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DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR SUSTAINABLE WATER PLANNING IN ABU DHABI, UAE

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This dissertation is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Under the Supervision of Professor Mohamed Mostafa Mohamed

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Declaration of Original Work

I, Mohamed Ibrahim Kizhisseri, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this dissertation entitled "*Development of a Decision Support System for Sustainable Water Planning in Abu Dhabi, UAE*", hereby, solemnly declare that this dissertation is my own original research work that has been done and prepared by me under the supervision of Professor Mohamed Mostafa, in the College of Engineering at UAEU. This work has not previously formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my dissertation have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this dissertation.

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Abstract

One of the main challenges for water managers is to foresee the future accurately; then, design appropriate policies and infrastructure plans accordingly. The use of decision support systems in the field of water resource management and planning is now widely implemented, but its use in sustainable water planning of a nation or state in arid and semi-arid areas, such as Middle East countries, remains limited. The main objective of this dissertation is to present a graphical software tool which can assist water planners and decision makers for long term water management and planning. Sustainable planning for Abu Dhabi's future water supply is a very challenging task which requires consideration of various drivers and decision criteria. To produce realistic future scenarios for the EAD, sound knowledge of the supply-side elements and demand-side elements; for existing and future usages is required. Therefore, Abu Dhabi Dynamic Water Budget Model (ADWBM) was developed to help water policy makers of Abu Dhabi to assess various components of Abu Dhabi water budget. The model, which is capable of producing future scenarios of water budget, was calibrated and validated using historical data. Additionally, sensitivity of the model outputs to changes in the inputs was determined by conducting a sensitivity analysis. A second tool named Abu Dhabi Capacity Planning Model (ADWPM) is developed to manage the supply of water which is designed to form part of an integrated plan of water resources and the capacity planning of infrastructures. This is a multi-period optimization model based on mixed integer linear programming (MILP) and incorporated several parameters including various types of economic and environmental costs, capacity expansion options of treatment plants and water transmission systems, and environmental aspects (such as carbon footprint and brine discharge). The AWCPM was programmed in General Algebraic Modeling System (GAMS) and solved using the Cplex solver. This provides an ability for water resource managers to identify the optimal combination of sources to meet both the present and future demands of Abu Dhabi. Finally, a decision support system for water resource managers is then provided by coupling key components of these models (ADWBM and ADWCPM) and is named "Sustainable Water Budgeter for Abu Dhabi" (SuWaB-AD). This has graphical interface such that various scenarios can be explored and consequences of particular decisions can be made. The use of SuWaB-AD is demonstrated through the case study of Abu Dhabi could help decision makers in promoting sustainable plans. The results and applications show that SuWaB-AD approach can be adapted to support long-term water decision making. The proposed tools would be helpful to water administrators, water professionals and other water management authorities for sustainable water planning worldwide.

Keywords: Water budget, Decision support system, General algebraic modeling system, Mixed integer linear programming, Water scenarios, Sustainability, Water planning.

Title and Abstract (in Arabic)

تطوير نظام دعم القرار للتخطيط المستدام للمياه في أبوظبي، الامارات العربية المتحدة

الملخص

يتمثل أحد التحديات الرئيسية لمديري المياه في التنبؤ بالمستقبل بدقة، وتصميم السياسات المناسبة وخطط البنية التحتية بناءً على المتطلبات المستقبلية. يتم الآن تنفيذ استخدام أنظمة دعم القرار في مجال إدارة الموارد المائية والتخطيط على نطاق واسع، ولكن استخدامها في التخطيط المائي المستدام لدولة أو امارة في المناطق القاحلة وشبه القاحلة ، مثل دول الشرق الأوسط ، لا يزال محدودًا. لذلك ، فإن الهدف الرئيسي من هذه الرسالة هو تقديم أداة برمجية رسومية يمكن أن تساعد مخططي المياه وصانعي القرار في إدارة المياه وتخطيطها على المدى الطويل ولقد تم تنفيذ هذه الدراسة في إمارة أبوظبي بدولة الإمارات العربية المتحدة. يعد التخطيط المستدام لإمدادات المياه المستقبلية في أبوظبي مهمة صعبة للغاية وتتطلب مراعاة العوامل المحركة ومعايير القرار المختلفة. لإنتاج سيناريوهات مستقبلية واقعية لهيئة البيئة - أبوظبي ، والمعرفة السليمة بعناصر جانب العرض وعناصر جانب الطلب ؛ كل من الاستخدام الحالي والمستقبلي مطلوب ويتم تحقيقه من خلال تحديد المحركات الرئيسية التي تتحكم في العرض والطلب المستقبلي في أبوظبي. لذلك، تم تطوير نموذج ميزانية مياه أبوظبي (ADWBM) الذي سيساعد صانعي السياسات المائية في أبوظبي على تقييم جميع مكونات المياه ، ويكون قادرًا على إنتاج سيناريوهات لميزانية المياه المستقبلية. تمت معايرة ADWBM والتحقق من صحتها باستخدام البيانات التاريخية. تم تحديد حساسية مدخلات النموذج بإجراء تحليل الحساسية. تم تطوير أداة ثانية تسمي نمودج تخطيط قدرة المياه في أبوظبي (ADWCPM). لإدارة إمدادات المياه والتي تم تصميمها لتشكل جزءًا من خطة متكا ملة للموارد المائية وتخطيط قدرة البنى التحتية. هذا نموذج تحسين متعدد الفترات يعتمد على البرمجة الخطية المختلطة الصحيحة (MILP) ودمج العديد من المعلمات بما في ذلك أنواع مختلفة من التكاليف الاقتصادية والبيئية، وخيارات توسيع السعة لمحطات المعالجة وأنظمة نقل المياه، والجوانب البيئية (مثل بصمة الكربون و تصريف محلول ملحي). تمت برمجة ADWCPM في نظام النمذجة الجبرية العامة (GAMS) وتم حلها باستخدام Cplex solver. يوفر ذلك قدرة لمديري الموارد المائية على تحديد التركيبة المثلى للمصادر لتلبية كل من المتطلبات الحالية والمستقبلية لإمارة أبوظبي. أخيرًا ، تم تطوير DSS من خلال دمج المكونات الرئيسية لـ ADWBM و ADWCPM ، لتقديمها

كأداة تفاعلية للمستخدم الرسومية. وهذا ما يسمى "الميزانية المستدامة للمياه لأبوظبي" (SuWaB-AD). تم دمج ADWBM لمحاكاة سيناريوهات المياه المستقبلية ولتقييم الظروف المستقبلية لتوازن المياه في إمارة أبوظبي و تهدف ADWCPM إلى إيجاد حلول التخطيط الأمثل من حيث التكلفة لأي سيناريوهات مائية تمت محاكاتها بواسطة ADWBM من خلال تقييم القيود الاقتصادية والبيئية المختلفة المدرجة في ADWCPM ولقد تم توضيح استخدام SuWaB-AD في دراسة حالة في أبوظبي. تكمن الأهمية الأساسية لـ SuWaB-AD في فائدتها لصانعي القرار في تعزيز الخطط المستدامة. تظهر النتائج والتطبيق أنه يمكن تكييف نهج SuWaB-AD لدعم اتخاذ القرارات المتعلقة بالمياه على المدى الطويل و ستكون الأداة المقترحة مفيدة لمديري المياه والمتخصصين في مجال المياه وسلطات إدارة المياه الأخرى لتخطيط المياه المستدام في جميع أنحاء العالم.

مفاهيم البحث الرئيسية: موازنة المياه، نظام دعم القرا، نظام النمذجة الجبرية العامة، البرمجة الخطية المختلطة، سيناريوهات المياه، الاستدامة، تخطيط المياه.

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Dedication

To my beloved parents and family

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List of Abbreviations

A	Agriculture
AD	Abu Dhabi
ADSSC	Abu Dhabi Sewerage Services Company
ADWBM	Abu Dhabi Dynamic Water Budget Model
ADWCPM	Abu Dhabi Water Capacity Planning Model
ADWEC	Abu Dhabi Water and Electricity Company
Am	Amenities
ASP	Activated Sludge Process
BAU	Business-as-Usual
BAU-SQ	Business-As-Usual - Status Quo
BAU-WC	Business As Usual-Worst case
BCM	Billion Cubic Meters
BWB	Balanced Water Budget
C	Commercial
CLT	Construction Lead Time
CO_2	Carbon dioxide
CPA	Consumption rate per unit area
CPM	Capacity Planning Model
DI	Ductile Iron
DP	Dynamic Programming
DSS	Decision Support System
DW	Desalinated Water
EAD	Emirate of Abu Dhabi

EF	Environment First
ET	Evapotranspiration
F	Forestry
GA	Genetic Algorithm
GAMS	General Algebraic Modeling System
GCC	Gulf Cooperation Council
GHG	Greenhouse Gas
GIS	Geographic Information System
GRACE	Gravity Recovery and Climate Experiment
GUI	Graphical User Interface
GW	Groundwater
I	Industrial
ir	Irrigation
IWMI	International Water Management Institute
LCA	Life Cycle Assessment
LP	Linear Programming
lpcd	liters per capita per day
M	Municipal
MBBR	Moving Bed Bioreactors
MBR	Membrane Bioreactors
MCDA	Multi-Criteria Decision Analysis
MCM	Million Cubic Meter
MED	Multiple Effect Distillation
MILP	Mixed Integer Linear Programming

MINLP	Mixed Integer Non- Linear Programming
MODA	Multiple Objective Decision Analysis
MRE	Mean Root Error
MSF	Multi-Stage Flash Distillation
MULINO	Multi-sectoral Integrated and Operational
NN	Non-National
np	Non-potable
NPV	Net Present Value
OM	Operation and Maintenance
PCD	Per-Capita–Demand
PF	Policy First
pot.	Potable
PWR	Potable Water Return Ratio
QP	Quadratic Programming
R	Residential
RCP	Representative Concentration Pathway
RES	Rainfall Enhanced Sustainability
RHS	Right Hand Side
RF	Rainfall
RF_SF	Rainfall Surface Run-off
RO	Reverse Osmosis
RR	Recovery Ratio
SA	Shallow Aquifers
SBR	Sequential Batch Reactor

SC	Sustainability by Conservation
SC-BG	Sustainability by Conservation-Balanced Growth
SC-EF	Sustainability by Conservation-Environment First
SC-MF	Sustainability by Conservation-Market First
SD	System Dynamics
SDS	Storm Drainage System
SES	Sustainable Environment Scenario
SOCOPSE	Source Control of Priority Substances in Europe
SQ	Status Quo
TRMM	Tropical Rainfall Measuring Mission
TS	Treated Sewage
UAE	United Arab Emirates
UN	United Nations
WTP	Wastewater Treatment Plant
WTS	Wastewater Treatment System
WW	Wastewater

Chapter 1: Introduction

This chapter describes the dissertation's context, the motives for conducting the research, the research objectives, and the structure of dissertation.

1.1 Overview

Water supply and demand are two of the most contentious topics, especially in countries with arid or semi-arid climates. Due to its arid climate and insufficient precipitation, the Middle East countries depend on Desalinated Water (DW) and Groundwater (GW) to fulfill their major water needs. In the Middle East, DW is the primary source of potable water, while GW is the primary source for non-potable uses. Water demand in Gulf Cooperation Council (GCC) countries has risen sevenfold in the last 40 years, from 5 Billion Cubic Meters per year (BCM/yr) to 35 BCM/yr, owing primarily to population growth and rapid socioeconomic development (Al-Zubari, 2009). Population growth, economic progress, and improvements in lifestyle have all contributed to increased water use. And has intensified the need for water for agriculture, human use, and industrial processes. With the drastic rise in water use in recent years, governments are making a concerted attempt to handle scarce water supply sources more sustainably. This necessitates effective water resource management in order to resolve potential future supply and demand imbalances. One of the most difficult challenges for water policymakers is making plans and strategies for dealing with this potential future water crisis.

Many countries are already struggling to sustain reliable water sources in order to satisfy rising demand, and the situation will only escalate as cities and industries expand. The United Arab Emirates (UAE) is no exception with astonishingly fast shifts in demographics, lifestyle, and economy. Currently, water use in the Emirate of Abu Dhabi (EAD) is unsustainable and a Business-As-Usual (BAU) scenario would result in a tripling of demand for desalinated water by 2030, and available groundwater (fresh and brackish) would be depleted in about 50 years, or earlier in areas of extensive irrigation (RTI International, 2015). Because of its arid climate, the EAD has very limited renewable resources of groundwater and negligible surface water, the key conventional sources of water (Environment Agency - Abu Dhabi, 2009a). In the EAD, water scarcity is usually addressed by supplying desalinated water and reusing treated wastewater, and abstracting groundwater (Statistics Centre - Abu Dhabi, 2012, 2015, 2018). Several studies have shown that desalination plants have a detrimental effect on the Arabian Gulf's climate in terms of brine discharge and carbon emissions (Alghafli, 2016; Al-Zubari, 2009; Ministry of water and environment, 2010). To further complicate EAD’s future supply-demand shortfall problem, Greenhouse Gas (GHG) emissions must be taken into consideration when evaluating sustainable and environment-friendly solutions for water management. Carbon dioxide (CO_2) is thought to be the primary GHG causing global warming and climate change. With a growing concern over global warming and its effects on the environment, there is a need to reduce CO_2 emissions. In terms of ratification of the international Kyoto protocol and Abu Dhabi’s sustainability initiative to reduce carbon emissions (Abu Dhabi Quality and Conformity Council, 2015), more efficient and clean scenarios have to be implemented in water production. As a result, combining supply and demand management is crucial for the region's sustainable water resource planning. It is important to determine how existing and future strategies will influence the EAD's long-term priorities of water supply and sustainability.

1.2 Statement of the Problem

The observation that there are multiple water components as inflows, outflows, and transition components within inside and interacting with outside the system shows that the EAD's water system is highly complex. This calls for a comprehensive approach for understanding EAD's water system where a conceptual model explaining all the water components, and its quantification needs to be developed. This involves sound knowledge of the supply-side elements and demand-side elements; both for extant and future usage. An integrated study is thus needed to develop a decision tool to assist in long-term water planning decisions.

Literature shows that there is scope of using a Decision Support System (DSS) for water management decisions. The observation that DSS has been implemented in various environmental and water decision making shows that there is further opportunity to develop a tailor-made tool for water management and planning for the Emirate of Abu Dhabi. But, while considering the opportunity for the same, it is not encouraging if the water system is not completely analyzed and mathematically interpreted. So this has lead for basic inquisitive questions like "Why not a user-friendly mathematical tool for decision making, if any". Based on this curiosity, an option of developing a DSS for water decisions for Abu Dhabi seemed to be plausible.

The core to all water management policies are best decisions and therefore, if the tool can handle key aspects related to water in the EAD; like economic, environmental and sustainable, a novel DSS for Abu Dhabi water planning and policy making is the product.

1.3 Motivation and Objectives of the Research

The Emirate of Abu Dhabi is under pressure to handle the increasing demand and the decline in available conventional water sources. Furthermore, as environmental regulations have become more stringent, consideration must be given to meeting the rising water demands in an environmentally sound and cost-effective manner. There are various supply technologies for specific water sources available that could be used to help meet EAD's water demand. These supply options differ based on a number of factors, including economic, environmental, and operational characteristics. Certain technologies have lower economic costs (capital and maintenance costs) at high environmental impacts, while others have higher economic costs but lower environmental effects. In light of all the issues discussed, the EAD must find a sustainable mix of water supply options in order to realize its future water challenges. Therefore, the underlining question then becomes what mix of water supply technologies and sources, and options should be selected to meet the EAD's water demands and environmental limits at a minimal cost while planning for a long-term. This is the key question that this dissertation aims to answer and is main motivation. From the literature survey conducted, no prior work has been found in the GCC addressing the problem of finding the optimal strategy for integrated water planning with environmental constraints.

The specific objectives of this research were:

1. To develop a dynamic water budget model for Abu Dhabi capable of providing scenarios of future water budget taking forward trends (e.g. 20, 30 years).

2. To build scenarios using the developed dynamic water budget model to evaluate future water balance as affected by population growth, economic growth, proposed water policies, consumption patterns and climate change.
3. To formulate a multi-period Mixed Integer Linear Programming (MILP) model that is capable of identifying the optimal mix of water supply sources and technologies to meet EAD's current and future water demands and environmental targets, and reduce the overall cost of water production.
4. To develop and implement the MILP model in General Algebraic Modeling System (GAMS), run the model for a case study scenario, and conduct sensitivity analysis.
5. To develop a user-interactive DSS architecture integrating dynamic water budget model and MILP model capable of providing optimized water supply solutions for all future water scenarios of Abu Dhabi.
6. Demonstrate the application of the DSS through the case study of Abu Dhabi.

1.4 Dissertation Structure

The remainder of dissertation is composed of seven main chapters as organized in Figure 1.

Chapter 2 presents a literature review of current and past research done in the field of water decisions and planning. This has subsections on journal review of the procedures and the steps required for developing a DSS.

Chapter 3 presents the complete methodology of the development of a dynamic water budget model for Abu Dhabi. Furthermore, this chapter presents the calibration and validation of the model.

Chapter 4 describes the development of water scenarios for the EAD using the dynamic water budget model developed. Moreover, it includes evaluation of each of them in detail.

Chapter 5 describes the development of a multi-period MILP model for Abu Dhabi water decisions and capacity planning by taking into account the economic and environmental factors.

Chapter 6 details the model implementation in GAMS, a case scenario and its results in detail.

Chapter 7 describes the development of a computer-interface for user interaction in which the two developed models are integrated to generate and find optimal solutions in a simpler way. An illustration of use of the DSS is also presented.

Finally, Chapter 8 presents the research conclusions and recommendations for future work.

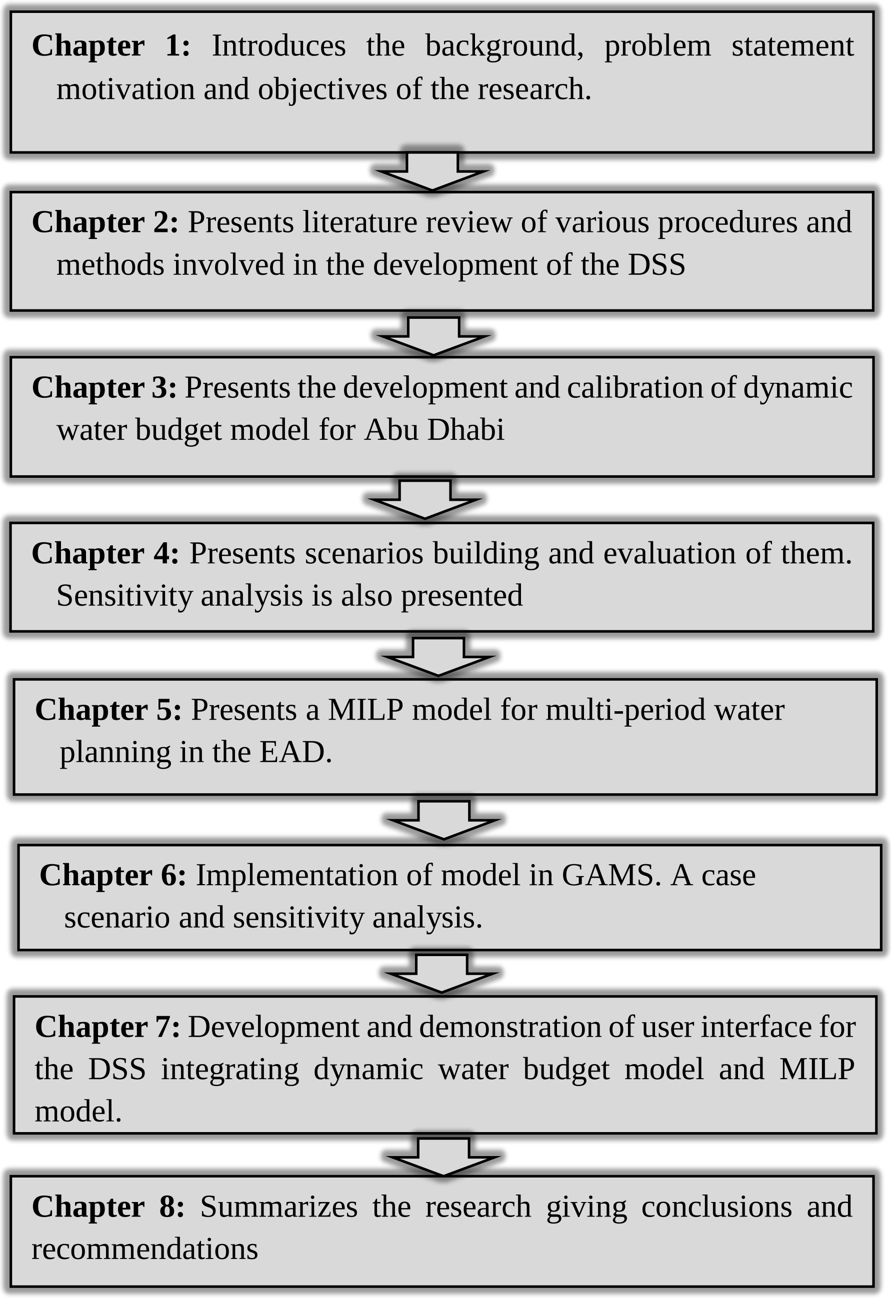


Figure 1: Dissertation structure

Chapter 2: Literature Review

This chapter provides the literature review of water balance models, scenario analysis applications in water management, optimization techniques in capacity expansion and water management, and decision support tools used in the field of water management. Section 2.1 provides a detailed literature review of the water balance models used in water resource planning. Section 2.2 provides a comprehensive review of application of scenarios analysis in water management. They also enlighten the application of scenario analysis is this research. Section 2.3 is on the optimization techniques used in water planning and the main focus is on the application of mixed integer linear programming in capacity panning of water sector. The later section 2.4 is on the detailed review of decision support systems used in the water resources planning and management.

2.1 Water Balance Models

A water balance review of a hydrologic system in an area is needed for decision-making including water supply management and planning. To develop a water balance model, a mass balance analysis for the study area must be created, which includes all inflows, outflows, and storage components within a given boundary. Inflows are those elements that add to a region's water source, while outflows are all water flowing out of the system. The storage aspect is the measured difference in the stored water over time. Rainfall and surface inflows into an area by streams and rivers are the main inflows for any region. Evapotranspiration from various land uses and drain flow from the area to the sea make up the majority of the outflow components. Various spatial and temporal processes that influence the overall water balance of a hydrological system vary depending on the geographical location and climatic zone of an area. Water drawn up from the sea into the terrestrial system is the main inflow in semi-arid and arid areas where rainfall is scarce. Since surface water supplies such as lakes and rivers are not available in such areas evaporation from water bodies is minimal, whereas evapotranspiration is high. As a result, each water budget analysis conducted at various geographical locations for particular purposes has evolved its own methodologies that are appropriate for their condition based on the various water components present. Water supplies are scarce in arid areas, limiting the amount of freshwater available for irrigation and other purposes.

