do you have any suggestions or proposed measures to decrease the water deficiency?

24- What is your opinion on the existing pricing of different water uses?

Using	Fair	Unfair	Do not know
Drinking water & domestic use			
Agriculture			
Industry			
Tourism			
Commerce			

25- What is your evaluation to the following measures to close the water gap with regard to the evaluation metrics?

Measures	**Cost**			**Risk**			**Implementation restrictions**		**Environmental compatibility**		**Political acceptability**		**Feasibility**		**Effectiveness**		**Solve the problem?**		**Public acceptability**	
	L	M	H	L	M	H	possible	impossible	compatible	incompatible	acceptable	rejected	feasible	infeasible	Effective	ineffective	Yes	No	Yes	No
- Increasing the water reuse																				
- Cropping patterns change																				
- Reducing the discharged water into the sea																				
- Completing the upper Nile projects																				
- Changing from Traditional to Modern Farming (modern irrigation techniques)																				
- Increasing Egypt's quota																				
- Desalinating of seawater																				
- Increasing the water pricing																				
- Increasing the public awareness to change the behaviour of the population																				
- Increasing the withdrawing of groundwater																				
-Creating a new storage for floods water																				
-Enhancing metering, smart metering																				
-Reducing the leakage																				

-Rehabilitation of old irrigation and domestic network																				
-Rainwater harvesting																				

L = Low, M = Medium, H = High

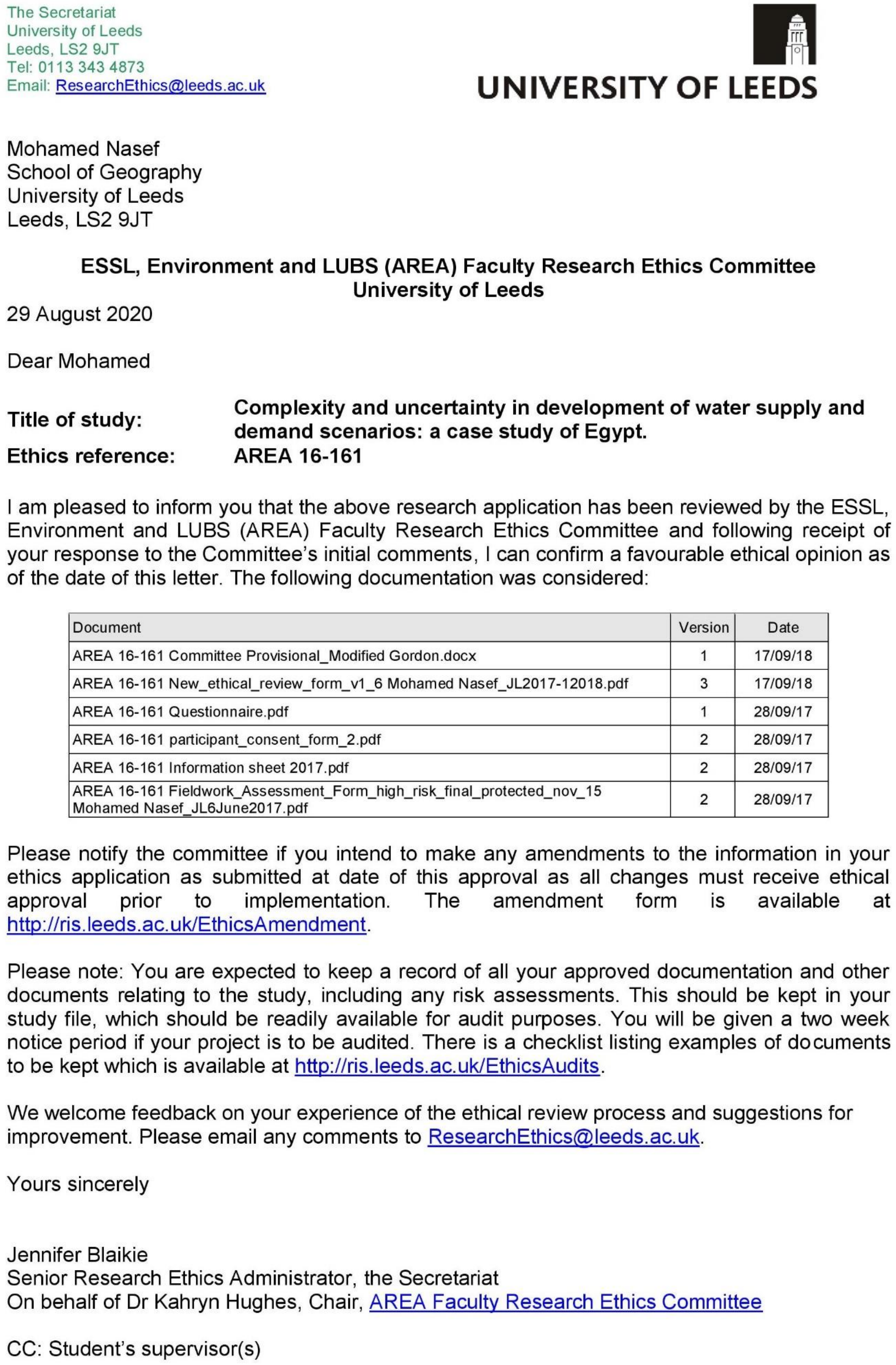
Note:

- **Cost:** the cost of a specific measure taking into account the overall costs. The judgment of the measures in terms of cost is divided into low, medium, or high.
- **Risk:** Risks and threats associated with the proposed measures. The judgment of the measures in terms of risk is divided into low, medium, or high.
- **Implementation restrictions:** There may be limitations in implementing a measure in the water management process such as the safe limit for groundwater withdrawal; presence of wars and conflicts that prevent the completion of water projects or funding problems.
- **Environmental compatibility:** the actions and measures should be non-hazardous to the environment and are compatible with it.
- **Political acceptability:** This refer to the attitudes of government and decision-makers' towards a specific management measure, such as changes in water tariffs, changes in crop patterns, or implementing a project.
- **Feasibility:** The economic and financial feasibility, and the probabilities of success by choosing from two metrics feasible or infeasible.
- **Effectiveness:** To what degree the measure or action succeeds in achieving the desired outcome. The desired result is to save water.
- **Solve the problem:** Is the measure able to solve the water gap problem or contribute to reducing the water gap?
- **Public acceptability:** The acceptability of the measure to promotion and increase depending on the attitude of citizens.

26- Do you think the evaluation metrics in the previous table are sufficient for the measures assessment?
27- Do you suggest other issues not discussed above?
28- Do you suggest other key people to participate in the questionnaire?

Thank you for your concern and participation

Appendix 4: Certificate of Ethical Approval



The Secretariat
University of Leeds
Leeds, LS2 9JT
Tel: 0113 343 4873
Email: ResearchEthics@leeds.ac.uk

UNIVERSITY OF LEEDS

Mohamed Nasef
School of Geography
University of Leeds
Leeds, LS2 9JT

ESSL, Environment and LUBS (AREA) Faculty Research Ethics Committee
University of Leeds

29 August 2020

Dear Mohamed

Title of study:	**Complexity and uncertainty in development of water supply and demand scenarios: a case study of Egypt.**
Ethics reference:	**AREA 16-161**

I am pleased to inform you that the above research application has been reviewed by the ESSL, Environment and LUBS (AREA) Faculty Research Ethics Committee and following receipt of your response to the Committee's initial comments, I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	Version	Date
AREA 16-161 Committee Provisional_Modified Gordon.docx	1	17/09/18
AREA 16-161 New_ethical_review_form_v1_6 Mohamed Nasef_JL2017-12018.pdf	3	17/09/18
AREA 16-161 Questionnaire.pdf	1	28/09/17
AREA 16-161 participant_consent_form_2.pdf	2	28/09/17
AREA 16-161 Information sheet 2017.pdf	2	28/09/17
AREA 16-161 Fieldwork_Assessment_Form_high_risk_final_protected_nov_15 Mohamed Nasef_JL6June2017.pdf	2	28/09/17

Please notify the committee if you intend to make any amendments to the information in your ethics application as submitted at date of this approval as all changes must receive ethical approval prior to implementation. The amendment form is available at http://ris.leeds.ac.uk/EthicsAmendment.

Please note: You are expected to keep a record of all your approved documentation and other documents relating to the study, including any risk assessments. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited. There is a checklist listing examples of documents to be kept which is available at http://ris.leeds.ac.uk/EthicsAudits.

We welcome feedback on your experience of the ethical review process and suggestions for improvement. Please email any comments to ResearchEthics@leeds.ac.uk.

Yours sincerely

Jennifer Blaikie
Senior Research Ethics Administrator, the Secretariat
On behalf of Dr Kahryn Hughes, Chair, AREA Faculty Research Ethics Committee

CC: Student's supervisor(s)