Researchers around the world have created a number of water balance models to address a variety of water-related problems at the local, state, and national levels. Various water balance models from around the world evaluate all of the water components in the research area (Cheng et al., 2014; Lv et al., 2017; Qaiser et al., 2011; Shimizu et al., 2015; Wei et al., 2016). Water balance methods developed by numerous organizations, including the United Nations (UN), the International Water Management Institute (IWMI), and the Australian government, have received considerable attention [e.g. (Karimi et al., 2013)].

The studies in the arid and semi-arid regions are based on different climatic and hydrologic criteria that are unique to desert conditions in order to assess the land and groundwater supply for various uses such as agriculture, domestic use, and other nondomestic use by the industrial and commercial sectors. In 2014, a study in Jordan's semi-arid zone used a transient model to analyze the watershed for a mountainous region and discovered that evapotranspiration is the main component of precipitation there, accounting for 87.5% of total precipitation (Oroud, 2015). A study by (Bandoc

& Pravalie, 2015) investigated the climatic water balance of Romania's most arid zone, utilizing data from nine weather stations to research water cycles over five decades and employing both statistical and GIS techniques for pattern analysis at annual and seasonal scales. The findings of the study revealed that there has been a rise in water shortage over the last five decades, and they called for more effective water supply management, with a greater emphasis on agricultural production. The water balance of arid regions in Columbia is examined for two time periods under two climate change conditions (RCP (Representative Concentration Pathway) 4.5 and RCP 8.5), taking into account various arid-specific parameters such as evapotranspiration, soil moisture, aquifer recharge, rainfall, water shortage and waste, and water use (Ospina Norena et al., 2017). In 2013, (Deus et al., 2013) used remote sensing data to estimate the water balance in an arid area of Tanzania. To aid lake maintenance and restoration in relation to soil erosion, climate change, and land use change, the spatial and temporal variability of water balance parameters within the catchment was investigated. A complex water balance model for key hydrological processes in drylands in Tunisia was created in a study by (Tarnavsky et al., 2013), which is useful for the spatial and temporal preparation of water harvesting as well as the optimization of agricultural activities. In their analysis in California's semi-arid areas, Roy and Duke Ophori studied the water balance to classify seasonal fluctuations in soil moisture, rebound, and runoff in order to quantify the water surplus or deficit due to judicious crop irrigation (Roy & Ophori, 2012). To better understand the effect of climate and land use on the hydrology of a semi-arid savanna in the southwest United States, researchers measured precipitation, runoff, evapotranspiration, and drainage (Scott & Biederman, 2019). In a research undertaken in the driest region of Europe, computational simulations were used to evaluate different mathematical models and create an updated water budget model for the Torrevieja aquifer, resulting in better water management (Duque et al., 2018). Surface evapotranspiration is one of the main processes that decides the amount of rainfall available to support vegetation and recharge in an arid environment. Evapotranspiration calculation using the Surface Evaporation Capacitor (SEC) model was included in some of the research (Lehmann et al., 2019). By combining remote sensing, reanalysis, data assimilation datasets, and field measurements, Yao et al. increased the estimation precision of Evapotranspiration (ET), precipitation, and runoff forecasts (Yao et al., 2014). Satellite-based water cycle components were used in several experiments, including precipitation from the Tropical Rainfall Measuring Mission (TRMM) and ET from the moderate resolution imaging [e.g. (H. Wang et al., 2014)]. In a study by (Niazi et al., 2014), a comprehensive System Dynamics (SD) model was developed for an arid region in Iran to help in conserving water resources and reducing depletion in arid regions and semi-arid areas. In 2017, (Nassery et al., 2017) used system dynamics to predict groundwater level fluctuations, and to determine the supply surplus or deficit for various water management strategies.

In the Middle East, the United Arab Emirates (Mohamed, 2014) completed one of the few water budget studies in the field. According to the study, the projected population increase would place increased strain on the country's water supply. As a result, the city requires a budgeted water allocation, which the author discusses in the article. In a separate study, (Gonzalez et al., 2016) looked at the decline of ground water supplies and increased reliance on desalination in the UAE as a result of population growth and economic progress. To aid in the optimum distribution of water, they used the Gravity Recovery and Climate Experiment (GRACE) and TRMM data to consider the differences in groundwater conservation as a balance of overall runoff, evapotranspiration, and desalinated water.

Based on the findings of the literature review, it is clear that defining the relationship between all water components is critical for long-term water resource management, but that using analysis techniques to model potential future scenarios is also essential. As a result, once a water balance has been developed for every water environment, it can be used to create a dynamic model that predicts future changes.

A variety of methods can be used to model water environments dynamically. The use of SD models and parameter models in the development of dynamic water budget models has been established. There are dynamic models that predict future conditions using a series of validated parameters known from water balance models. In 2006, Jazim developed a six-parameter water model to predict monthly rainfall in arid and semiarid catchments (Jazim, 2006). In 2015, Camp et al. used a lumped parameter approach to create a model that can be used to model intramountain basins in Iran (Camp et al., 2015). Previously, several summaries of how various parameters are used in selected models produced by various researchers were presented (e.g. (Abdollahi et al., 2018) and (Thapa et al., 2017). To test the robustness of the methodology, (Perez-Sanchez et al., 2019) conducted a comparative analysis of six models produced in Spain between 1977 and 2010, concluding that all models considered in the study performed well in humid and sub-humid areas (Perez-Sanchez et al., 2019). Other recent research, such as (Maloszewski, 2000) and (Lindhe et al., 2020), have shown the use of a parametric method for assessing water source security.

Although various dynamic water budget models have been created around the world for specific purposes, to our knowledge, no systematic dynamic model for long-term water scenario production and prediction of potential water conditions exists for any semi-arid or arid climatic zone.

Although there are numerous dynamic water budget models developed all over the world with specific purposes, to the best of our knowledge, a comprehensive dynamic model for long-term water scenarios development and analysis of future water situations is not available for any semi-arid or arid climatic region. As a result, Chapter 3 of this study presents a model to simulate possible scenarios of the water system, which may aid long-term preparation and policy formulation for water budgeting in an arid environment.

2.2 Scenario Analysis

Mathematical models help explain and assess the effect of socioeconomic, political, and environmental conditions on the present and future water supply-demand structure. Scenarios are expositions of potential scenarios that are useful for analyzing shifting factors in defining the future, judging possible deviations from present patterns, and strategizing for long-term uncertainty and complexities. Scenarios are used to evaluate potential risks and help in the implementation of water conservation plans (Carter et al., 2007). As a result, scenario analysis will aid in the selection of a sound water policy for a state or country by highlighting the best options among those expected. Since the United States first used scenarios in military planning, scenario construction has become a hot subject (Van Der Heijden, 2005). Scenario development has become prominent as a strategic planning method in a variety of fields, including social forecasting, public policy research and decision-making, environmental sustainability, market development, and water resource management (Hulse & Gregory, 2001).

There are several scenario research studies for water supply management. Zhuo et al. used scenario analysis to determine water footprints and simulated water exchanges for time horizons of 2030 and 2050, with an emphasis on crop production (Zhuo et al., 2016). In 2018, Proskuryakova et al. used scenario analysis, data processing, and other specialist tools to create water scenarios with Russia for a time period of 2030 (Proskuryakova et al., 2018).The scenarios were based on biodiversity, household and industrial water demands, and other critical needs. In India, (Amarasinghe et al., 2007) developed food and water futures scenarios for the years 2025–2050 in India, addressing different problems in the business as normal scenarios for water futures. In Nepal, (Saraswat et al., 2017) published a report on urban water management and used scenario analysis to create plans for implementing sustainable water management activities by 2030. In 2018, (Cetinkaya & Gunacti, 2018) created scenarios for Turkey and measured success using a multi-criteria analysis. Dong et al. conducted a comprehensive analysis of the state of scenarios methodology of water resources management in 2013, and discovered that the scenario strategy was commonly used for analyzing potential water supply situations and designing contingency strategies (Dong et al., 2013). In another study, Amer et al. looked at the benefits and drawbacks of common scenario planning methods (Amer et al., 2013). This study has looked at scenario collection, the number of scenarios that could be used, and how to validate scenarios. Stewart et al. proposed a five-step iterative approach to scenario construction in 2007 (Stewart et al., 2007). In the US, (Mahmoud, 2008) suggested a systematic scenario planning approach for water resource control in the southwest United States. In 2015, (Henriques et al., 2015) produced four potential scenarios focused on stakeholder consultations and expert recommendations to solve water supply issues in England and Wales for the years up to 2050. In 2014, water footprint models were created for 2050 to better explain trends in global and regional water footprints (Ercin & Hoekstra, 2014). A review analysis conducted in the Netherlands concluded that scenario methods are useful for dealing with the uncertainties encountered by water managers in decision making (Haasnoot & Middelkoop, 2012). In the Middle East, (Al-Zubari, 2009) created four water scenarios for the Gulf Cooperation Council (GCC) countries, taking into account the various economic growth trends that can be applied in the region. Market, sustainability, policies, and security are the four factors defined by Al-Zubari as potential scenarios. The literature supports scenario creation and prediction as a critical method for promoting sustainable water resources planning.

Several government policies can have an effect on water usage. For example, policies encouraging agricultural expansion in order to preserve the nation's heritage and reduce reliance on imported food could increase demand for irrigation water. Similarly, desert greening policies aimed at providing shelter for wild animals and stabilizing sand around roads may raise irrigation water demand. Other policies that are important include the development of public parks, the implementation of residential and commercial megaprojects to benefit the local population and tourism, and industrialization fueled by the government's diversification into non-petroleum based industries. Climate change can also be a significant factor in sustainable growth, as it can result in rising sea levels, the drying up of soil and groundwater, and severe droughts (National Center of Meteorology, 2020).

As presented in Chapter 4, this study investigates four possible futures and the strategic measures necessary to ensure a prosperous future for Abu Dhabi. A number of drivers were taken into account when creating the simulations, including population development, economic growth, water use patterns, and climate change. A suite of four scenarios, namely, BAU, Policy First (PF), Sustainability by Conservation (SC), and Rainfall Enhanced Sustainability (RES) were both considered and assessed for their efficacy. This research, which is the first of its kind in the field, will serve as a foundation for future refinement in water resource planning and management in arid and semi-arid regions using scenario production.

2.3 Optimization Methods in Water Management and Capacity Planning

Several countries are facing challenges related to water supply to meet the ever-growing demand because of economic and population growth (Al-Zubari, 2009; Ercin & Hoekstra, 2014; Lutz et al., 2014; O. Saif et al., 2014). Most arid and semi-arid countries are facing the problem of increasing demand and a decline in available renewable sources of water (Al-Damkhi et al., 2009; O. Saif et al., 2014; WEF, 2007). In most countries, increasing water demand is managed by enhancing the capacity of water treatment and supply facilities by either the expansion of the existing or construction of new facilities (Al-Zubari, 2009; Environment Agency - Abu Dhabi, 2014; Ministry of water and environment, 2010; WEF, 2007). Therefore, future change in demand should be considered for optimum capacity expansion or building of new facilities. The optimal planning of water resources to meet the demand is challenging because of the complexity involved in choosing from large and varied options available. To determine the optimal combinations of technologies, a model that incurs minimal treatment and supply costs and satisfies all water demands and quality standards.

Mathematical programming and optimization techniques have been used in solving complex water problems, such as water planning, water supply planning, water resource allocation, irrigation management, and capacity planning (AlQattan et al., 2015; Marcovecchio et al., 2005; Ortega Álvarez et al., 2004; Pakzad Shahabi, 2015; Wu et al., 2010). Water planners develop planning models using approaches such as Linear Programming (LP) (Jacovkis et al., 1989), Quadratic Programming (QP) (Huang et al., 2015), Dynamic Programming (DP) (Davidsen et al., 2015), Mixed Integer Non-Linear Programming (MINLP) (Belotti et al., 2013), or MILP (Liu et al., 2011).

Recently, the aforementioned optimization techniques have been widely used in water-related fields, which focus on minimizing the cost or maximizing the benefits from water resources. Several optimization models are available in the literature to address specific objectives relevant to regions, periods, quality, supply, and sectors. The approach involved formulating the real problem into a series of mathematical equations by using techniques LP, nonlinear programming, MILP and MINLP for developing the model.

Several studies have implemented the MILP to optimize water supply. In Greece, (Voivontas et al., 2003) developed a model that minimized the Net Present Value (NPV) of the water cost for 2002–2030 by implementing a nonlinear gradient method. The model comprised decision variables that included the capacity and operation of various conventional and nonconventional sources available. In the year 2005, (Yamout & El-Fadel, 2005) presented a model to help in making decisions about water supply to multisectors considering economic and socioenvironmental factors. This regional LP model was developed to assist decision makers in planning and developing policies for optimal water resource allocation. In another study conducted in Greece (Gikas & Tchobanoglous, 2009), various alternatives of water supply were compared and optimized to meet the steady increase of demand in Aegean Islands. Three alternatives, namely, desalination, importation to island, and water reclamation were optimized considering long-term sustainability in addition to cost and energy requirements. Other studies conducted by (Draper et al., 2003) and (Medellin-Azuara et al., 2007) used an optimization model to evaluate the economic-engineering optimization of water management. They used CALVIN, an optimization model to explore and economically integrate water supply options such as Wastewater (WW) reuse, desalination, and other water supply options. In Kuwait, (AlQattan et al., 2015) optimized the supply of desalinated water to users by developing a multiperiod optimization model that considered the co-generation of water using power. The MILP considered the capacity expansion options of both desalination plants and power plants to meet the demand for a planning horizon of 37 years. In 2014, Kang and Lansey introduced a novel optimization approach to scenario-based planning for the optimal design of regional-scale water supply infrastructure to minimize the economic costs of the projects (Kang & Lansey, 2014). Pakzad Shahabi in 2015 focused on the water supply of desalinated water by developing a desalination supply chain optimization life cycle framework and applied Life-Cycle Assessment (LCA) to analyze the economic and environmental impacts of different desalination supply planning scenarios (Pakzad Shahabi, 2015). The study considered the trade-offs between different environmental impact indicators for various sizes of desalination plant and pipeline infrastructure. Saif and Al Mansoori had formulated and solved a MILP supply chain problem for desalinated water supply in the UAE (Y. Saif & Almansoori, 2014). The major decision variables included the optimal capacity and location of various desalination supply chain infrastructures, over a long planning horizon. In an another study, (Y. Saif & Almansoori, 2016), focused on the optimal capacity expansion of co-generation plants.

Other category of optimization studies is related to the water resources management. There are several single- or multi-objective studies. A study by (Wu et al., 2010) focused on comparative single-objective and multi-objective problem formulations and recommended multi-objective approach while making decisions on water resources management; showing the greenhouse gas emissions as an example. A goal programming based multi-objective model was developed by (Al-Zahrani et al., 2016) to distribute water to multiple users from multiple sources of water. Priorities and weightages were assigned for all goals to be achieved in the optimization. Major goals considered included meeting the sector-wise demands, maximize the use of Treated Sewage (TS), minimize GW extraction, maximize GW conservation, minimize DW production, and minimize overall cost of using water from different supply resources in the city of Riyadh, Saudi Arabia. In a study conducted by (Kondili et al., 2010)**,** in order to optimize the water system that comprised water supply and distribution to an island with water shortages, they took into account both technical and environmental parameters related to supply sources, required infrastructure projects, water production cost and values for the exploitation of water resources. In Egypt, (Lamei, 2009) followed a technical-model approach to manage the growing water demand in the tourism sector and used DP to optimize the capacity expansion schedule of RO desalination plants. (Liu et al., 2011) used MILP to model the problem of integrated water resources management in two Greek Islands where potable and non-potable systems of water supply are integrated in the model to find minimized annualized total capital and operating costs by taking into consideration the decision variables like location of desalination, wastewater treatment, and pipelines and storage tanks for desalinated water, wastewater and reclaimed water. Studies by (Abdulbaki et al., 2017) and (Han et al., 2008) deployed MILP to allocate water to various urban users and their model was to minimize the total water cost which included the economic and environment cost of treatment and distribution.

Several studies on WW management are available in the literature. In 2001, (Bakir, 2001) proposed an integrated approach to sustainable WW management. At a regional level, (Cunha et al., 2009) developed an optimization model for integrated WW systems planning, which included to determine the best possible configuration of WW treatment plants, layout of sewer networks, location of WW treatment plants taking into account the economic, environmental, and technical criteria . Some of the optimization models by (Ray et al., 2010; Y. Saif et al., 2008; C. G. Wang & Jamieson, 2002) used quality of water as a criterion for optimal capacity planning of WW systems.

A literature review of the various optimization problems developed in the area of water and its use showed that several models were developed to help water planners, and decision makers in water supply and planning. However, most works were developed with specific scope and objectives applicable to a specific region or a time. Moreover, many did not consider environmental impact as variables for decision making.

Therefore, optimization problems could be improved for better management of water resources and planning. Besides, to the best of our knowledge, there is no comprehensive research work in arid or semi-arid geographical location in The Middle East so far for an integrated water supply planning and management that considered the multi-period, multi-regional management of water demands of multi-quality levels that took into account various technologies for water production of potable and non-potable water, transmission of produced water by export and import options, and the integration of both potable and non-potable water systems. Therefore, this study focuses on developing a MILP considering all these criteria. The objective was to provide a comprehensive tool to water policy makers and governments to minimize the economic and environment costs while making plans for future demands and supply. This tool offers many potential benefits to a nation's water sector by providing an integrated water resource management and planning solution taking sustainability into consideration.

In this research, a new multi-period MILP model that could solve for the optimal mix of water supply options to meet current and future water demand by minimizing CO_2 emissions, GW extractions and brine disposal based on the associated environmental costs, and the overall cost of water production and transmission of water to meet the multi-regional water demands of various quality levels is proposed.

2.4 Decision Support Systems in Water Management

Long-term planning of the water supply in arid and semi-arid countries has become a difficult challenge for governments because of a gradual rise in demand and concurrent reduction in available sustainable supplies of water. It is also important for water managers to focus their decisions on long-term financial and environmental protection. Therefore, a decision support system that can forecast the future demands and supply, and provide optimal solutions for satisfying these demands, can speed the decision making process for successful water planning. In an effort to help the governments and decision-makers in the Middle East region meet these challenges, this study presents a user-interactive DSS tool to identify economically and environmentally feasible solutions to ensure water supply on long-term basis effectively despite the rising demand and costs.

The use of decision-making tools is recently encouraged to achieve more sustainable and integrated solutions for water planning. These tools are computer-based interactive programs that can help decision-makers in their area of application (Noor Maizura Mohamad Noor & Rosmayati Mohemad, 2010). The history of DSS use for managing different issues dates to the early 1960s and involved applications of information technology. Since then, several different DSSs have been developed to help decision-makers address challenges in the realm of water resources management and planning, water and wastewater treatments, water supply infrastructure and capacity planning, river management, irrigation management, and other areas relevant to water. The components of each DSS depend on the purpose for which the tool is developed. For sustainable water resources management, a DSS requires specific targets and definitions, forecast tools, and quantifiable indicators (Kay, 2000). Information technology tools are adapted to facilitate smart management of the water resource. One difficulty in developing optimization models for DSSs is the high computational requirement for solving large-scale optimization problems (Galelli et al., 2010). Common approaches and tools incorporated into a DSS are fuzzy logic, Multi-criteria Decision Analysis (MCDA), dynamic programming, geographic information systems, artificial neural networks, numerical models, statistical models, optimization models, conditional operating rules, genetic algorithms, and other techniques with or without a Graphical User Interface (GUI).

An early DSS in the water sector is AQUATOOL, developed by Andreu et al., which aided in the planning and management of river basins in Spain and other countries (Andreu et al., 1996). In 2005, Leung et al. developed a DSS in which mathematical models were made more user-friendly for environmental decision-making related to water pollution in rivers (Leung et al., 2005). In two other studies, researchers developed a DSS for integrated river basin management in Germany (de Kok et al., 2009) and China (Cai et al., 2015). In the field of water and wastewater treatment operations, a DSS was developed to simulate the dynamic behavior of the Wastewater Treatment Plant (WTP) process by integrating various process models and an expert system (Xu et al., 2006). In a study related to wastewater treatment, life-cycle assessment was applied to evaluate the environmental impact of municipal WTPs (Pasqualino et al., 2009). To help the municipal water planners for optimal expansion planning of sewers, geographic information system-based DSSs were used in which cost was minimized under various constraints (Ariaratnam & MacLeod, 2002; M. Halfawy et al., 2008; M. R. Halfawy et al., 2007; Wirahadikusumah & Abraham, 2003). For a pipeline water distribution system in Canada, a DSS named Q-WARP was developed to predict the risk of water quality failure in pipelines (Sadiq et al., 2014). In other studies, DSSs for water resource management have been developed by various authors to address water problems such as the following: water allocation (L. Zhang et al., 2011), water policy (Ward, 2007), water use management for agriculture (Rinaldi & He, 2014),water resources management (Giupponi & Sgobbi, 2013a; Serrat-Capdevila et al., 2011), water supply management (Freund et al., 2017), GW management (Pierce et al., 2016), water reuse (Ahmed et al., 2003), and storm water management (Morales-Torres et al., 2016). Finally, in a study with agricultural applications, a DSS was developed in the hilly regions of India to yield appropriate decisions on selection of the crop, sowing time, irrigation, fertilization, and harvest (Nain & Singh, 2016).

Many DSSs are not easily adaptable, nor are they an effective decision-making tool for another geographic location. For example, DSSs have been developed to help implement aspects of the EU Water Framework Directive, such as the Multi-sectoral Integrated and Operational Decision Support System (MULINO), in association with Source Control of Priority Substances in Europe (K. Zhang et al., 2014). Other DSSs were developed with specific objectives for the Mediterranean countries (Merot & Bergez, 2010) and Southern Italy (Portoghese et al., 2013).

All DSSs require different numeric techniques to carry out the optimization and produce the decisions based on the objective functions. Because issues to address in the water management sector have multiple objectives, the use of MCDA and Multiple Objective Decision Analysis (MODA) are common. Various researchers have used MCDA/multiple objective decision analysis techniques at different levels of DSS development. Examples of two MCDA-based DSSs with user-friendly interfaces for capturing user preferences are WARPLAM (Coelho et al., 2012) and Mulino DSS (mDSS) (Mysiak et al., 2005). In another study, technological advances in information technology were used to develop a real-time DSS for adaptive management of the reservoir system to provide drinking water to the metropolitan region of Boston, Massachusetts (Westphal et al., 2003).

For comprehensive sustainable planning at the country or state level, the two major challenges for decision-makers are the complexity involved in foreseeing future water scenarios and finding a cost-optimal planning solution for the same. This responsibility is daunting because the decision-makers must find the optimal balance between the environmental sustainability, financial budget, and social aspects. As budgets are becoming increasingly constrained and many stakeholders are involved, optimal planning by governments is essential for sustainable development (McCormick et al., 2013). Dynamic water budget models that can simulate future water scenarios are useful for decision-makers to have an indication of water balance in terms of deficit or surplus (Kizhisseri et al., 2021). This modeling involves an understanding of the drivers of water demands and available water resources relevant to the study area. Growing water demand is typically managed by increased production of water from available sources. The key question then becomes: "What is the best or optimal method for processing water to satisfy multiple quality water demands in a sustainable manner?". This question is one of the many that the decision-makers must answer while planning for water sector. In this context, optimal planning of water production to meet the water demand is challenging because of the complexity involved in choosing from the large number of varied options available. A capacity planning model is necessary to solve for the optimal mix of water supply alternatives to meet current and future water demand while reducing carbon dioxide emissions, GW extractions, and brine disposal based on related environmental costs, and the overall cost of water production and transmission to meet water demands of different quality levels. Water planners typically use linear programming, quadratic programming, dynamic programming, mixed integer linear programming, or mixed integer non-linear programming to construct planning models for long planning horizon.

The primary aim of this research is to provide a new DSS that facilitates the joint use of a complex dynamic water budget model and a water capacity planning model to assist policy makers in water planning for a nation or state. The proposed tool is to simulate future scenarios in context to Abu Dhabi, and to find optimal solutions for any such simulated scenarios in terms of economic and environmental cost.

2.5 Chapter Summary

The literature discussed in this chapter enlightens the importance of water balance models, and scenario analysis while planning for future on a long term basis. Different modelling and optimization techniques of water management and supply have been discussed along-with various applications. In addition, the use of user interactive computer based tools to assist in water planning are also discussed.

Chapter 3: Development of a Dynamic Water Budget Model for Abu Dhabi

This chapter presents a dynamic water budget model for the study area, Abu Dhabi. The model, called Abu Dhabi Water Budget Model (ADWBM), accounts for a number of drivers such as population growth, economic growth, consumption pattern and climatic factors. Model formulation, calibration and validation of the ADWBM are presented in this chapter.

3.1 Study Area

The planned study site is Abu Dhabi, the largest of the UAE's seven emirates, with a total area of 67,340 km^2 and a desert climate. As seen in Figure 2, it is divided into three regions: Abu Dhabi, Al-Ain, and Western. The emirate is bordered on the east by Oman, on the south and west by Saudi Arabia, and on the north by the Arabian (Persian) Gulf. During the majority of the months, the climate is arid, with a hot and humid atmosphere. During the summer months of April to September, the mean temperature averages above 40°C (104°F). Abu Dhabi has a 600-kilometer-long coastline, which results in humid climatic conditions owing to the sun's heat. The months of October to March are relatively cool. The coldest months are January and February. Due to the emirate's lack of rainfall, natural recharge into groundwater is very poor, at about 40 MCM/yr (Environment Agency - Abu Dhabi, 2009a), adding to the emirate's water issues.

Figure 2: Proposed site of the study, the EAD (Western, Abu Dhabi and Al Ain regions)

Water demand in the EAD has risen dramatically in recent decades, with population growth and economic development serving as the primary drivers. The population of Abu Dhabi Emirate has increased many times in the last few decades, driving much of the increase in water consumption in the Emirate, especially residential, industrial, and municipal consumption (Statistics Centre - Abu Dhabi, 2015). The overall population has increased by more than 6.6 times since 1975 (Statistics Centre - Abu Dhabi, 2015). Water demand for agriculture, human use, and industrial activities has also risen as a result of shifts in lifestyle. Several government policies exacerbated the rise in water demand. Few of these policies promote agricultural growth in order to preserve rural heritage and reduce the EAD's reliance on imported produce. Some proposals advocate for desert greening in order to provide shelter for wild animals and to keep sand from accumulating along highways. A few advocate for the creation of public parks to improve the aesthetic appeal of open areas, while others advocate for the construction of residential and industrial megaprojects to meet the needs of the local community as well as the growing tourism industry. The government's diversification vision of conversion into non-oil sectors is a major driver of industrialization.

Water is supplied from a variety of sources, including groundwater, seawater desalination, recycled sewage, and rainfall runoff. Based on the types of demands they can meet; they can be classified as potable (*pot*) or non-potable (*np*) sources. Residential, industrial, municipal, and commercial are four of the seven demand sectors listed in EAD that are considered potable. These sectors need high-quality fresh water. Desalinated water is the only way to satisfy all four potable sector water demands. Desalination plants are located in the EAD in various strategic locations. Groundwater, on the other hand, is the primary source for the three non-potable sectors of agriculture, forestry, and amenities. Non-potable demand is partially supported by TS and surface runoff. TS is only used to meet the needs of the forestry and amenities. TS is a non-conventional source of water produced by treating wastewater to reusable quality. In EAD, there are wastewater treatment plants at all key population centers to produce and distribute TS.

The annual rainfall in the EAD is normally less than 100 mm (Environment Agency - Abu Dhabi, 2009a). As a result, rainfall and drainage are scarce water supplies in the region. There is very little information On Abu Dhabi's surface runoff. The landscape is mostly flat, with sandy soil, sparse dunes, and a few low-elevation sabkhas (flat area with salt deposits). As a result, very little runoff is generated. Rainfall creates drainage in the east of the EAD, which floods into the wadis (creeks) and flows westward, crossing into Abu Dhabi and supplying about 7.6 MCM annually

(Environment Agency - Abu Dhabi, 2014). Rainfall is measured using data from 24 stations spread around the EAD.

The EAD's overall water consumption in 2011 was about 3416 MCM, indicating a large rise in demand (Statistics Centre - Abu Dhabi, 2012). Population growth and economic prosperity are the major drivers of this rise. Much of the water consumption in Abu Dhabi Emirate has increased as a result of population growth, especially in the residential, industrial, and municipal sectors. The estimated population in 1975 was 211,812, and by 2005 it had risen to 1,399,484, a 6-fold growth in 30 years (Statistics Centre - Abu Dhabi, 2015). In the nine years since, the population of Abu Dhabi has doubled, reaching 2,656,448 in mid-2014 (Statistics Centre - Abu Dhabi, 2018). The average annual population growth trend from 2005 to 2014 was 7.6%. 507,479 Emirati inhabitants make up 19.1% of the total population, while the remaining 80.9% are non-citizens. Males account for more than 66.5% of the workforce, owing to an influx of male migrant workers (Statistics Centre - Abu Dhabi, 2018). The birth rate in the Emirate of Abu Dhabi is higher than in most developing countries, and the mortality rate is low. In 2014, the approximate crude birth and death rates were 14.3 and 1.2 per 1000 people, respectively (Statistics Centre - Abu Dhabi, 2018), reflecting the population's high net growth rates. In 2014, the population density of the Emirate of Abu Dhabi was 44.7 people per square kilometer. The population density in the Abu Dhabi Emirate's three regions (Abu Dhabi, Al Ain, and Western) is 148.9, 52.6, and 8.9 people per square kilometer, respectively, representing the different levels of urbanization (Statistics Centre - Abu Dhabi, 2018).

Water demand for agriculture, human use, and industrial activities has also risen as a result of shifts in lifestyle. The growth in water demand was exacerbated by a number of public policies. For example, expansion of agriculture to protect rural heritage and reduce dependency on imported food.

3.2 Conceptual Water Balance Model

The dynamic water structure of the EAD was analyzed using a systemic approach with the aim of establishing a conceptual basis for the water balance model. The study's mathematical model was framed by looking at all of the water inflows, outflows, transportation, and transition elements, with the EAD as the study's boundary. For the whole system, a comprehensive water balance was created. The Abu Dhabi water system was divided into three subsystems for the creation of the water balance model: water supply, water demand, and water transfer. Figure 3 depicts the system's conceptualized model framework. It revealed that the elements of the three subsystems have dynamic interactive relationships. In order to construct the mass balance equations, the model considers all possible interconnections among the various water supplies, demand sectors, and transfer constituents. Thus, for the EAD, a conceptual model was created that included four water supply sources, seven demand sectors, and three transfer elements. Two workshops with governmental institutions and stakeholders were held as part of this research to explore and collect more reliable data for the model creation.

The choice of dynamic system software is driven by the nature and relative importance of the system, the data, and the application environment. Stella, Simantics, and Powersim were also taken into consideration. However, given (i) the early stage thrust of the work: (based on stocks, flows and balances, the data to determine these and the possible changes driven by different intervention policies) (ii) the need for familiarity and trust of potential users and data providers with the software and (iii) ease of data transfer, an established spreadsheet format (MS Excel) was used.

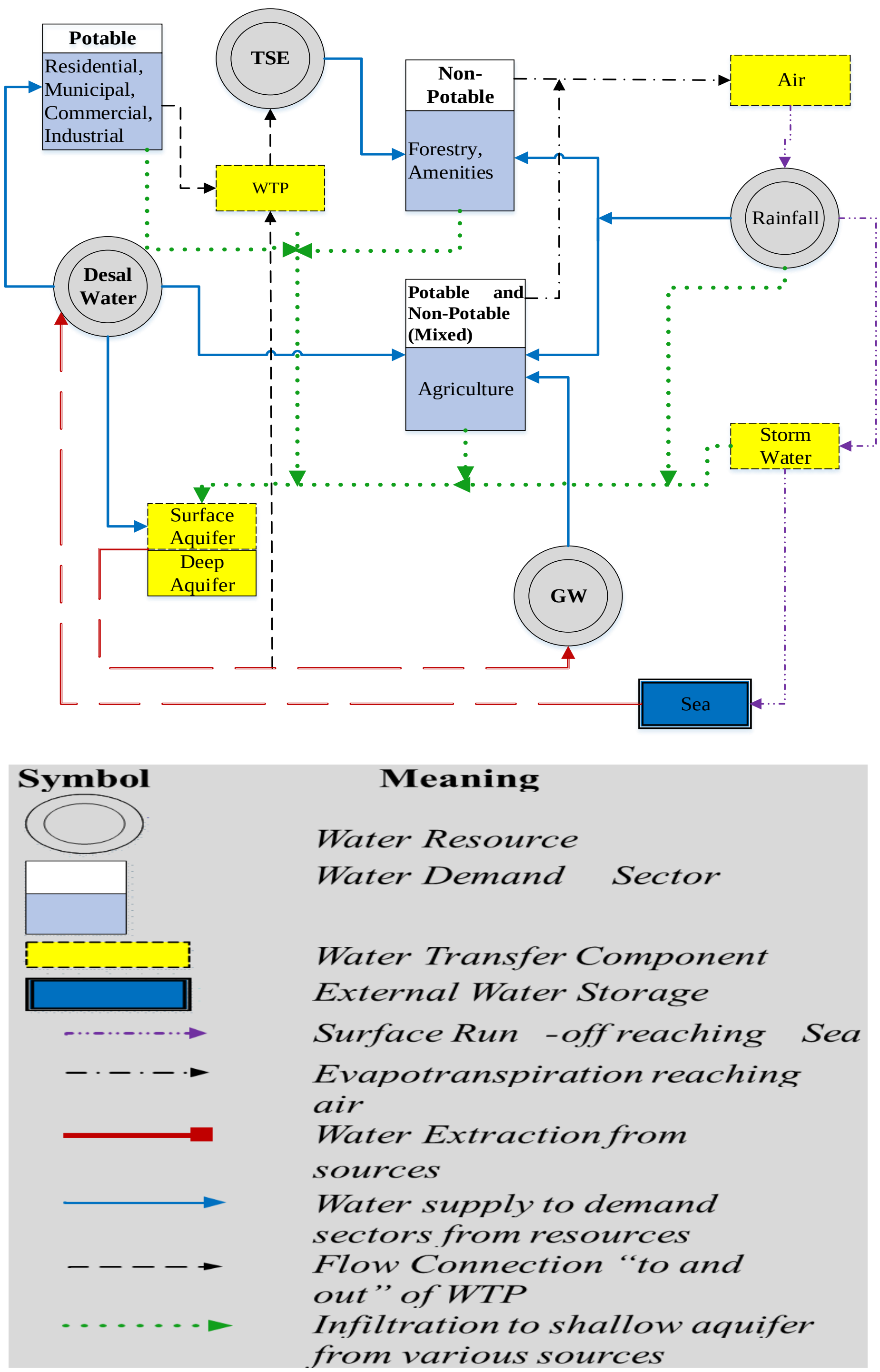


Figure 3: Schematic representation of water system of Abu Dhabi.

3.2.1 Mass Balance Equations for Water Supply Subsystem

This subsystem includes all of the main water supply sources presently in operation in the EAD to satisfy water demands. GW, DW, TS, and rainfall surface-runoff (RF_SR) are the four water supply sources in the model. The first three sources account for the majority of Abu Dhabi's water supply. According to (Statistics Centre - Abu Dhabi, 2018), GW provides approximately 62 percent of Abu Dhabi's water supply, with 30.5% coming from DW and 7.5% from TS. The average annual water supply was calculated using a mass balance equation that combined the supplies from all of these sources, as shown in equation (3.1).

$$WS_{Total} = GW_{Total} + DW_{Total} + TS_{Total} + RF\_SR_{Total}, \qquad (3.1)$$

where WS_{Total} is the total annual water supplied, GW_{Total} is total GW supply, DW_{Total} is DW supply, TS_{Total} is total TS supply, and RF_SR_{Total} is total surface-runoff from total rainfall (RF_{Total}).

3.2.1.1 Groundwater

In Abu Dhabi, GW is found in either shallow or deep aquifers, with shallow aquifers having a very low rainfall recharge. All GW users were established, and a mass balance equation based on GW extraction and consumption data was devised to account for the flow of water from the GW resource to different demand sectors. GW is used for irrigation in agricultural, woodland, and public amenities in the EAD. Equation (3.2) shows this.

$$GW_{Total} = GW_{A} + GW_{AM} + GW_{F}, \qquad (3.2)$$

where GW_A, GW_{AM}, and GW_F are the annual GW consumption by agriculture, amenities and forestry, respectively. GW_{Total} is the total annual GW abstraction.

3.2.1.2 Desalinated Water

DW has been established as the sole source of water for all potable demand industries, including domestic, urban, commercial, and industrial water. Based on surplus production, DW is also channeled to drainage lands and groundwater recharge. The EAD's DW generation and usage figures were obtained from the Abu Dhabi Water and Electricity Company's (ADWEC) official website (Abu Dhabi Water and Electricity Company, 2018). As a result, equation (3.3) was used to establish the mass balance for DW produced and consumed:

$$DW_{Total} = DW_A + DW_F + DW_{AM} + DW_R + DW_M + DW_C + DW_I + DW_{inf\text{-}SA} + DW_{AR\text{-}SA}, \qquad (3.3)$$

where DW_A, DW_F, DW_{AM}, DW_R, DW_M, DW_C, *and* DW_I, are DW consumption by agriculture, forestry, amenities, residential, municipal, commercial, and industrial sectors, respectively. $DW_{inf\text{-}SA}$ is the transmission and distribution losses and leakages. $DW_{AR\text{-}SA}$ is the DW supplied for artificial aquifer recharge.

3.2.1.3 Treated Sewage

In the EAD, TS stands for treated wastewater and is an alternative supply of water for non-potable purposes. It is made by treating wastewater from the domestic, commercial, municipal, and industrial sectors to a reusable quality at a WTP. For forestry and amenity irrigation, the EAD uses TS. Despite the fact that the TS generated is of sufficient quality for agricultural irrigation, it has yet to be used on a wide scale due to consumer adoption barriers. As a result, TS is mostly used in forestry and recreation. As a result, TS is only used for forestry and recreational purposes. Owing to capacity constraints in the TS distribution system, a portion of TS is currently discharged into the Arabian Gulf. The details of TS were collected from the Abu Dhabi Sewerage Services Company (ADSSC), (Statistics Centre - Abu Dhabi, 2018) and (Environment Agency - Abu Dhabi, 2014). The TS balance was calculated considering all these components and is represented as in equation (3.4):

$$TS_{Total} = TS_{AM} + TS_F + TS_{Sea}, \tag{3.4}$$

where TS_{Total} is the total annual TS production, while TS_{AM} and TS_F represent TS used in amenities and forestry, respectively. TS_{Sea} is the TS discharged into the sea.

3.2.1.4 Rainfall

The EAD, which is located in an arid area, receives very little rain, normally less than 100 mm per year (Environment Agency - Abu Dhabi, 2009a). As a result, rainfall is a minor source of water availability in the EAD. The mass balance of rainfall was calculated using its various components and is given by equation (3.5).

$$RF\_SR_{Total} = RF_{Total} - RF_{SDS} - RF_{inf\text{-}SA} - RF_{E\text{-}OA}, \tag{3.5}$$

where RF_SR_{Total} is the surface-runoff that comprises RF_SR_A, RF_SR_F, and RF_SR_{AM} components that can be made available to agriculture, forestry, and amenities sectors, respectively. RF_{SDS} is the rainfall component which is discharged into the sea through storm water collection system present in Abu Dhabi. $RF_{inf\text{-}SA}$ is the portion that reaches shallow aquifer through infiltration. $RF_{E\text{-}OA}$ is the evaporation components which is lost into atmosphere.

3.2.2 Mass Balance Equations for Water Demand Subsystem

Water demand subsystem comprises all the water demand sectors, which are the consumers of water in the EAD. In the model, there are seven water demand sectors identified in the EAD: residential, municipal, commercial, industrial, amenities, agricultural, and forestry. Depending on the water supplies on which they depend, all of these demand sectors are categorized as either potable or non-potable. Potable demand industries are those that depend solely on the DW for their water supply. Non-potable demand sectors depend on all of the non-potable outlets, such as GW, TS, or RF_SR, as well as DW if available.

3.2.2.1 Residential

The residential sector is a potable demand sector, with people using water both indoors and outdoors. In the EAD, residential water use is twice that of certain developing countries. This is due to subsidized water tariffs, which are affected by outdoor water uses, especially for garden irrigation. The residential consumption is given in equation (3.6).

$$\mathrm{R}_{\,Consumption\_Total} = DW_R, \tag{3.6}$$

where $R_{\,Consumption\_Total}$ is the total annual residential consumption and is supplied by DW.

3.2.2.2 Municipal

The water demand of all governmental offices and relevant agencies, such as ambassador, administration, police, educational, mosques, and so on, is referred to as municipal water demand. Only DW is used to meet municipal water demand, as seen in equation (3.7):

$$M_{Consumption\_Total} = DW_M, \tag{3.7}$$

where $M_{Consumption\_Total}$ is the total annual municipal consumption.

3.2.2.3 Commercial

The commercial sector includes properties like hotels, restaurants, cafeterias, car washes, and laundries. The source of water for this demand sector is DW, and the consumption is given by equation (3.8):

$$C_{Consumption\_Total} = DW_C, \tag{3.8}$$

where $C_{Consumption\_Total}$ is the total annual commercial consumption and is supplied by DW.

3.2.2.4 Industrial

The water available for various industrial operations is referred to as industrial demand. Oil and gas, petrochemical plants, mining, engineering, and other industries are main industrial activities in EAD. Water is mostly used in these industries for processing, cooling, and cleaning. Since there is very little data on industrial water use, the analysis was complicated. The amount of water used in the industrial sector, on the other hand, was found to be very small, accounting for only about 2% of the DW generated in the EAD (Environment Agency - Abu Dhabi, 2014; Statistics Centre - Abu Dhabi, 2015, 2018). Industrial consumption is given by equation (3.9):

$$I_{Consumption\_Total} = DW_I, \tag{3.9}$$

where $I_{Consumption\_Total}$ is the total industrial consumption and is supplied by DW.

3.2.2.5 Amenities

Public parks, landscapes, gardens, recreational areas, and roadside planting where water is supplied as irrigation water are also included in the amenities sector. According to (Environment Agency - Abu Dhabi, 2018), public realm facilities (such as parks, gardens, recreational areas, and roadside planting) accounted for around 10% of overall water use. The amenities industry is reliant on TS and GW. If DW is accessible, however, it is also provided for amenities. Equation (3.10) is used to construct the amenities consumption equation:

$$AM_{Consumption\_Total} = GW_{AM} + DW_{AM} + TS_{AM} + RF\_SR_{AM}, \quad (3.10)$$

where $AM_{Consumption\_Total}$ is the total annual amenities consumption. GW_{AM}, DW_{AM}, TS_{AM} and RF_SR_{AM} are water supply to amenities from GW, DW, TS, and surface-runoff, respectively.

3.2.2.6 Agricultural

Agriculture (A) is the EAD's most water-intensive industry. The irrigational water usage in the planted region of the three major crop types: fruit trees, field crops, and vegetable crops is referred to as agricultural demand. GW (non-potable) extraction and DW (potable) supply meet agriculture need. For agricultural purposes, there is no metered measurement of GW withdrawal. In the absence of precise metered results, the mass balance was calculated using approximate values recorded by (Environment Agency - Abu Dhabi, 2009a, 2014). Agricultural consumption is shown by equation (3.11).

$$A_{Consumption\_Total} = GW_A + DW_A + RF\_SR_A, \quad (3.11)$$

where $A_{Consumption\_Total}$ is the total annual agricultural irrigation. GW_A, DW_A and RF_SR_A are water supply to agriculture from GW, DW, and surface-runoff, respectively.

3.2.2.7 Forestry

All forests owned by the EAD municipality or privately managed in the EAD are included in the forestry sector. They account for about 11% of global water intake (Environment Agency - Abu Dhabi, 2009a, 2014). Forestry water demand is mostly dependent on non-potable water supplies, such as GW and TS. Equation (3.12) gives the forestry consumption:

$$F_{Consumption\_Total} = GW_F + DW_F + RF\_SR_F, \quad (3.12)$$

where $F_{Consumption\_Total}$ is the total consumption of forestry sector. GW_F, DW_F and RF_SR_F are water supply to agriculture from GW, DW, and surface-runoff, respectively.

3.2.3 Mass Balance Equations for Water Transfer Subsystem

The transitional storage of water supplies is known as this subsystem. Between the demand and resource subsystems, they serve as intermediate storage or carriers. In this analysis, three such systems were defined as being essential for mass balance calculations in the EAD. The Shallow Aquifers (SA), the wastewater treatment system (WTS) that collects and treats wastewater formed in the EAD, and the Storm Drainage System (SDS) that collects and discharges stormwater to the sea are the three. The water from SA percolates to the Deep Aquifer (DA), the treated wastewater from WTS becomes a source of water (i.e, TS), and the SDS water becomes a part of the seawater.

3.2.3.1 Shallow Aquifer System

The GW is stored in shallow aquifers, from which water is extracted by boreholes. Near Al Ain in the Al Ain Region and Liwa in the Western Region, the EAD has groundwater aquifers. The Liwa Aquifer includes 'fossilized' water from the last ice age, which occurred 10,000 years ago. Due to precipitation in the neighboring Hajar Mountains, the aquifers in the Al Ain Region have seen more periodic recharging. At the current rate of demand, the country is depleting underground water supplies 20 times faster than rainfall can replenish them (Environment Agency - Abu Dhabi, 2014). The water used for the irrigation reaches back to the aquifer system as a component, termed as infiltration water, from sectors like agriculture ($A_{inf\text{-}SA}$), forestry ($F_{inf\text{-}SA}$), and amenities ($Am_{inf\text{-}SA}$). Aside from that, the EAD is building a man-made aquifer in Liwa, Western region, which will house a seven-million-gallon underground water storage facility for serious emergency use (Environment Agency - Abu Dhabi, 2018). All of these factors were taken into consideration when calculating the total inflow into the aquifer, which is expressed by equation (3.13).

$$SA_{Total\text{-}inflow} = A_{inf\text{-}SA} + F_{inf\text{-}SA} + Am_{inf\text{-}SA} + R_{inf\text{-}SA} + DW_{inf\text{-}SA} + DW_{AR\text{-}SA} + RF_{inf\text{-}SA} + DA_{inf\text{-}SA} + GWE_{inf\text{-}SA}, \quad (3.13)$$

where $SA_{Total\text{-}inflow}$ is the total recharge into the SA, while $A_{inf\text{-}SA}$, $F_{inf\text{-}SA}$, $Am_{inf\text{-}SA}$, $R_{inf\text{-}SA}$, $DW_{AR\text{-}SA}$, $RF_{inf\text{-}SA}$, $DA_{inf\text{-}SA}$, and $GWE_{inf\text{-}SA}$ represent the infiltration from agriculture, forestry, residential, amenities, municipal, commercial, industrial, leakage of DW, artificial recharge, natural rainfall recharge, inflow from a deep aquifer, and external aquifer inflow, respectively.

3.2.3.2 Wastewater Treatment Plants

Wastewater treatment plants are the intermediate step in the conversion of wastewater to functional treated sewage. The ADSSC manages the EAD's well-developed wastewater collection and treatment network. ADSSC wastewater treatment plants are geographically situated in Abu Dhabi, Al Ain, and a few other population centers in the Western region. All WTPs process wastewater to a tertiary level in order to generate TS, which is mainly used for landscape irrigation. However, only about 52% of reclaimed water is used for agriculture or other uses, while the remaining 48% is released into the environment (Environment Agency - Abu Dhabi, 2014; Statistics Centre - Abu Dhabi, 2018). Equation (3.14), which was established by taking into account all wastewater components in the EAD, was used to determine the mass balance of the WTPs.

$$WTP_{Total\text{-}inflow} = R_{WTP} + C_{WTP} + M_{WTP} + I_{WTP} + inf_{WTP} \tag{3.14}$$

where $WTP_{Total\text{-}inflow}$ is total WTP inflow, while R_{WTP}, C_{WTP}, M_{WTP} and I_{WTP} are the WW from residential, commercial, municipal, and industrial sectors, respectively, reaching the WTP. inf_{WTP} is the GW infiltration to sewer systems.

3.2.3.3 Storm Drainage System

The SDS collects and discharges stormwater to the sea from rainfalls that occur in the EAD's city zones. As a result, it acts as a transitional system for rainfall in the emirate. The SDS is also used for subsurface drainage in the emirate to manage the GW level by draining excess subsurface water when the maximum level is reached. In Abu Dhabi, GW is frequently encountered in construction projects, and needs to be accounted for and dealt with during construction in order to complete the project successfully (Abu Dhabi City Municipality, 2014). The GW pumped out from building sites in Abu Dhabi's coastal regions due to high GW levels is referred to as "dewatering water". The SDS has been taken into account in mass balance estimates, but in the absence of a continuous calculated value, data was gathered from members of government agencies through workshops, interviews, and meetings to address interdependencies and their effect on the Abu Dhabi water system, as well as from the EAD's published paper on the SDS (Abu Dhabi City Municipality, 2015), provided the basis for estimating the SDS data. This is given by equation (3.15).

$$SDS_{Total\text{-}inflow} = RF_{SDS} + SA_{inf\_SDS}, \quad (3.15)$$

where $SA_{inf-SDS}$ is the infiltration from SA into the SDS system. $SDS_{Total-Inflow}$ represents the total water that is discharged into sea through storm water collection system.

3.3 Development of Dynamic Water Budget Model

The conceptual water balance model was then used to create a dynamic model to investigate the supply-demand balance in the Emirate of Abu Dhabi over time. The ADWBM is a dynamic model that was created to produce simulation results for yearly water budgeting. The ADWBM is designed with three main modules: 1) a demographic forecast to forecast yearly population of nationals and expats separately based on population growth rates, 2) a water demand forecast to forecast sector-wise yearly water demands based on factors, and 3) a water supply forecast to forecast yearly water resource availability. The dynamic model uses a series of parameters, variables, and operating laws to operate the water balance model for future years. The operating rules include things like how much of a given water source can be supplied to each market area, how much of a given water source can be supplied, how much of a given water source can be supplied, how much of a given water source can be supplied, how much of a given water source can be supplied, and so on. These rules were used to produce annual water balances from model demand and supply projections. Figure 4 depicts a schematic representation of the ADWBM, whereas Table 1 lists several of the model's main parameters.

Table 1: Sample values and data source of key model parameters

Model Components	**Sample**	**Unit**	**Sources**
GW reserve	220	BCM	(RTI International, 2015)
GW extraction rate	2217	MCM/yr	(Environment Agency - Abu Dhabi, 2014)
GW inflow from external aquifers	90-140	MCM/yr	(Environment Agency - Abu Dhabi, 2014)
GW recharge from rainfall	24 -30.9	MCM/yr	(Environment Agency - Abu Dhabi, 2009a)
Surface-runoff	7.6	MCM/yr	Environment Agency - Abu Dhabi, 2009a)
Leaching rate	5-20	%	(Environment Agency - Abu Dhabi, 2009b)
DW Plant Capacities	1280 (2014)	MCM/yr	(Abu Dhabi Water and Electricity Company, 2018)
DW transmission and distribution loss and leakage	8-10	%	Environment Agency - Abu Dhabi, 2009a)
Evaporation rate	5.3- 5.5	mm/day	(Environment Agency - Abu Dhabi, 2009a; Terrestrial Environment Research Centre, 2015)
Evapotranspiration rate	6.85- 8.2	mm/day	(Elhakeem Abubaker et al., 2015)
WTP Capacity	408	MCM/yr	(Statistics Centre - Abu Dhabi, 2015, 2018)
TS use data	284	MCM/yr	(Statistics Centre - Abu Dhabi, 2015, 2018)

Table 1: Sample values and data source of key model parameters (Continued)

Model	Sample	Unit	Sources
Agricultural consumption data	1716	MCM/yr	(Environment Agency - Abu Dhabi, 2009a; Statistics Centre - Abu Dhabi, 2015)
Forestry consumption data	375	MCM/yr	(Environment Agency - Abu Dhabi, 2009a; RTI International, 2015; Statistics Centre - Abu Dhabi, 2015)
Amenities Consumption data	112	MCM/yr	(Environment Agency - Abu Dhabi, 2009a; Statistics Centre - Abu Dhabi, 2015, 2018)
Water requirements for crops	603.7 - 2040.7	liters/m^2/yr	(Environment Agency - Abu Dhabi, 2009a)
Water requirements for	156 -221	liters/m^2/yr	(RTI International, 2015)
Amenities water requirement	6.5 – 10.2	liters/m^2/day	(RTI International, 2009b)
Irrigation efficiency	54- 90	%	(Environment Agency - Abu Dhabi, 2009a, 2009b; RTI International, 2009c)
Offices consumption rate	30.3 -56.6	liters/emp./day	(RTI International, 2009a)
Retail consumption rate	9.9 – 47	liters/emp./day	(RTI International, 2009a)
Restaurant consumption rate	9.5 – 30.8	liters/m^2/yr	(RTI International, 2009a)
Hotel consumption rate	130 - 501	liters/room/day	(RTI International, 2009a)
Consumption rate in-bay vehicle washing	250-300	liters/vehicle	(RTI International, 2009a)
Consumption rate by visitors at amenities	3.52-7.04	liters/visitor/day	(RTI International, 2009c)

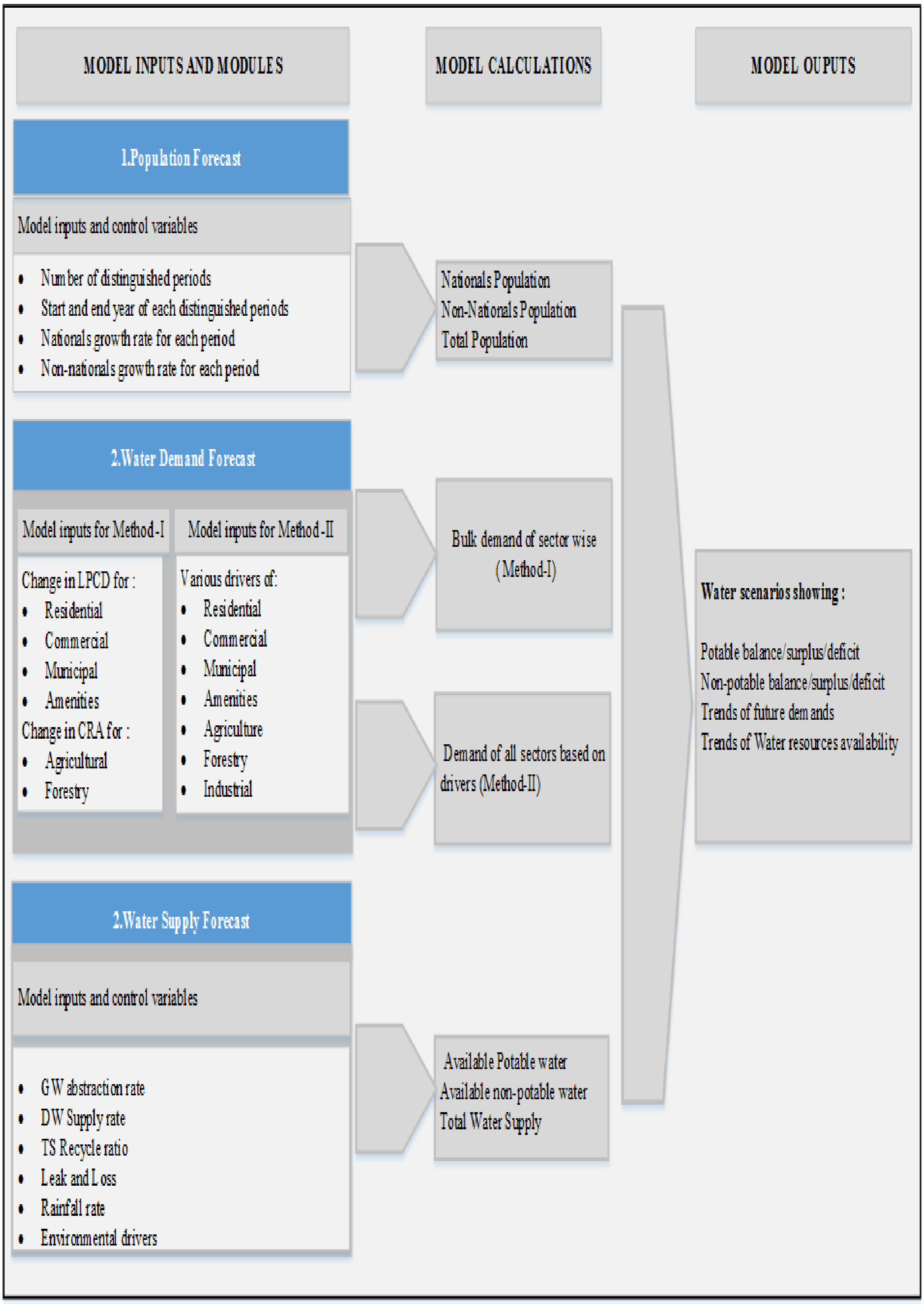


Figure 4: Schematic representation of dynamic model (ADWBM)

3.3.1 Population Forecast Module

Population is identified as the primary driver of water use in the EAD in this study. The study focused on identifying different parameters, known as "population drivers", that can accurately forecast Abu Dhabi's potential population. The study shows that the Abu Dhabi population follows entirely distinct growth patterns for nationals and non-nationals. Furthermore, the growth rate will not be constant over the planning period until 2050, as the Abu Dhabi government has set visions for 2020, 2030, and 2050. Each distinguished period follows different growth rates with different values for nationals and non-nationals. Each of them is a population driver. The model is planned to estimate the population of both nations and non-nationals until the year 2050 using these drivers.

3.3.2 Water Supply Forecast Module

Each water resource's potential supply is determined by a variety of climatic and environmental factors, as well as government policies focused on visions and sustainability. The net annual recharge rate (MCM/yr), net external flow to SA (MCM/yr), and abstraction rates (MCM/yr) determine GW availability. For a sustainable future, government policy determines the annual abstraction thresholds that are permissible. As a result, in order to forecast potential GW conditions, the model is configured to satisfy three parameters: net annual recharge rate, net external flow to the SA, and abstraction limits. The baseline values used in the model are 200 BCM for the current GW reserve, 110 MCM/yr for net recharge rate, 0 MCM/yr for net external flow to SA, and 2,200 MCM/yr for current GW abstraction rate, based on the most recent approximate values accessible.

Government decisions will determine the conditions of potential desalination. The two main parameters related to DW in the model are "annual desalination capacity" and "leakage and loss." Based on current standards, 10% is considered the reference value for "leakage and damage" (Environment Agency - Abu Dhabi, 2014).

The supply of TS is determined by the amount of potable water consumed and the amount of wastewater produced. The parameters used in the model to predict future TS generation are the Potable Water Return-ratio (*PWR*), infiltration rate to sewer pipe, and Recycle Ratio of TS (RR_{TS}). PWR is defined as the ratio of wastewater reaching at the inlets of WTP to the total potable water consumption. RR_{TS} is dependent on the quality of the water produced and the capacity of the TS distribution system. Data from related agencies and operators of wastewater treatment plants and pumping facilities in the EAD are baseline parameter values into the model.

Surface runoff, infiltration rate, and evaporation rate are the main components that determine the availability of water from rainfall.

All forecasting data are gathered from a variety of databases, including historical documents, technical journals, and official and government publications.

3.3.3 Water Demand Forecast Module

To forecast water demands, the ADWBM is built using two approaches. Method-I is a straightforward method for forecasting a sector's bulk demand using a single coefficient. The determinants contributing to or driving consumption in a market, referred to as demand drivers in Method-II, serve as the foundation for demand forecasting.

3.3.3.1 Method-I for Water Demand Forecast

Water demand functions were created to relate a sector's bulk demand to a unit consumption rate. The Per-Capita–Demand (PCD) coefficient is used to model water demands by population-dependent sectors in liters per capita per day (lpcd). It is clear that the population has a strong association with residential demands; this relationship also persists with municipal, commercial and amenities demands. As seen in equation (3.16), water demand is determined as a function of the total population "P" and the "PCD" for each sector. The PCD for each population-dependent demand market was calculated using historical data from the EAD on water use by various sectors.

$$D_{BPD} = P*PCD_{PD}*365*10^{-9}, \qquad (3.16)$$

where, D_{BPD} is the annual bulk demand of population dependent sectors expressed in MCM/yr, P is the forecasted population, and PCD_{PD} is the *lpcd* determined for respective population related sectors.

The water demand for agricultural and forestry sectors are determined by the area under irrigation. The demand prediction was based on the unit usage rates per area of these industries. he “Consumption Rate per Unit Area” (CPA) for the agriculture and forestry sectors was estimated using historical data on yearly consumption by these sectors and area under irrigation for respective sectors. Equation (3.17) gives the demands of these two sectors:

$$D_{BNPD} = A_{Di} * CPA_{Di}*365*10^{-9}, \qquad (3.17)$$

Where D_{BNPD} is the annual bulk demand of sectors (A and F) in MCM/yr, A_{Di} is the irrigated area in m^2 under a respective sectors and CPA_{Di} is consumption rate of respective sector in liters/m^2/day.

Therefore, Method-I in ADWBM is designed to forecast demand based on *PCD* for population dependent sectors and *CPA* for population independent irrigation demands.

3.3.3.2 Method-II for Water Demand Forecast

In Method-II, components leading to or driving consumption of a sector, referred to as demand drivers, are the core of demand forecasting. Several drivers exist for each demand sector, and their details were needed to enable a better estimation (projection) of each type of demand as per its categorized drivers. Because of its comprehensiveness and degree of aggregation, this form of modeling is favored, since it produces more inclusive estimates of sub-sectors within a sector and, as a result, better outcomes for future planning. The equations to organize water demand forecasting based on drivers were derived by making necessary adjustments to the equations based on the experience of forecasting for the majority of United Kingdom water companies over the last three decades. They were updated to represent Abu Dhabi requirements and were derived by making necessary adjustments to the equations (3.16). Therefore, for Method-II equations, it entailed determining the demand drivers for each sector in Abu Dhabi and formulating demand equations based on them.

(a) Residential:

Residential usage in EAD was broken down into five components (drivers) that corresponded to three different categories of housing: shabiyats, villas, and flats. Shabiyats are one-story low-income family homes with an unknown number of occupants. Equations (3.18) – (3.23) describe the equations formed to structure residential water demands in the EAD, based on these drivers.

Since Abu Dhabi's population is divided into two distinct categories, nationals (n) and non-nationals (nn), the PCD-based demand equation (3.16) was modified to reflect this shift in residential demand (3.18). This was done to forecast residential demand for both nationals and non-nationals.

$$D_R = (P_n * PCD_{R\text{-}n} + P_{nn} * PCD_{R\text{-}nn}) * 365 * 10^{-9}, \qquad (3.18)$$

where P_n and P_{nn} are nationals' and non-nationals' population, respectively. $PCD_{R\text{-}n}$ and $PCD_{R\text{-}nn}$ are their respective consumption rates in *lpcd*.

However, the utilization patterns in equation (3.18) is calculated either by aggregate data (population and supply to residences) or from sampling or surveys of household numbers. Metered data, which is obtained at the household level, is the simplest data on direct use. The overall residential demand was calculated from the EAD's aggregation of use by household types, where N_j is the number of households of type *j*. Then, equation (3.19) is obtained as follows:

$$D_R = \sum_0^j N_j \, CR_j * 365 * 10^{-9}, \qquad (3.20)$$

in which CR_j is the consumption rate by *j* type households.

It was further changed as equation (3.20) by considering nationals and non-nationals as separate modeling components in various household groups.

$$D_R = \left(\sum_0^j (N_{jn} \, CR_{jn}) + \sum_0^j (N_{jnn} \, CR_{jnn})\right) * 365 * 10^{-9}, \qquad (3.21)$$

where N_{jn} and N_{jnn} are the number of j type household occupied by nationals and non-nationals, respectively. CR_{jn} and CR_{jnn} are consumption rate by j type households occupied by nationals and non-nationals, respectively.

Finally, understanding the need to distinguish indoor consumption "i'' from outdoor consumption "x'' at each household type resulted in equation (3.21), which is the residential demand equation, which includes all of the residential sector's drivers.

$$D_R = (\sum_0^j N_{jn} (CR_{jni} + CR_{jnx}) + \sum_0^j N_{jnn} (CR_{jnni} + CR_{jnnx})) *365*10^{-9}, \qquad (3.22)$$

(b) Municipal:

Government offices, hospitals, schools, mosques, and visits to recreational facilities were listed as the primary drivers of municipal demand in the EAD. The estimated municipal demand using Method-II was based on the unit consumption rates for these drivers per head or per area, whichever is applicable. In equation (3.22), the municipal demand equation based on these drivers is given.

$$D_M = (Ar_{gov\text{-}off} * CR_{M\text{-}gov\text{-}emp} + N_{mq}*CR_{M\text{-}mq} + N_{hs\text{-}bed} *CR_{M\text{-}hs}$$

$$+ CR_{M\text{-}sc}*N_{st} + N_{vs}* CR_{M\text{-}vs}) *365*10^{-9}, \qquad (3.23)$$

where $N_{hs\text{-}bed}$, N_{mq}, N_{st} and N_{vs} are total number of hospital beds, mosques, students, and visitors to recreational facilities. $Ar_{gov\text{-}off}$ is the gross floor area of governmental offices in m^2. The other parameters (consumption rates) in the equation are: $CR_{M\text{-}gov\text{-}off}$ - liters/m^2 /day, $CR_{M\text{-}mq}$ - liters/m^2/day, $CR_{M\text{-}hs}$ - liters/hospital bed/day, $CR_{M\text{-}sc}$ - liters/m^2/day, and $CR_{M\text{-}vs}$ - liters/visitor/day.

(c) Commercial:

Hotels, restaurants, cafeterias, car washes, and laundries were the major demand drivers of commercial sector in the EAD. The demand equation was therefore developed as in equation (3.24):

$$D_C = (N_{off\text{-}emp} * CR_{C\text{-}off} + N_{ret\text{-}emp} * CR_{C\text{-}ret} + Ar_{res} * CR_{C\text{-}res} + N_{hr} * O_{hr} * CR_{C\text{-}hr} + N_{cw} * CR_{C\text{-}cw}) * 365 * 10^{-9}, \quad (3.25)$$

where, D_C – total annual commercial demand in MCM/yr, $N_{off\text{-}emp}$ – number of office employees, $CR_{off\text{-}emp}$ – consumption rate per office employee in l/employee/day, $N_{ret\text{-}emp}$ – number of retails employees, $CR_{C\text{-}ret}$ - consumption rate per retail employee in l/employee/day, Ar_{res} - gross area of restaurants in m^2, $CR_{c\text{-}res}$ – consumption rate per floor area in l/m^2/day, N_{hr} – total number of hotel rooms available for occupancy, $CR_{C\text{-}hr}$ - consumption rate per hotel room occupied l/occupied room/day, O_{hr} - occupancy rate of hotel rooms, N_{cw} – total number of all vehicle washes in all car wash units, and $CR_{C\text{-}cw}$ – consumption rate per vehicle wash in liters/vehicle.

(d) Industrial:

The forecast equation in the model has been developed to quantify potential industrial demands based on the shift in rate of annual industrial consumption, using 20 MCM/yr as the base value, since the development of industries in EAD is influenced by governmental policies and visions. The rate of transition, whether it is a rise or a decline, is determined by government economic policies.

(e) Amenities:

For two types of lands: parks and ornamental fields, main drivers of amenities demand are amenities areas and irrigation efficiency. Using Method-II, equation (3.24) was created to predict the amenities water demand.

$$D_{Am}=(\sum (AmR_k*Ar_k) /IE_{Am} + L_r) *10^{-6}, \quad (3.26)$$

in which D_{Am} is the annual water demand of amenities in MCM/yr, *k*- type of amenities, AmR_k is *y*early amenities water requirement per unit area for type *k* amenities, Ar_k is the irrigated area of *k* type amenities, IE_{Am} is the irrigation efficiency for landscape irrigation and L_r is the leaching requirement.

(f) Agricultural:

Method-II in the model forecasts the water demand of the agricultural sector based on drivers such as cultivated area of each type of crop, irrigation requirements of each crop type, irrigation efficiency, and leaching requirements of agricultural lands. As a result, the agricultural demand equation (3.25) was formed as follows:

$$D_A = (\sum (CWR_i * Ar_i) / IE_A + L_r) *10^{-6}, \quad (3.27)$$

in which D_A is total annual water demand of agriculture sector, CWR_i is the yearly crop water requirement for type *i* crop per unit area, Ar_i is the area under cultivation for *i* type crop, IE_A is the irrigation efficiency, and L_r is the leaching requirement.

(g) Forestry**:**

The forest area under irrigation, consumption rates in the eastern and western regions of the EAD, and irrigation efficiency influence the forestry sector's irrigation demand. As a result, the demand equation for the forestry sector was formed as follows:

$$D_F = (\sum(FWR_r * Ar_r) / IE_F + L_r) * 10^{-6}, \quad (3.28)$$

in which D_F is the total annual water demand of forest, FWR_r *is y*early forestry requirement per unit area for region *r*, *r* refers two regions where forests are located, Ar_r is the irrigated forest area in region *r*, IE_F is the irrigation efficiency and L_r is the leaching requirement.

3.4 Model Calibration and Validation

To ensure that the forecasting approach used is suitable, the model needs to be calibrated and validated (Sterman, 2000). In this analysis, calibration was carried out, which included adjusting and optimizing different model parameters in order to maximize simulation performance. Demands of all sectors and TS availability (based on wastewater forecast) are among the forecasted model outputs. The calibration primarily centered on adjusting and optimizing the values of the parameters (drivers) used in the model forecast.

The parameters were adjusted until the observed and simulated values were in fair statistical agreement. Indoor consumption rate in shabiyat, outdoor consumption rate in shabiyat; indoor consumption rate in villas, outdoor consumption rate in villas, and consumption rate in flats, for example, were used to calibrate residential demand. Calibration was also carried out for non-potable sectors by changing their respective drivers. The calibration for the TS was focused on modifying two parameters: the potable water return ratio and the penetration rate into the sewage system, as the model forecasts the overall wastewater that would be required for TS production. Table 2 summarizes the parameter values that have been optimized and calibrated. This should be seen as a starting point for creating water simulations for Abu Dhabi's water vision.

Table 2: Optimized values of parameters after calibration

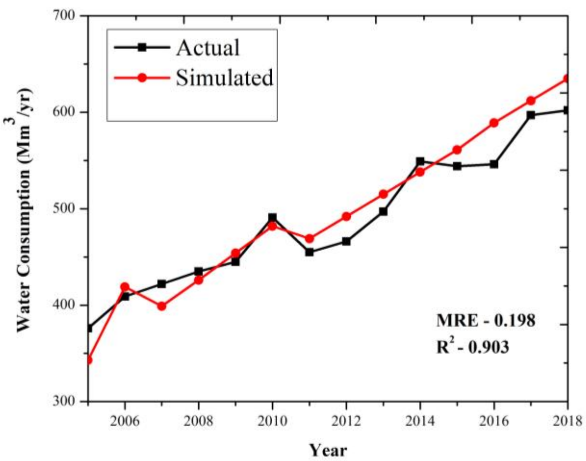
Sector	Drivers	Value (unit)
Residential	Shabiyat Indoor	320 lpcd
	Shabiyat Outdoor	1280 lpcd
	Villas Indoor	240 lpcd
	Villas Outdoor	960 lpcd
	Flats	400 lpcd
Commercial	Office Employees	56 liters/emp./day
	Retail Employees	47 liters/emp./day
	Restaurants	30 l/m^2/day
	Hotel Rooms	330 liters/room/day
	Carwash	284 liters/vehicle
Municipal	Government offices	2.2 liters/m^2/day
	Mosques	12,774 liters/mosque/day
	Schools	34 liters/student/day
	Hospitals	259 liters/bed/day
Agricultural	Water requirement for fruit crop	2040.7 liters/m^2/yr
	Water requirement for field crop	603.7 liters/m^2/yr
	Water requirement for vegetable crop	605.6 liters/m^2/yr
	Irrigation efficiency (%)	54
Forestry	Water requirement - Western Region	156 liters/m^2/yr
	Water requirement - Eastern Region	221 liters/m^2/yr
	Irrigation efficiency for forest land (%)	56
Amenities	Water requirement for irrigation	9.6 liters/m^2/day
	Irrigation efficiency for amenities (%)	54
TS	Potable water return ratio (PWR)	0.286
	Infiltration rate to sewer line	10%

The calibration period was from 2005 to 2014, while the validation period was from 2015 to 2018. The output was evaluated using statistical parameters such as the Mean of Relative Error (MRE) and coefficient of determination (R^2). The relative variations between the model and real values were calculated by MRE. R^2, a number between 0 and 1, was used to calculate the model's accuracy by describing the collinearity between the model and real values. The closer the value is to 1, the more the model simulates the device.

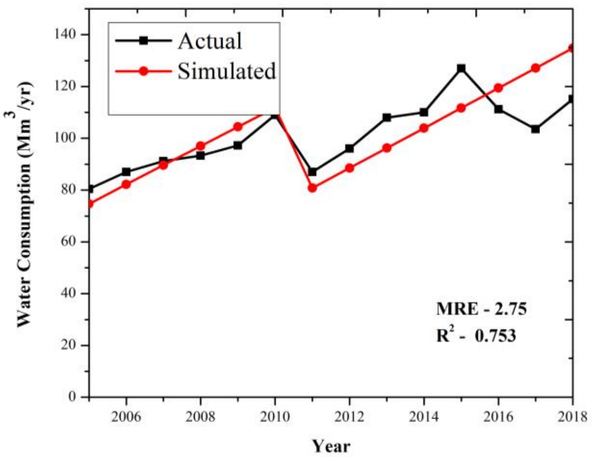
The analysis of performance using the aforementioned statistical metrics are presented in Table 3. It shows that MRE ranges from -9.89 to 0.198%, and R^2 is between 0.661 - 0.97. The plots (Figure 5) show that the model was able to reproduce the results that fit well with the historical values. Few sectors showed a relatively low value for the R^2. These comparatively low values are due to inaccuracies in drivers' data for these sectors, which when updated could improve the model prediction. However, a value of above 0.6 for R^2 is considered as satisfactory (D. N. Moriasi et al., 2007). Therefore, the overall results of the calibration and validation showed that the model is able to reproduce the water demand and supply trends adequately well and is suitable for use.

Table 3: Statistical analysis of calibration performance

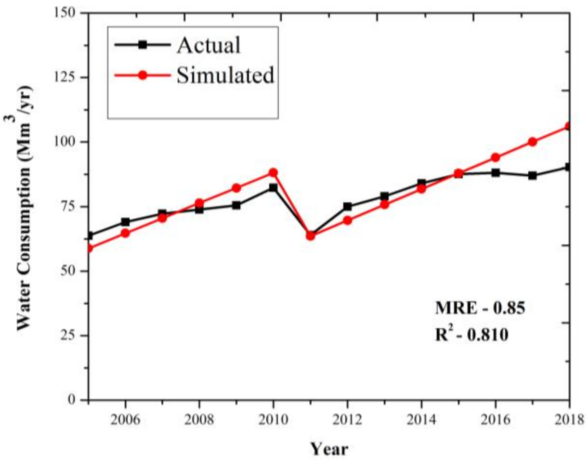
Model Parameters	**Statistical Analysis Values**	
	MRE %	**R^2**
Agricultural Demand	6.75	0.661
Residential Demand	0.198	0.903
Municipal Demand	2.75	0.753
Commercial Demand	0.85	0.810
Forestry Demand	4.35	0.798
Amenities Demand	-4.09	0.746
TS Availability	-9.89	0.971



(a) Residential demand

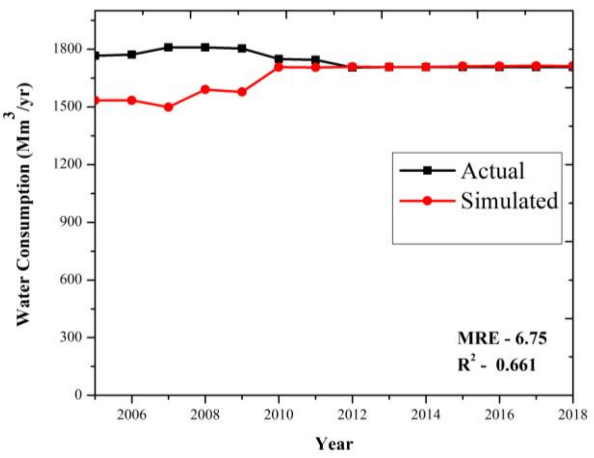


(b) Municipal demand

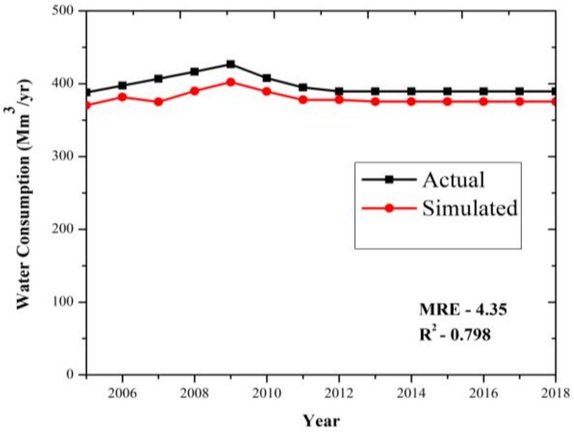


(b) Commercial demand

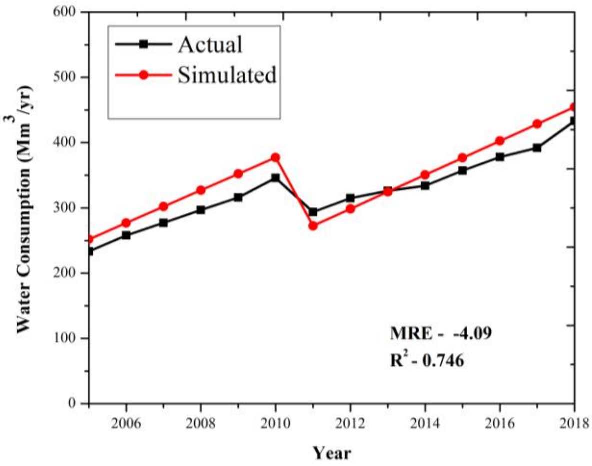
Figure 5: Comparison of simulated results using drivers based Method-II and historical (actual) data



(d) Agricultural demand

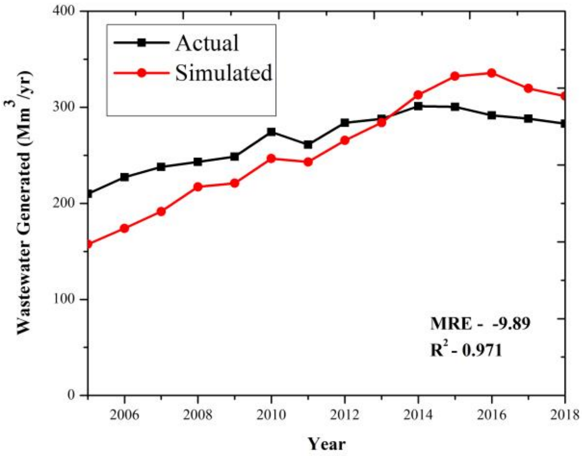


(e) Forestry demand



(f) Amenities demand

Figure 5: Comparison of simulated results using drivers based Method-II and historical (actual) data (Continued)



(g) Wastewater generation

Figure 5: Comparison of simulated results using drivers based Method-II and historical (actual) data (Continued)

3.5 Chapter Summary

This study produced a numerical tool to project as accurate figures as possible for water supply-and-demand in the EAD until 2050 for planning and accommodating actions needed to eliminate the potential shortage. This chapter explains the methodology of modelling of ADWBMC. The development of conceptual water balance model, modelling of mass balance equations, and forecast equations based on drivers are discussed. At the end, this chapter explains the working of the model, and also details the calibration and validation procedure used to optimize and finalize the parameters of the model. All the symbols in the model and their description are given in Table 4.

Table 4: Model symbols used and their descriptions

Symbols	Description
BCM	Billion cubic meter
MCM/yr	Million cubic meter per year
BCM	Billion cubic meter
WS_{Total}	Total annual water supply
GW_{Total}	The total annual supply from GW
DW_{Total}	Total annual supply from DW
TS_{Total}	Total annual supply from TS
RF_{Total}	Total annual RF
GW_{A}	Annual Groundwater consumption by agriculture
GW_{AM}	Annual Groundwater consumption by amenities
GW_{F}	Annual Groundwater consumption by forestry
DW_{A}	Annual Desalinated water consumption by agriculture
DW_{F}	Annual Desalinated water consumption by forestry
DW_{AM}	Annual Desalinated water consumption by amenities
DW_{R}	Annual Desalinated water consumption by residential
DW_{M}	Annual Desalinated water consumption by municipal
DW_{C}	Annual Desalinated water consumption by commercial
DW_{I}	Annual Desalinated water consumption by industrial
$DW_{AR\text{-}SA}$	Annual Artificial recharge to shallow aquifer
TS_{Total}	Total annual reusable TS produced
TS_{AM}	Annual TS consumption by amenities
TS_{F}	Annual TS consumption by forestry
TS_{Sea}	Annual TS discharged into sea
RF_SR_{Total}	Total annual surface-runoff
RF_{SDS}	Rainfall component reaching storm drainage system
$RF_{inf\text{-}SA}$	Rainfall infiltrated to shallow aquifer
$RF_{E\text{-}OA}$	Evaporation components of rainfall received

Table 4: Model symbols used and their descriptions (Continued)

Symbols	**Description**
PWR	Potable water return ratio
RR_{TS}	Recycle ratio of produced TS
WTP	Wastewater treatment plants
P	Population
PCD_R	Per capita consumption per day for residential demand
D_R	Residential demand
P_n	Nationals' population
$PCD_{R\text{-}n}$	Nationals' per capita consumption per day for residential
P_{nn}	Non-nationals' population
$PCD_{R\text{-}nn}$	Non-Nationals' per capita consumption per day for residential demand
Nj	Number of *j* type households
CRj	Consumption rate by *j* type households
$CRjn$	Consumption rate by *j* type household by nationals
$CRjnn$	Consumption rate by *j* type household by non-nationals
$CRjni$	Indoor consumption rate by *j* type household by nationals
$CRjnx$	Outdoor consumption rate by *j* type household by
$CRjnni$	Indoor consumption rate by *j* type household by non-
$CRjnnx$	Outdoor consumption rate by *j* type household by non-nationals
D_M	Municipal demand
PCD_M	Per capita municipal demand per day
$Ar_{gov\text{-}off}$	Gross floor area of governmental offices
$CR_{M\text{-}gov\text{-}emp}$	Consumption rate per government office employees
N_{mq}	Number of mosques
$CR_{M\text{-}mq}$	Consumption rate per mosque
$N_{hs\text{-}bed}$	Number of hospital bed
$CR_{M\text{-}hs}$	Consumption rate per hospital bed
$CR_{M\text{-}sc}$	Consumption rate per school students
N_{st}	Number of students
N_{vs}	Number of visitors to recreation places

Table 4: Model symbols used and their descriptions (Continued)

$C_{M\text{-}vs}$	Consumption rate per visitor
PCD_C	Per capita commercial demand per day
$N_{off\text{-}emp}$	Number of office employees
$CR_{C\text{-}off}$	Consumption rate per office employee
$N_{ret\text{-}emp}$	Number of retail employees
$CR_{C\text{-}ret}$	Consumption rate per retail employee
Ar_{res}	Average area of restaurants
$CR_{C\text{-}res}$	Consumption rate per restaurant area
N_{hr}	Number of hotel room
O_{hr}	Occupancy rate of hotel rooms
$CR_{C\text{-}hr}$	Consumption rate per hotel room occupied
N_{cw}	Number of car wash units
$CR_{C\text{-}cw}$	Consumption rate per vehicle
D_I	Industrial demand
D_{Am}	Amenities demand
AmR_k	Water requirement for k type amenities
k	Type of amenities facilities
Ar_k	Area of *k* amenities facilities
IE_{Am}	Irrigation efficiency at amenities
L_r	Leaching requirement
D_A	Agricultural demand
CWR_i	Water requirement for *i* type crop
Ar_i	Area of *i* type irrigated vegetation
IE_A	Irrigation efficiency at agricultural lands
FWR_r	Water requirement for *r* region forest
Ar_r	Area of forest in *r* region
R	Regions of forestry : eastern and western
IE_F	Irrigation efficiency at forest lands
$SA_{Total\text{-}inflow}$	Total recharge into the SA
$A_{inf\text{-}SA}$	Infiltration to SA from agriculture

Table 4: Model symbols used and their descriptions (Continued)

Symbols	**Description**
$F_{inf\text{-}SA}$	infiltration to SA from forestry
$Am_{inf\text{-}SA}$	Infiltration to SA from amenities
$R_{inf\text{-}SA}$	Infiltration to SA from residential outdoor use
$DW_{inf\text{-}SA}$	Infiltration to SA from DW leakage and loss
$DW_{AR\text{-}SA}$	Artificial recharge of DW
$RF_{inf\text{-}SA}$	Natural rainfall recharge
$DA_{inf\text{-}SA}$	Inflow from a deep aquifer to SA
$GWE_{inf\text{-}SA}$	External aquifer inflow
$WTP_{Total\text{-}inflow}$	Total wastewater inflow at WTP
R_{WTP}	Wastewater generated from residential
C_{WTP}	Wastewater generated from commercial
M_{WTP}	Wastewater generated from municipal
I_{WTP}	Wastewater generated from industrial
inf_{WTP}	Infiltrated water reaching WTPs

Chapter 4: Scenario Analysis using ADWBM and Sensitivity Analysis

In this chapter, the use of ADWBM to assess water supply and demand for Abu Dhabi's sustainable water resource management by developing potential water scenarios is discussed. The ADWBM evaluates the annual water balance for each time step by working on the specific time step of each year. A number of drivers were taken into account during the development of these scenarios, including population growth, economic growth, water use patterns, and climate change. The overall goal of this chapter is to look at different possibilities for EAD water supply and demand in the year 2050. Water decision-makers, policy makers, and stakeholders can use the findings of this study to create long-term plans and policies for the EAD water sector until 2050. In arid or semi-arid areas, it could also serve as a foundation for future refinement in water resource planning and management using scenarios production.

4.1 Basis for Scenarios Building

Scenarios refer to a series of assumptions or storylines depicting how the future of Abu Dhabi water system might unfold. They can also be treated as a form of sensitivity analysis of the relationship between the changing forces and their outcomes, the possible futures (Parsons et al., 2007). The future water demand of the EAD is dependent on many factors such as population growth, urbanization, environmental and governmental policies. The values of these factors are diverse according to the scenario configuration. Different assumptions are needed to test the effects of these factors. Hence, scenario analysis is used to explore the balance of water supply and demand to achieve the goal of sustainable Abu Dhabi as proposed in the Environment Vision 2030 (Environment Agency - Abu Dhabi, 2012). Therefore, in order to identify the key driving forces that determine the future of water system in Abu Dhabi, stakeholders' workshops were organized to discuss the current situation, to find out the focal questions and objectives relevant to sustainable Abu Dhabi.

The overall framework of scenarios building is illustrated in Figure 6. Scenario building used control parameters and drivers to forecast future situation, as shown in part one of Figure 6. Finally, the scenarios developed were simulated using the ADWBM developed in Chapter 3 to evaluate the future water balance, and to identify required changes in the consumption and supply pattern to achieve water balance.

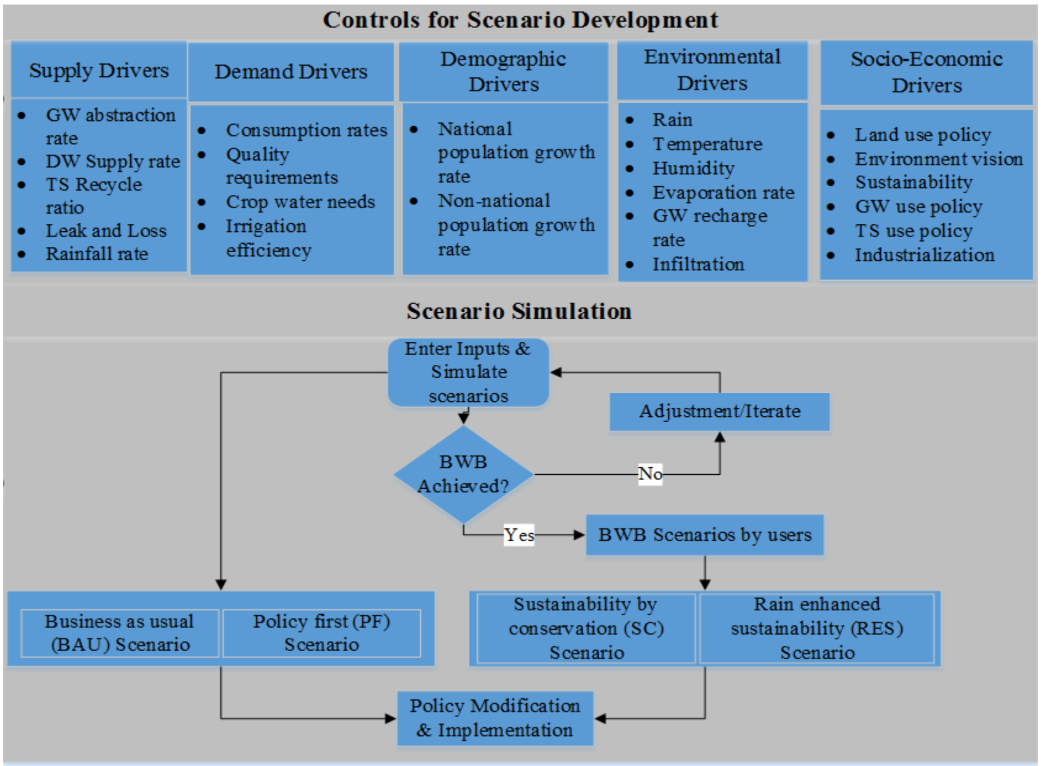


Figure 6: The stepwise framework of the scenario simulation using ADWBM

Population growth rates and other ADWBM parameters formed the foundation of this scenario analysis. Table 5, and Table 6 represent their baseline values, respectively. Water demand, especially the potable water demand sector, is directly linked to population. Therefore, population is incorporated as one of the key demand drivers for all potable sectors. Four population growth rates are considered in this analysis. They are very high (P1), high (P2), medium (P3), and low (P4) growth rates (Table 5). These growth rates P1, P2, P3 and P4 are aligned with population trends described in the Abu Dhabi Environment Vision 2030" (Environment Agency - Abu Dhabi, 2012) and (Lutz et al., 2014). The high growth rates, P1 and P2, represent the "Worst Case" (WC) and the "Market First (MF)" growths, respectively, as described in (Environment Agency - Abu Dhabi, 2012). The MF growth represents high immigration rates into the UAE for continuing rapid economic growth in the region. The medium population growth P3 represents a balanced environment and gradual economic growth in Abu Dhabi whereas the lowest population growth P4 represents a green economy. The Environment First (EF) scenario used in this study represents a green economy.

Table 5: Average annual population growth rates used in the developed scenarios

Population Growth rate	**Population Category**	**Average Annual Growth Rate (%)**		
		2015–2020[a]	**2021–2030[a]**	**2031–2050[b]**
P1	Nationals	3.2	2.8	2.5
	Non-Nationals	8.6	7.7	4.7
(Very high rate)	Total	7.6	7.0	4.4
P2	Nationals	3.2	2.8	2.5
	Non-Nationals	5.7	5.2	2.7
(High rate)	Total	5.2	4.8	2.7
P3	Nationals	3.2	2.8	2.5
	Non-Nationals	5.7	4.7	3.0
(Medium rate)	Total	5.2	4.4	2.9
P4	Nationals	3.2	2.8	2.5
	Non-Nationals	5.0	3.9	2.0
(Medium rate)	Total	4.6	3.7	2.1

Note: [a]Estimated based on (Environment Agency - Abu Dhabi, 2012); [b]Estimated based on (Lutz et al., 2014)

The availability of renewable water resources depends on climate factors like rainfall and temperature, and their availability may adversely be affected by future climate change in the region. EAD is vulnerable to the impact of climate change due to its extreme arid climate and low-lying coastal areas, and is already experiencing climate change, with higher temperatures and lower rainfall levels. The Emirate of Abu Dhabi has developed a climate change strategy that was incorporated into Abu Dhabi Plan (Environment Agency - Abu Dhabi, 2012). The change in climate is determined by past greenhouse gas emissions and, for Abu Dhabi, the impact of climate change is unlikely to make a severe change on water resources by 2050 (Dougherty et al., 2009; Environment Agency - Abu Dhabi, 2014).

4.2 Scenarios Development

This study designed four suites of water scenarios, namely Business as Usual, Policy First, Sustainability by Conservation, and Rainfall Enhanced Sustainability. The first two scenarios focus on predicting the future of Abu Dhabi water under a continuing pattern of economic growth in the EAD. Whereas the latter two were designed to achieve a Balanced Water Budget (BWB) until 2050. Each scenario has a set of assumptions and constraints for water use and supply. They are discussed under respective subsections (Sections 4.2.1 to 4.2.4) in detail. Furthermore, each of them was examined for multiple population growth models discussed in section 4.1.

4.2.1 Business as Usual (BAU) Scenarios

The BAU was built as a base scenario, which represents a continuation of current trends of water demand and supply. All the key parameter values are assumed to remain unchanged as in the baseline year 2015 except the population will continue to grow. Two population growth models, medium (P3) and very high (P1), were used to develop the BAU scenarios. This led to two sub-scenarios of BAU. The BAU scenario with P3 (medium) population growth represents a balanced environment and a gradual economic growth, and it is termed as BAU-Status Quo (BAU-SQ) scenario. The BAU-Worst Case (BAU- WC) scenario considers a very high population growth rate, P1, without a balanced environmental and economic growth.

These reference scenarios illustrate a situation where there is no improvement in water supply and demand infrastructures with respect to the baseline year (2015). Furthermore, the BAU scenarios assumed no restriction on groundwater extraction. Therefore, under BAU scenarios, water allocated per capita will remain same, and therefore, consumption will grow with time for population dependent sectors (residential, for example). The agricultural and forestry sectors are to maintain the baseline consumption throughout. The consumptions of agricultural and forestry sectors are kept constant as these sectors are independent of the population growth but only governmental decisions. Therefore, under BAU scenario, for forestry and agriculture sectors no increase in land area under cultivation is considered. The BAU water allocation rates values based on baseline year 2015 are summarized in Table 6.

Table 6: Inputs to BAU scenario building

Demand Sector	**Drivers**	**Value (unit)**
Residential	Sector allocation rate	610 lpcd
Commercial	Sector allocation rate	170 lpcd
Municipal	Sector allocation rate	250 lpcd
Agricultural	Sector allocation rate	2040.7 Mm^3/yr
Forestry	Sector allocation rate	375 Mm^3/yr
Amenities	Sector allocation rate	410 lpcd
TS	Potable water return ratio (PWR) GW infiltration rate to sewer	0.286 10%

4.2.2 Policy First (PF) Scenarios

The PF scenario considered the currently approved policies to reduce water consumption in different demand sectors. The Abu Dhabi Water Strategy document (Environment Agency - Abu Dhabi, 2014) specifies these policies which are: (i) desalination water demand is set to increase by 20% from the 2020 level in commercial/municipal mega projects, (ii) annual groundwater extraction limit 1,430 MCM (35% reduction) by 2030, (iii) 20% reduction of water use in public parks and gardens (amenities) relative to 2010 consumption, (iv) 20% reduction of water use in forestry sector by 2030, relative to 2010 water consumption, and (v) 20% reduction of indoor and outdoor water consumption in residential sector relative to 2010 water consumption.

Based on population growth models, the PF scenario is divided into three sub-scenarios. The Policy First-Balanced Growth (PF-BG) sub-scenario uses medium population growth P3 whereas the Policy First-Market First (PF-MF) and Policy First-Environment First (PF-EF) sub-scenario consider high growth (P1) and low growth (P4), respectively.

4.2.3 Sustainability by Conservation (SC) Scenarios

This scenario was developed to represent a sustainable future as explained in the Abu Dhabi Environment Vision 2030. Under such future, there is a growing interest on sustainability across economic, social, and environmental sectors. The current water consumptions rates in the EAD are not considered to be sustainable. Over-exploitation of scarce groundwater resources for agriculture should be constrained Therefore, this scenario is a target-based scenario in which reductions in water consumption rates (demand management) in different sectors are sought through an iterative process to achieve a BWB until 2050. The SC sub-scenarios were developed considering three population growth models, Sustainability by Conservation-Balanced Growth (SC-BG) using P3, Sustainability by Conservation-Market First (SC-MF) using P2, and Sustainability by Conservation-Environment First (SC-EF) using P4.

4.2.4 Rainfall Enhanced Sustainability (RES) Scenarios

The RES scenario was designed as yet another target-based scenario, which is developed to achieve a balanced water budget until 2050 taking into account key assumptions on rainfall and other water resources utilization factors. Rain enhancement technologies through cloud seeding is a promising solution offering a cost-effective tool towards supplementing water supplies in the UAE. In this technology, harmless natural salts such as potassium chloride and sodium chloride are used for cloud seeding. Therefore, in this suite of sub-scenarios, it is assumed that Abu Dhabi will have an increased rainfall by 20%. In addition, strict sustainable use of available water sources (desalination water, groundwater and treated sewage), is also assumed. The desalination capacity can only be increased by 20% while remaining sustainable. Sustainable use of GW requires recharge rates to exceed abstraction rates. For TS, the sustainability condition is achieved by maximum utilization of generated TS in non-potable demand sectors. Accordingly, 95% utilization of generated TS is assumed in this scenario. Therefore, an iterative simulation process was followed to find the optimized reductions needed for major potable and non-potable sectors. The main objective of this scenario is to determine an optimal solution for achieving water security in the EAD. Like previous scenarios, three sub-scenarios are developed for three population growth rates, which are RES-Balanced Growth (RES-BG) using P3, RES-Market First (RES-MF) using P2, and RES-Environment First (RES-EF) using P4.

4.3 Evaluation and Analysis of Scenarios Using ADWBM

All scenarios should be analyzed using a suitable mathematical simulation model, to assess the consistency and coherence of the resulting data (Gallopin & Rijsberman, 2000). In this study, the ADWBM, developed as part of this study, was used to evaluate the impacts of these developed scenarios through the results from simulations. All the scenarios are evaluated with regard to water balance (surplus or deficit), compatibility with environmental and sustainability targets, and sensitivity to key variables. The input values which are relevant to population forecast, demand forecast of all sectors, water resources availability forecast, implementation of governmental and environmental policies, and climate changes in terms of percentage changes from the baseline values are modified in the ADWBM to fit the scenario generated. A schematic representation of steps involved in scenarios simulation using ADWBM is given in part two of Figure 6.

4.3.1 Simulation Results

This section presents the simulation results obtained from ADWBM for all scenarios. The baseline values and other reference values (Table 1, Table 2, Table 5, and Table 6) were assigned to the model for simulation and data analysis.

4.3.1.1 Business as Usual Simulation Results

Two cases were simulated under this scenario. In the first case of BAU-SQ, the water demand is driven by moderate population growth (P3). Total annual water demand of Abu Dhabi will grow from 3518 MCM in 2015 to 6107 MCM in 2050, a 74% increase in water demand. The key simulation results of BAU-SQ scenario are given in Figure 7. The bar graphs show the annual sector-wise demand. The trend of GW decline and annual supply by each source are represented by trend lines.

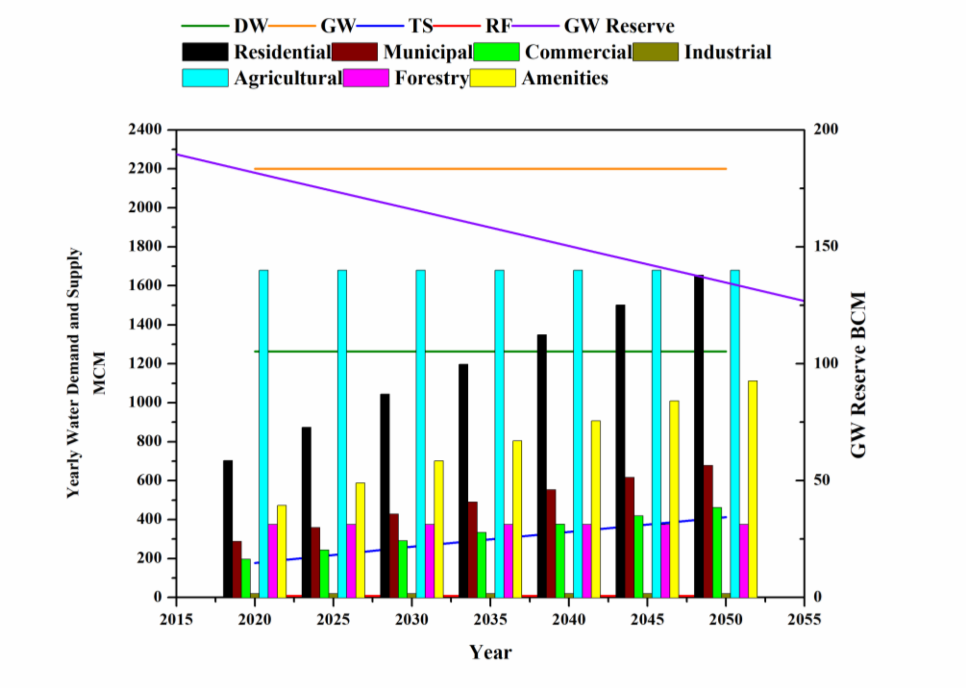


Figure 7: Simulation results from ADWBM for BAU-SQ scenario (for every fifth year, 2020-2050)

The results showed that the potable and non-potable water requirement will face a deficit unless changes are implemented. The water deficit forecast under this scenario for the years 2020, 2030, 2040 and 2050 are presented in the Table 7. For BAU-SQ, the model predicts a shortage of 1675 MCM and 555 MCM in potable and non-potable water supply, respectively, by the year 2050; an overall shortage of 2230 MCM. The GW reserves under this scenario continue to decline steadily and will be reduced to half of the current GW reserve by 2050 (Figure 7). The increase in water demand and water shortages, and steady decline in GW in the EAD are alarming. This, therefore, calls for achievable strategies to prevent water crisis in the future if the current trend of BAU-SQ scenario is continued. The BAU-SQ scenario is not a balanced water budget scenario and thus cannot be adopted.

Table 7: Increasing trend of water deficit over years for BAU-SQ and BAU-WC

Year	BAU-SQ			BAU-WC		
	Potable	Non-Potable	Total	Potable	Non-Potable	Total
2020	70	150	220	179	178	357
2030	647	295	942	1236	444	1680
2040	1161	425	1586	2272	705	2977
2050	1675	555	2230	3308	966	4274

In the suite of BAU scenarios, a worst-case future, BAU-WC scenario was simulated as the second case. It reflects potentially large increases in population identified by P1 in Table 5. Generally, BAU takes current trends forward. In the case of Abu Dhabi, however, population and economic growth has been dramatic, and it is this continuation of dramatic growth that made to generate one extreme case of the BAU envelope. Although this worst case is unlikely to happen, it was included to show the huge impacts of such high population growth rates on water demands in the future. In BAU-WC, total water demand will reach 8389 MCM in 2050, nearly double that of the BAU-SQ scenario. Figure 8 shows the sector-wise demand over time. The most consuming sectors, if a BAU-WC scenario is adopted, are those driven directly by population, namely, residential, municipal, commercial, and amenities. The huge increases in annual demand in the residential sector will approach 3,000 MCM in 2050.

Although the results showed that there are significant differences in water deficit between BAU-SQ and BAU-WC, both show an alarming increase of water deficit requiring the government of Abu Dhabi to develop practical strategies and policies to avoid water crisis in the future.

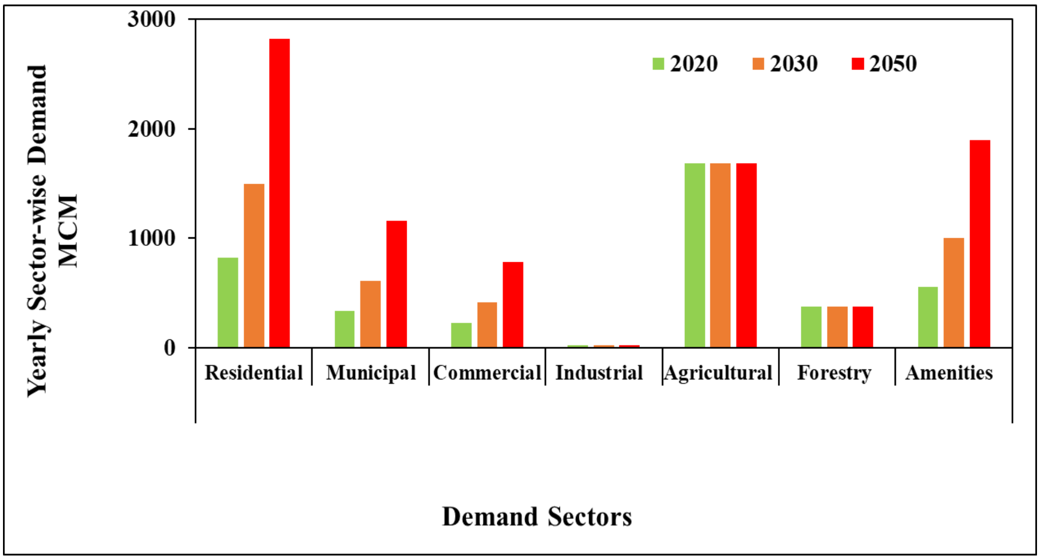


Figure 8: Water demand in all sectors under the BAU-WC scenarios for 2020 (first bars), 2030 (second bars), and 2050 (third bars)

4.3.1.2 Policy First Scenarios

The key results; sector-wise water demands, water supply and decline of GW reserves for the PF-BG scenario are shown in Figure 9. The results demonstrate the positive impacts of approved policies against the BAU scenario. The impacts on reducing water demands in all sectors are clear, especially for the potable sectors. Based on these results, these polices, if implemented and realized, will be effective in achieving a water balance until 2027. This is as expected as these policies were originally designed to help address water demands through 2030. However, the results predict that some shortages will appear in 2028 and 2029 (Figure 10), for non-potable and potable demands, respectively, which might require another set of policies such as an additional increase in the desalination capacity. The model presented estimates of these shortages in both the potable and non-potable sectors, and these data could help to shape these new polices if needed.

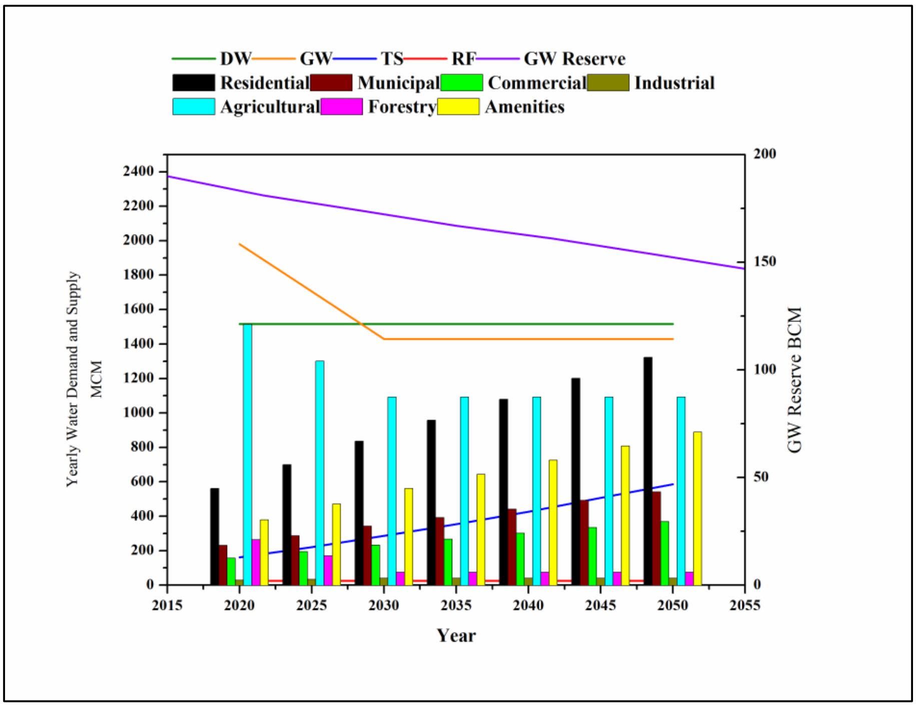


Figure 9: Simulation results from ADWBM for PF-BG scenario

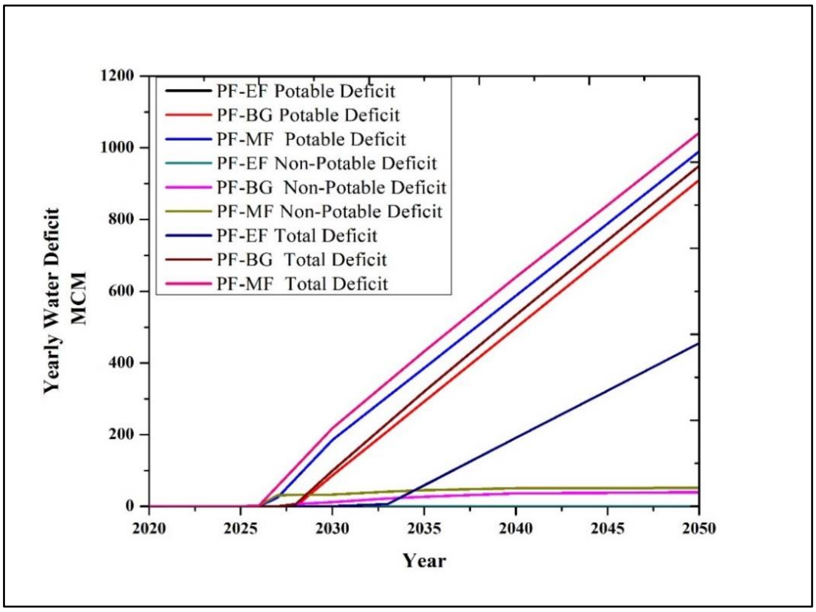


Figure 10: Growth of potable, non-potable and total deficit for PF-EF, PF-BG and PF- MF scenarios

Within the PF scenarios, another two cases were simulated to check the impact of high (MF) and low (EF) population growth rates on the policies. From the results, PF-MF scenario with high population growth showed a water deficit as early as 2026 (Figure 10), earlier than PF-BG scenario and will require an earlier change in policies. However, in the case of PF-EF scenario, the low population growth would maintain a positive water balance until 2033 (Figure 10). Thereafter, deficiencies appear in the potable supply-demand balance which must be addressed. There is no non-potable deficit forecast in this case.

4.3.1.3 Sustainability by Conservation Scenarios

For SC scenarios, iterative simulations were carried out until no water deficit occurred before 2050 and the corresponding conservations to be implemented for each demand sectors were found. The demand and supply details are shown in Figure 11. For SC-BG, only less than 15% of the strategic groundwater reserves will be utilized until 2050 (Figure 11). Huge induced reductions in all sectors are required. The most notable are in the residential, commercial, agricultural, and amenities sectors. Two additional cases associated with different population levels, namely, SC-MF and SC-EF, were also simulated.

In order to achieve the BWB, a second level of simulations were carried out to identify demand drivers or sub-sectors responsible for controlling majority of the water consumption. It is important to identify these drivers to implement the demand reductions required. The breakdown of the reductions at driver level to achieve a BWB in the four major demand sectors is presented in Table 8.

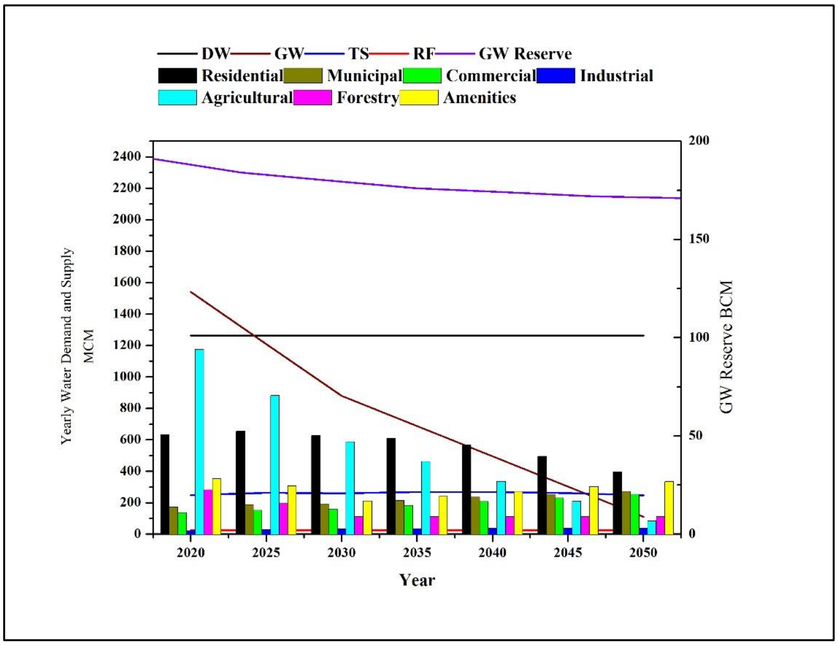


Figure 11: Simulation results from ADWBM for SC-BG scenario

Residential sector uses eight drivers which control residential demand. Table 8 summarizes the values of these drivers required to achieve the sought BWB, for all three cases of SC scenarios. It is worth noting the extreme reductions are needed in outdoor consumption; for nationals and non-nationals as well, especially by the year 2050.

Commercial sector consumption is driven by five main drivers: (1) office employees, (2) retail employees, (3) restaurants, (4) hotel rooms, and (5) carwashes. The target consumption rates to be achieved for these drivers are shown in Table 8.

Reducing the water consumptions in agriculture without affecting the agricultural production could be feasible by increasing the irrigation efficiency while keeping the same plant water requirements. So, the efficiencies were iteratively increased to reach the sought reductions in consumptions at different years for achieving BWB scenario. For the year 2020 and afterward, it was not feasible to achieve BWB by just improving the irrigation efficiency because of the large required reductions in consumptions in these years. The only solution to achieve this was to reduce crop area. After assigning a 60% increase in efficiency at these years, the minimum reduction in area was found to be 50% in 2030 and 86% in 2050 for all the SC scenario cases (Table 8). The selected 60% irrigation efficiency is perceived to be practical and feasible. However, irrigation efficiency improvements for vegetable crops and field crops are expected to be more achievable because of the likely increase in the use of drones for optimizing irrigation though assessments of crop health and soil moisture as this is more applicable for low lying field crops rather than orchards.

For forestry, similar to the agricultural sector, the first option considered was to increase irrigation efficiency without changing the current forestry area. Increasing efficiency alone will not be sufficient to achieve a BWB from 2020 and beyond, which implies that reductions in the forest area will be needed. Reductions required are 30% in 2030 and 2050 if the irrigation efficiency can be increased to 60% (Table 8).

Although, SC scenarios showed the target values needed to achieve BWB for Abu Dhabi until 2050, some of the conservation requirements are very challenging and needs a total change in consumption pattern in Abu Dhabi. Hence, this scenario calls on policy makers to have long term strategy implementing stringent water conservation policies for Abu Dhabi.

4.3.1.4 Rainfall Enhanced Sustainability Scenarios

The demand, supply, and GW conditions for the RES-BG scenario are shown in Figure 12. Two sub-scenarios for the high and low population growth rates were again simulated. Analysis of all SC scenarios indicate that with the effective implementation of different demand conservation strategies it will be possible to achieve a BWB.

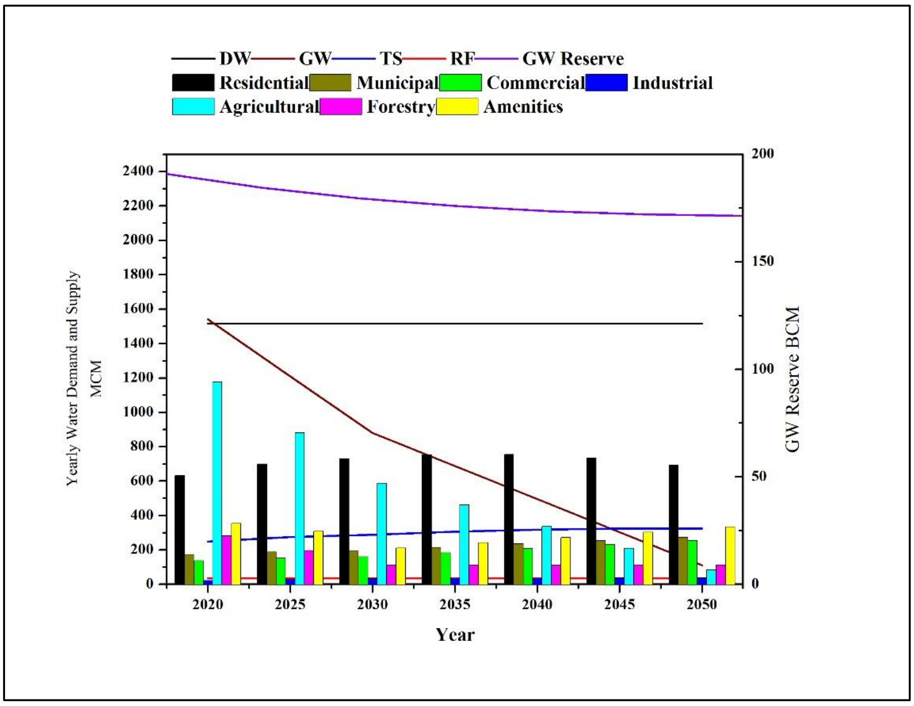


Figure 12: Simulation results from ADWBM for RES-BG scenario

Similar to SC scenarios, iterative simulations were conducted to find the optimized reductions needed for various demand sectors, particularly, residential, commercial, agricultural and forestry sectors. Table 8 summarizes the reductions to be achieved for two timelines (2030 and 2050) for the different drivers (relative to their current values) to ensure a BWB in all RES scenarios (RES-BG, RES-MF, RES-EF). Such reductions for residential and commercial drivers when compared to SC scenarios are understandably lower for the RES scenarios. It can be seen that for a balance water budget major reductions are required in the residential sector when compared to commercial sector. This is because the expected reductions in the residential sector are in the outdoor usage. Therefore, the reductions are to be implemented in outdoor consumptions. For agriculture and forestry sectors outcomes were similar to the SC scenarios.

In this scenario, the increase in supply from RF and DW will not relax the future water crisis. One of the reason is that the addition in rainfall and sustainable increase in DW, is not in par with growing population. Also, high rate of evaporation of surface-runoffs collected in dams is a major cause of loss of RF. However, the increased rainfall can help in natural recharge of groundwater thus helping in sustainability of GW aquifers. Thus, for a sustainable future, large scale, sustainable, increased RF and DW are required to avoid strict conservation measures to be adopted at the user level. The other options of maximum utilization of TS (95 %) and minimum use of GW (abstraction equal to recharge) are already considered in this scenario.

Thus, from the analyzed scenarios, only strict conservation strategies can support the management of the existing water supply and demand system of Abu Dhabi, and in turn can contribute to the realization of sustainable Abu Dhabi. However, RES scenario may be preferred over SC scenario because comparatively lenient conservation measures may prevent water shortages in future.

Table 8: Target consumption rates to be achieved in sub-sectors by 2030 and 2050, under RES and SC scenarios

Sectors / sector wise Demand Drivers	2030						2050					
	RES-BG	REF-MF	RES-EF	SC-BG	SC-MF	SC-EF	RES-BG	REF-MF	RES-EF	SC-BG	SC-MF	SC-EF
Residential												
Shabiyats Indoor, Nationals (lpcd)	256	256	272	256	256	256	224	224	240	208	208	208
Shabiyats Outdoor, Nationals (lpcd)	705	705	960	640	640	640	448	448	768	665	665	665
Villas Indoor, Nationals (lpcd)	192	192	204	192	192	192	168	168	180	156	156	156
Villas Outdoor, Nationals (lpcd)	528	528	720	480	480	480	336	336	576	240	240	240
Villas Indoor, Non-Nationals (lpcd)	192	192	204	204	204	204	168	168	180	156	156	156
Villas Outdoor, Non-Nationals (lpcd)	528	528	720	480	480	480	336	336	624	240	240	240
Flats, Nationals (lpcd)	132	132	140	180	180	180	100	100	108	144	144	144
Flats, Non-Nationals (lpcd)	240	240	300	180	180	180	180	160	260	110	100	124
Commercial												
Office Employees (liters/emp./day)	33	30	32	30	31	32	31	29	32	29	29	32
Retail Employees (liters/emp./day)	25	26	27	25	25	26	24	24	25	25	25	26
Restaurants (l/m^2/day)	16	15	17	15	15	15	15	15	15	15	15	15
Hotel Rooms (liters/room/day)	185	152	139	148	172	191	172	172	182	172	172	172
Car wash (liters/vehicle)	159	153	160	156	148	159	142	148	154	142	148	148
Agriculture												
Irrigation efficiency (%)	60	60	60	60	60	60	60	60	60	60	60	60
Cultivated crop area (% reduction)	(50)	(50)	(50)	(50)	(50)	(50)	(86	(86)	(86)	(86)	(86)	(86)
Forestry												
Irrigation efficiency (%)	60	60	60	60	60	60	60	60	60	60	60	60
Forestry area - (% reduction)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)	(30)

4.4 Sensitivity Analysis

Since there are many drivers associated with different demand sectors, it is necessary to identify the drivers that have the largest influence on the calculated demand so that future efforts can be focused on gathering data for those drivers. Therefore, a sensitivity analysis was conducted to evaluate the impact of drivers on the calculated consumption. This analysis was performed separately for each demand sector by changing the value of an individual driver (% increase and decrease), keeping other drivers unchanged, and reporting the percentage change of that demand sector at years 2020, 2030, and 2050. It is worth mentioning that it was assumed that changing the driver(s) of any demand sector does not affect other demand sectors. The residential sector is used as an example to explain the sensitivity analysis approach. It shows that the input parameters that affect the residential demand mostly in all three-time horizons (2020, 2030, and 2050), are the flats water consumption followed by the Shabiyat' outdoor water consumption. The villas outdoor consumption acts as the third most influential parameter for all the three time horizons considered. The effect of each driver (while other drivers remain the same) on the residential demand for 2020, 2030, and 2050 is shown in Figure 13. It is identified that though the flats water consumption rate is relatively low, the high population in this category of dwelling makes it the most influential input driver. The changes in demand increase with time; that is, changes in 2050 are larger than those in 2030 and 2020.

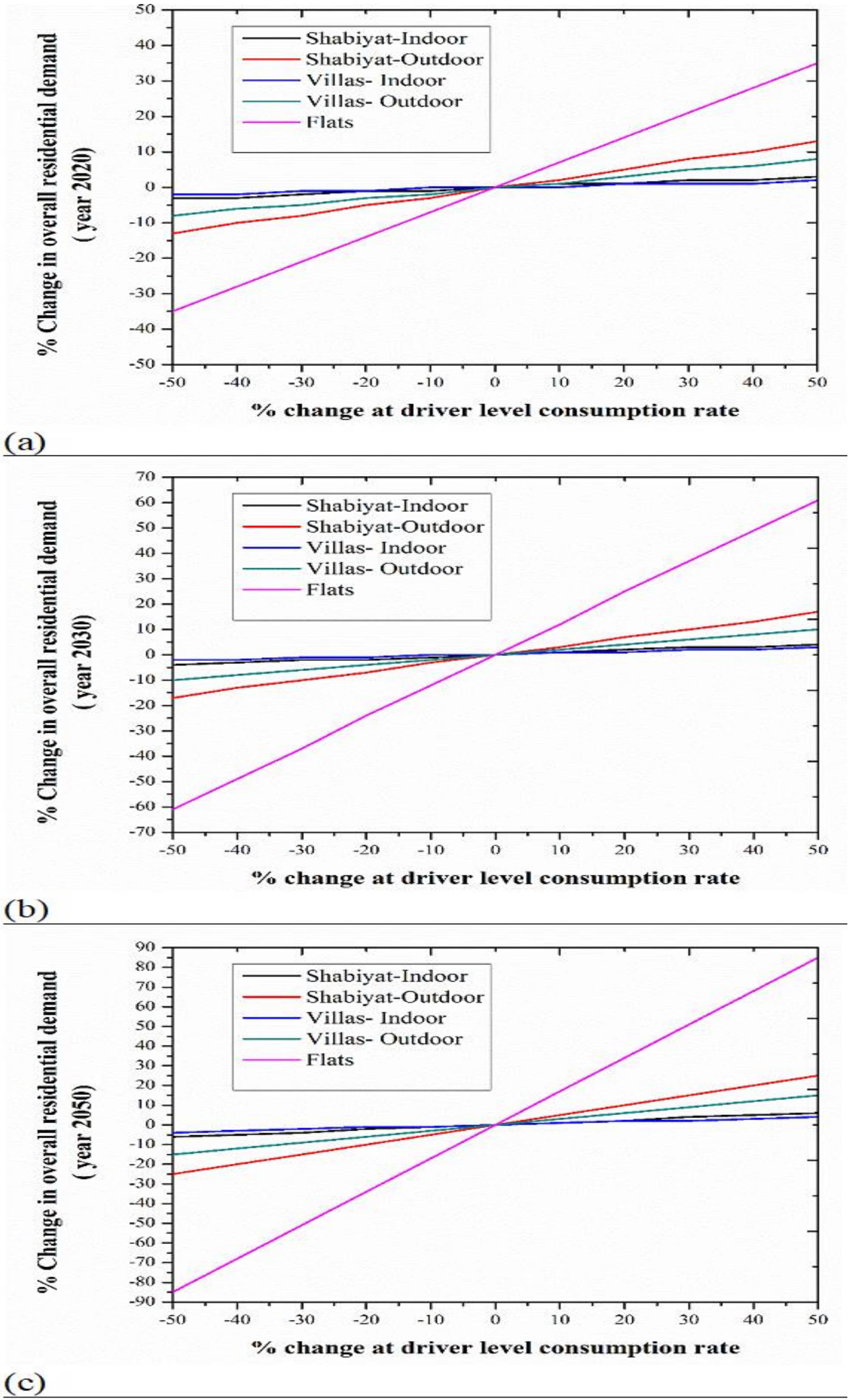


Figure 13: Sensitivity Analysis-Effect of drivers on residential demand. (a) For year 2020 (b) For year 2030 (c) For year 2050

A similar approach was followed for all other sectors having detailed drivers' data. In the municipal sector, the government offices area and its consumption rate are the drivers that mainly influence the municipal water demand in 2020, 2030 and 2050. According to the effect on the commercial water demand, the most influential input parameters for all the three time horizons are the water consumptions by restaurants. The retail employee and the office employee number have the similar impact on the demand. The water consumption for car wash and in hotel have minimum effect on the commercial water demand. In the agriculture sector, the controllable driver, namely, irrigation efficiency and area under cultivation (fruits, field and vegetables) affect the agriculture demands significantly. There are two controllable drivers in the forestry sector. These are the total area of forestry (region-wise) and the irrigation efficiency. Both drivers significantly affect the overall forestry water consumption in the 2020, 2030 and 2050. In the amenities sector, the irrigated area is broadly divided into two categories, park and ornamental areas. Therefore, the input drivers, namely, amenities area (park area and ornamental area), consumption rates and their irrigation efficiencies. It was observed that the amenities area and irrigation efficiency affect the overall amenity water demand without altering the consumption rate.

4.5 Strengths and Limitations

The use of scenarios analysis revealed water management challenges for the EAD up to 2050. A set of existing scenarios relevant to water management were elaborated through stakeholder and relevant governmental entities workshops, interviews, and expert knowledge to identify drivers of water supply-demand, their interdependencies, and influence on Abu Dhabi water system. Thus, this study provided insights to the real context and challenges of Abu Dhabi in the realm of water management. The model parameters like drivers of various demands sectors which forms the basis of the future demand forecast were incorporated based on the data available at the time of model development. The drivers' data (like consumption rates of various subsectors) needs to be updated in coming years to improve the model accuracy in predicting the future.

4.6 Chapter Summary

A series of future water scenarios were constructed to represent different future water conditions. Demographic conditions related to present and future water consumption in the Emirate of Abu Dhabi were central to the analyses. While both the SC and RES scenarios achieved a BWB throughout the entire period (no shortage), the RES scenario is proposed to be adopted because the interventions are judged more achievable and flexible given future uncertainties. The study showed that new resources will be required, e.g., desalinated water, to support the major increase in potable demands in later years if the Business as Usual and Policy First scenarios are followed. The business as usual path is not sustainable and the EAD must make major changes in order to pursue the alternative sustainable pathways modelled. However, efforts need to be maximized at all levels, from household to nationwide, in order to make sustainability a reality. Sensitivity analysis was carried out to identify significant drivers of various demand sectors. The sensitivity analysis results are discussed in the end.

Chapter 5: Abu Dhabi Water Capacity Planning Model

In this chapter, a multi-period mixed integer optimization model for Integrated Water Resources Management and Capacity Expansion planning is developed. This model could provide the optimal mix of water supply options to meet current and future water demand is proposed. The model considered environmental aspect by minimizing CO_2 emissions, GW extractions and brine disposal based on the associated environmental costs, and the overall cost of water production and transmission to meet the multiregional water demands with various quality levels. The methodology for developing the MILP model which includes the model constraints development, parameter identification, and development of objective function equation taking into consideration the economic and environment cost are discussed.

5.1 Problem Statement

In this study, a capacity expansion planning model for the EAD, characterized by limited renewable water resources, is proposed. GW is the only conventional source in the EAD, and it is non-renewable owing to scanty rainfall and low natural recharge. Non-conventional supply sources are DW from seawater and TS from WW. Another option, namely, importation of water from places outside the EAD mainland is feasible, and therefore included. However, this option of long distance transportation via pipeline is limited to DW.

As the EAD covers a large region with multiple economic development zones, the area can be divided to constitute several regions based on population distribution and terrain. Each region has demands for specific uses, and it originates from each population centers located within each region. It is also assumed that there are several locations '*l*' representing the locations of DW and TS production plants and extraction of GW. In addition, there are several technology sets *k* for water production from each source and *n* number of plants on *k* technology is possible at any plant location *l* in any region *r*. These plants associated with DW and TS plants differ in capital, operation and environmental costs. The population centers and plant locations or origin of water supply are referred to as nodes in this study.

Therefore, the overall water supply system in the EAD comprises three main supply sources, namely, DW, TS and GW. DW is produced by treating seawater using various technologies in desalination plants located within or outside the EAD. Moreover, DW that is produced can be imported to any of the population centers in the EAD by long-distance pipelines. Therefore, DW system at regional level comprises DW plants, inter-regional pipelines, and external DW plants and the pipelines connecting the sub-regions and external plants. The study was focused only to that point that DW is made available at the key distribution points within each sub-region to meet demands. Owing to the complexity in determining the distribution networks and its relatively low contribution to the overall cost of DW infrastructure and operation, the distribution to end users is not included. TS supply system can otherwise be called as non-potable system which comprises collection and transport of wastewaters from all population centers to the treatment plants to produce TS, and a distribution network of TS to the users. However, in this study the focus was only on the production of TS from the WW at the treatment plants, without considering the transportation of WW and distribution of TS. This was neglected because this study assumed that a sewer system and TS distribution already exist in all the major population centers and expanding these systems cost lesser when compared to the overall cost. It was assumed that GW supply is for both irrigational and non-potable purposes. In this case too, the distribution cost is not considered. In addition, it was assumed that the pipeline for TS and GW supply is well established. To identify types of demand based on water quality and specific uses, demand types were classified as potable (*pot*), non-potable (*np*) and irrigation (*ir*), together representing the annual water demands. Potable water systems refer to the DW supply system with high purity of water that can be used to meet all types of demands including those by residential, industrial, commercial and other domestic purposes requiring drinking water quality. Irrigation demand is a special case of non-potable demand as TS water quality is not satisfactory on aesthetic grounds. Therefore, irrigation demand is satisfied by two sources, namely, DW and GW. Finally, the non-potable demands are satisfied with the quality of tertiary-treated wastewater called TS. This represents irrigating non-agricultural lands such as forests, landscapes, public places with lawns and other recreational activities.

All types of demands in each region are considered to vary annually. The annual demands depend on population growth, and governmental strategies and policies. The study period is therefore divided into several time periods; each represent a year. Therefore, a planning horizon of T years is divided into t periods of demands. Seasonal variations within a year are not considered in the study. This means the average daily demands and production of water are assumed to be same throughout the year.

In this optimization problem of water supply management of multiple regions for a multiperiod planning, the following data are considered to be given: regions of water demand and supply; population centers within each region; distance between DW plant locations and key distribution points of adjacent regions; regional annual potable, non-potable and irrigation demands; WW generation at each population center in each region; total available GW reserve, unit capital and operation cost data of all technologies of treatments for different size capacity intervals, unit costs for installation of pipelines of different diameter sizes and materials, environmental cost of GW in terms of associated economic value, environmental costs of all production technologies and transportation in terms of carbon footprint, and cost of desalination brine discharge into sea.

The objective is to minimize the NPV of the multiperiod water supply problem over the planning horizon that includes the capital cost of treatment plants and pipelines, Operation and Maintenance (OM) cost of treatment plants and transportation, and environmental cost of treatment plants and transportation. The main decision variables to be determined from the optimization problem are optimal capacity planning of treatment plants for DW and TS, selection of optimal technologies for capacity increase of DW and TS plants, optimal retrofit of existing pipeline routes connecting regions and DW plants, year of retrofit/expansion of capacities of plants in the planning horizon, and optimal production and use of DW and TS water at all production locations in every region, and optimal extraction of GW to sustainably meet water demands in the EAD.

5.2 Capacity Planning Model Development

A schematic representation of the proposed model structure is given in Figure 14. It is named as Abu Dhabi Water Capacity Planning Model (ADWCPM). The ADWCPM comprises parameters, model constraints, objective function and model outputs. The data input into the model include the detailed composition of all water supply options at the beginning of the planning horizon, the projected yearly water demand for each region (*pot.*, *np* and *ir* categories), technological and economic parameters related to all water production technologies and transport, carbon footprint from all types of water production and transport, brine discharge into sea from DW plants for all technologies and the cost of GW converted into environmental costs as a factor of depletion ($/m^3). The model approach is structured as follows:

(1) The water demand in each year of *t* years of the planning horizon of *T* is to be satisfied individually for all regions and demand types.

(2) The processes of expansion of water infrastructure by construction of new assets or retrofitting, and decommissioning of retiring infrastructure that complete lifetime are accounted for the available capacity for each year, with corresponding costs taken into consideration.

(3) On environmental and sustainability grounds, carbon footprint, GW extraction, and brine discharge to sea are minimized.

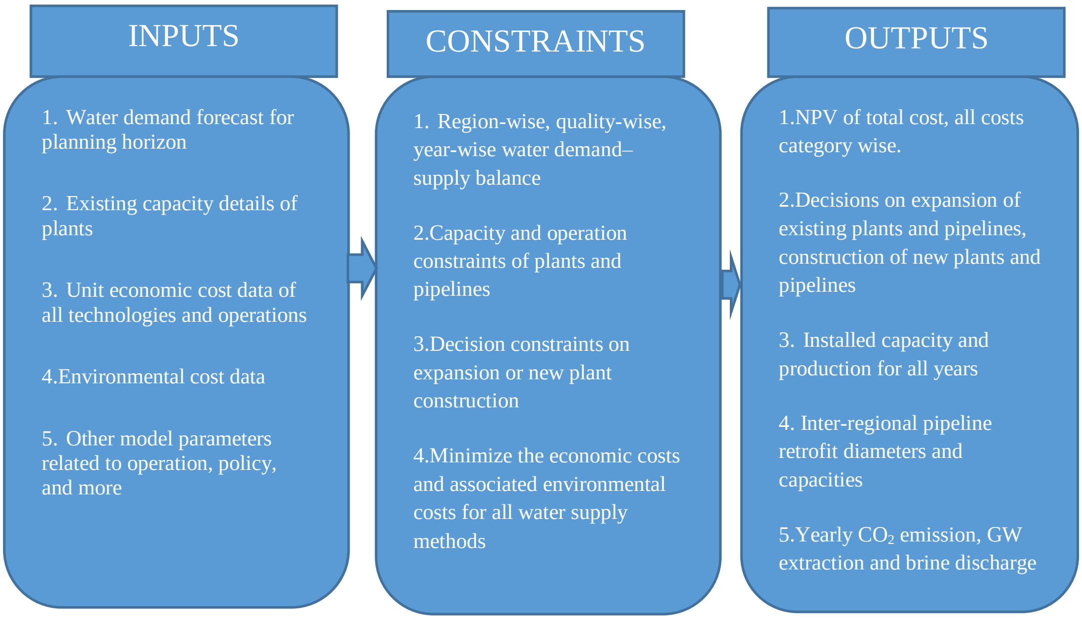


Figure 14: An illustrative representation of the model structure

5.2.1 Model Constraints

This section describes the mathematical formulation of the MILP model for water supply planning and management for a long planning horizon. This section describes the objective function and key constraints used for the design of the model. Physical meanings of the parameters and variables used in the formulation of the MILP model are shown in Table 9. The key constraints are categorized into various modules.

Table 9: Physical meanings of all components of the proposed MILP model

Model Components	Physical Meanings
Sets	
d	Set of water demand types (Potable(Pot), Non-potable (np) and irrigational (ir)
s	Set of water supply source types (DW, TS and GW)
r	Set of regions of a large area under study
l	Set of locations of production or extraction of existing water sources
k	Technology types available to produce water from various water sources
ne	set of existing plants under each category of water source and technology types
t	Set of time periods
pi	Set of all pipeline diameters
Parameters	
$D_{r,t}^{Pot}$	Potable demand in region *r* in year *t*
$D_{r.t}^{Np}$	Potable demand in region *r* in year *t*
$D_{r,t}^{ir}$	Irrigation demand in region *r* in year *t*
$CAP_{pi,r-r',t}^{Pipe}$	Carrying capacity of a pipe diameter size of *pi* between region *r* and *r'* in year t for DW export or import in year *t*
$CAP\_Import_{r,t}^{DW}$	Import capacity of all pipelines to a region *r* in year *t*
$CAP\_Export_{r,t}^{DW}$	Export capacity of all pipelines from a region *r* in year *t*

Table 9: Physical meanings of all components of the proposed MILP model (Continued)

Model Components	Physical Meanings
$CAP\_DECOM^{Plant}_{r,k,l,n,t}$	Capacity decommissioned n^{th} number of plant (DW and TS) at plant location *l* within the region *r* working on the plant technology *k* in year *t*
$CAP\_PIPE\_DECOM^{DW\_Pipe}_{pi,r-r',t-1}$	Capacity of pipeline with diameter *pi* decommissioned in year *t*, for route *r-r'*
$EXPANSION\_UP^{Plant}_{r,k,l,n,t}$	Expandable upper limit at n^{th} number of plant (DW and TS) at plant location *l* within the region *r* working on the production technology *k* in year *t*
$NEW\_UP^{Plant}_{r,k\prime,l,n,t}$	Installation upper limit at n^{th} number of plant (DW and TS) at plant location *l* within the region *r* working on the production technology *k* in year *t*
$EXPANSION\_LO^{Plant}_{r,k,l,n,t}$	Expandable lower limit at n^{th} number of plant (DW and TS) at plant location *l* within the region *r* working on the production technology *k* in year *t*
$NEW\_UP^{Plant}_{r,k\prime,l,n,t}$	Installation lower limit at n^{th} number of plant (DW and TS) at plant location *l* within the region *r* working on the production technology *k* in year *t*
CLT^{Plant_Exp}	Construction lead time for expansion of a Plant (TS and DW)
CLT^{Plant_New}	Construction lead time for installing a new Plant (TS and DW)
CLT^{DS_Pipe}	Construction lead time for installing a DW pipeline between regions
N_pipe	Number of pipe sizes that can be chosen for retrofit in a year for a route
g	Number of years' gap between successive construction decision at a site

Table 9: Physical meanings of all components of the proposed MILP model (Continued)

Model Components	Physical Meanings
N_Pipe_Retro	Number of times retrofit is allowed in a route in whole planning period
N_Plant_Exp	Number of times plant expansion *t* is allowed in a site in whole planning period
$CO2_k^{DW}$	Carbon footprint of different *k* technologies of DW production
$CO2_k^{TS}$	Carbon footprint of different *k* technologies of TS production
$CO2^{GW}$	Carbon footprint of GW abstraction
$CO2^{DS\_Transport}$	Carbon footprint on transporting I m^3 of water by I Km
$\text{Annual\_Limit}_t^{CO2}$	Annual limit on CO_2 emission
$\text{Annual\_Limit}_t^{DS-Brine}$	Annual limit on brine discharge
RR_k^{DW}	Recovery ratio for respective DW technologies
$GEN_{r,l,t}^{WW}$	Wastewater generated at a location *l* in region *r* in year *t*
$Cap\_unit\_cost_k^{DW\_Plant}$	Unit capital cost of DW plant working on *k* type technology
i	Annual Interest rate over the planning horizon
$L_{r,r'}^{DW\_pipe}$	Distance between the points connecting pipelines
$CAP\_unit\_cost_{pi}^{DW\_Pipe}$	Unit capital cost of pipe retrofitting with pipe size of *pi* diameter
$OP\_Unit\_cost_k^{DW\_plant}$	Unit OM cost for DW plant working on *k* technology, $/m^3$
$OP\_Unit\_cost_k^{TS}$	Unit OM cost for TS plant working on *k* technology $/m^3$

Table 9: Physical meanings of all components of the proposed MILP model (Continued)

Model Components	Physical Meanings
$OP\_Unit\_cost^{GW}$	Unit OM cost for GW pumping \$/m3
$OM\_COST^{DW\_Pipe}$	Unit OM cost for DW pipeline transmission pumping \$/m^3/km
$ENV\_unit\_cost^{CO2}$	Unit carbon cost(Tax) for carbon emission \$/ Kg-e CO_2
$CO2\_Emi_k^{DS\_Plant}$	Carbon emission rate from DW plant of *k* technology Kg-e/ m^3
$CO2\_Emi_k^{TS\_Plant}$	Carbon emission rate from TS plant of *k* technology Kg-e/ m^3
$CO2_{Emi}{}_k^{GW}$	Carbon emission rate from GW pumping Kg-e/ m^3
$CO2\_Emi^{DW\_Trans}$	Unit carbon emission to transport DW water by 1 km, \$ / m^3 / km
$ENV\_unit\_cost^{GW}$	Environment cost for GW usage based on GW economic value, \$/m^3
Continuous variables	
$Qi_{pi,r'-r,t}^{DW}$	DW import from adjacent region *r´ to r* in the year *t* through the pipe of *pi* diameter size
$Qe_{pi,r'-r,t}^{DW}$	DW export to adjacent region *r´* from *r* in the year *t* through the pipe of *pi* diameter size
$Qpot_{r,l,k,n,t}^{DW}$	DW supply by *nth* number of plant at production location *l* within the region *r* by using production technology *k* in year *t*
$Q_{Np}{}_{r,t}^{GW}$	GW supply to the non-potable sector in region *r* in year *t*

Table 9: Physical meanings of all components of the proposed MILP model (Continued)

Model Components	Physical Meanings
${Q_{Np}}_{r,t}^{DW}$	DW supply to the non-potable sector in region *r* in year *t*
${Q_{ir}}_{r,t}^{GW}$	GW supply to irrigation sector in region *r* in year *t*
${Q_{ir}}_{r,t}^{DW}$	DW supply to irrigation sector in region *r* in year *t*
$P_{r,l,k,n,t}^{TS}$	TS produced at n^{th} WWT plant at production location *l* within the region *r* by working on the production technology *k* in year *t*
P_{rt}^{GW}	GW produced in the region *r* in year *t*
$P_{r,l,k,n,t}^{plant}$	Production at n^{th} plant (DW and TS) at production location *l* in the region *r* by working on production technology *k* in year *t*
$CAP_{r,l,k,n,t}^{Plant}$	Installed capacity of n^{th} plant (DW and TS) at production location *l* in the region *r* by working on the production technology *k* in year *t*
$CAP_{r,t}^{Plant}$	Overall Installed capacity of all plants (applicable for both DW and TS) in a region *r* in year *t*
$Q_{pi,r-r\prime,t}^{Pipe}$	Quantity of DW water that is exported or imported through a pipe diameter size of *pi* between region *r* and *r'* in year *t*
$CAP\_EXPANDED_{r,k,l,n,t}^{Plant}$	Increment at n^{th} plant (DW and TS) at plant location *l* in region *r* by working on the production technology *k* in year *t* with existing *k* technologies
$INSTALL\_NEW_{r,k,l,n,t}^{Plant}$	Increment in the of n^{th} plant (DW and TS) at plant location *l* in the region *r* by working on the production technology *k* in year *t* with new technologies (*k'*)
$CAP\_PIPE\_RETRO_{pi,r-r',t}^{DW\_Pipe}$	Increased capacity by retrofit with *pi* diameter in year *t*, for *r*-*r'* route

Table 9: Physical meanings of all components of the proposed MILP model (Continued)

Model Components	Physical Meanings
$\text{Q\_Brine}^{DW}_{r,k,l,n,t}$	Brine Produced from all DW technologies in year *t*
Q_CO2_t	Total CO_2 emitted in a year *t*
$CAP\_COST^{DW\_Plant}$	Total capital cost for DW plants for the planning period
$CAP\_COST^{TS\_Plant}$	Total capital cost for TS plants for the planning period
$CAP\_COST^{DW\_pipe}$	Total capital cost for all pipe retrofitting happening between all regional connection in whole planning horizon
$OM\_COST^{DS\_plant}$	Total OM cost for DW plants for the planning period
$OM\_COST^{TS\_plant}$	Total OM cost for TS plants for the planning period
OM_COST^{GW}	Total OM cost for GW pumping for the planning period
$OM\_COST^{DW\_Pipe}$	Total OM cost for DW pipeline transmission for the planning period
${ENV_{COST}}^{DW_{plant}}$	Total environment cost for running DW plants for the planning period B$
$ENV\_COST^{TS\_plant}$	Total environment cost for running TS plants for the planning period B$
ENV_COST^{GW}	Total environment cost for using GW for the planning period B$
$ENV\_COST^{DW\_Trans}$	Total environment cost for transporting DW for the planning period B$

Table 9: Physical meanings of all components of the proposed MILP model (Continued)

Model Components	Physical Meanings
Binary Variables	
$y\_exp^{Plant}_{r,k,l,n,t\prime}$	Binary variable to decide installation of new plant based on *k* technology in year *t'*
$y\_\mathrm{NEW}^{Plant}_{r,k\prime,l,n,t}$	Binary variable to decide installation of new plant based on *k'* technology in year *t*
$y\_\mathrm{exp}^{Plant}_{r,k,l,n,t}$	Binary variable to expansion of plant in year *t'* with technology *k*
$y\_\mathrm{retro}\ \_pipe^{DW\_pipe}_{pi,r-r',t\prime}$	Binary variable to decide expansion of retrofit of pipeline with diameter of *pi* size in year *t*

5.2.1.1 Regional Water Demand Constraints

This section discusses all equations formulated to establish how regional water demand types are satisfied with the respect to water supply sources in terms of quality and quantity. All the demand and capacity terms in the following equations are annual values expressed in Mm^3/yr. Regional potable demands are to be met by either regional production of DW or inter-regional transmission, or mix of both. This constraint is written by equation (5.1):

$$D^{Pot}_{r,t} = \sum^{l}\sum^{k}\sum^{n} Qpot^{DW}_{r,l,k,n,t} + \sum^{pi}\sum^{r'} Qi^{DW\_Pipe}_{pi,r'-r,t} - \sum^{dia}\sum^{r'} Qe^{DW\_Pipe}_{pi,r'-r,t} \quad \forall \ \ r, t \qquad (5.1)$$

$D^{Pot}_{r,t}$ is the potable demand in region r in year t. The first term on the Right Hand Side (RHS) denotes the summation of the supply by all DW plants in a region.

$Qpot_{r,l,k,n,t}^{DW}$ is the individual supply of DW by *n^th^* number of plant at a production location *l* within the region *r* using the production technology *k.* The second term, $(Qi_{pi,r'-r,t}^{DW\_pipe})$, is the summation of inflows from all adjacent regions (r'), and can be read as DW imported from a DW plant at *l* in region *r´ to r* in year *t* through the pipe *pi* diameter. The third term is the summation of outflows from a region *r* to adjacent regions *r´*.

Non-potable demand can be supplied with GW and TS, depending on availability, and government's sustainability policies and priorities. However, DW is also an option for the non-potable sector if surplus DW production capacity is available. Therefore, the non-potable demand $(D_{r,t}^{Np})$ can be written by the equation (5.2):

$$D_{r,t}^{Np} = \sum^{l} \sum^{k} \sum^{n} P_{r,l,k,n,t}^{TS} + {Q_{Np}}_{r,t}^{GW} + {Q_{Np}}_{r,t}^{DW} \qquad \forall \ r, t \qquad (5.2)$$

where $\sum^{l} \sum^{k} \sum^{n} P_{r,l,k,n,t}^{TS}$ represents the overall TS produced in a region (summation of annual production at all TS plants in a region *r*). ${Q_{Np}}_{r,t}^{GW}$ and ${Q_{Np}}_{r,t}^{DW}$ are GW and DW supplied to the non-potable sector annually, respectively.

Finally, annual irrigational demand in any region *r* in year *t* should be equal to the supply of GW for irrigation $({Q_{ir}}_{r,t}^{GW})$, and the supply of DW for irrigation ${Q_{ir}}_{r,t}^{DW}$, as shown by the equation (5.3):

$$D_{r,t}^{ir} = {Q_{Ir}}_{r,t}^{GW} + {Q_{Ir}}_{r,t}^{DW} \qquad \forall \ r, t \qquad (5.3)$$

5.2.1.2 Capacity and Operation Constraints

At any region *r*, the production of GW is for non-potable and irrigational use but is limited by the allowable abstraction rate based on the number of years to which GW reserve should exist. It is also assumed that the GW is applicable only for use within a region, and therefore, the inter-regional components (exportation and importation) were not included.

GW produced (P_{rt}^{GW}) in a region annually is equal to the supply to irrigation and non-potable sectors as given by equation (5.4).

$$P_r^{GW} = {Q_{Ir}}_{r,t}^{GW} + {Q_{Np}}_{r,t}^{GW} \qquad \forall \; r, t \qquad (5.4)$$

The DW and TS are produced at the respective treatment plants. Therefore, the production at a plant is limited by its installed capacity. This is implemented by the constraint in equation (5.5).

$$P_{r,l,k,n,t}^{plant} \leq CAP_{r,l,k,n,t}^{Plant} \qquad \forall \; r, k, l, n, t \qquad (5.5)$$

Similarly, the exportation and importation of DW for a region is through pipelines connecting the region and treatment plant locations in adjacent regions. The pipeline's capacity depends on the pipe diameter, velocity of water in the pipeline and daily hours of operation. Pipeline capacity is a parameter to the model and can be calculated heuristically for all diameter sizes considered in the model assuming a velocity (V^{DW_Pipe}) and daily hours of operation ($Hr_{Op}^{DW\_Pipe}$) excluding the required maintenance time. Therefore, pipeline's carrying capacity can be calculated based on the basic flowrate equation ($CAP_{pi}^{DW\_Pipe} = V^{DW\_Pipe} * \pi/4 * pi^2 * Hr_{Op}^{DW\_Pipe}$). V^{DW_Pipe} is velocity of water in pipe, pi is the pipe diameter, $Hr_{Op}^{DW\_Pipe}$ is the hours of operation, and $CAP_{pi}^{DW\_Pipe}$ is the annual carrying capacity. The volume of water exported or imported through a pipeline should be always less than the pipeline's carrying capacity. This is represented by the equation (5.6).

$$Q_{pi,r-r\prime,t}^{DW\_Pipe} \leq CAP_{pi,r-r\prime,t}^{DW\_Pipe} \qquad (5.6)$$

5.2.1.3 Capacity Expansion constraints

This section discusses the constraints on increasing the capacity of water assets like water treatment plants and inter-regional pipelines during the planning horizon.

(a) Plant Capacity:

Water sources, namely, seawater and wastewater, should be treated at treatment plants to achieve the required quality. GW is not subject to any treatment facilities and is used directly by pumping from wells. The plants' capacity planning is an important component in water management and planning. The overall plant capacity of a region ($CAP_{r,t}^{Plant}$) is defined as the summation of capacities of respective types (DW and TS) of plants within it, as given by equation (5.7). This verifies the capacity constraints for all regions in every *t*.

$$CAP_{r,t}^{Plant} = \sum^{r} \sum^{k} \sum^{l} \sum^{n} CAP_{r,k,l,n,t}^{Plant} \qquad \forall \; r, t \qquad (5.7)$$

In the model, it is considered that the capacity of DW and TS treatments can be increased by two types of processes: (1) by expansion/retrofit of the already existing treatment plants with the same existing technology, and (2) by installing new plants based on any of the technologies already in use in the Middle East or any new technology that has been identified as feasible for use in the Middle East. Furthermore, the capacity of an existing plant also depends on the age of the plant, and at the end of the life-span, it has to be retired or decommissioned, whose capacity must be deducted from the plant's total available capacity. Therefore, this was also considered in the model formulation.

Therefore, the capacity ($CAP^{Plant}_{r,k,l,n,t}$) of the n^{th} production plant at any location in a year *t* is given by equation (5.8).

$$CAP^{Plant}_{r,k,l,n,t} = CAP^{Plant}_{r,k,l,n,t-1} + CAP\_EXPANDED^{Plant}_{r,k,l,n,t} + INSTALL\_NEW^{Plant}_{r,k',l,n,t} - CAP\_DECOMM^{Plant}_{r,k,l,n,t-1} \quad \forall \; n, t > CLT \qquad (5.8)$$

The first term on the RHS represents the plant's capacity in the previous year. The second and third terms represent the increments in the site using existing technologies (k) and new installations based on new technologies (k'). Therefore, if the option of capacity increase by installing any new technologies other than the existing ones at the site is not considered, then the third term on RHS becomes null. The final term is the capacity decommissioned in the preceding year. Any expansion or new installation requires a Construction Lead Time (CLT). Therefore, this equation ensures that capacity is added only after the completion of plant construction or expansion.

(b) Pipeline Capacity:

For a region, the total inter-regional import is the summation of capacities of all the inter-regional pipelines installed to bring water from all possible adjacent regions. The model does not consider a reverse flow through the same pipeline simultaneously, which is given by equation (5.9).

$$CAP\_Import_{r,t}^{DS\_pipe} = \sum^{r'} \sum^{Pi} CAP_{pi,r-r',t}^{DS\_Pipe} \qquad \forall \; r, t \qquad (5.9)$$

Similar to the import equation, the export equation with respect to a region is given by equation (5.10).

$$CAP\_Export_{r,t}^{DW\_pipe} = \sum^{r'} \sum^{Pi} CAP_{pi,r-r',t}^{DW\_Pipe} \qquad \forall \; r, t \qquad (5.10)$$

In the proposed model, the option to retrofit the existing pipeline routes with pipelines from a set of discrete values of diameters for any time period *t* is included. For instance, the capacity of importing DW to a region *r* from another region *r'* in year *t* is the capacities of all existing pipelines plus the retrofitted pipelines in year *t* minus the decommissioned pipelines (all diameters) capacities between them in year *t*. This is given by equation (5.11).

$$CAP_{r-r',t}^{DW\_pipe} = \sum^{Pdi} CAP_{pi,r-r',t-1}^{DW\_pipe} + \sum^{pi} CAP\_PIPE\_RETRO_{Pdi,r-r',t}^{DW\_Pipe} - \sum^{Pdi} CAP\_PIPE\_DECOMM_{pi,r-r',t-1}^{DW\_Pipe} \qquad \forall \; r, t > CLT \qquad (5.11)$$

5.2.1.4 Construction Limits and Lead time

The multi-period water model should consider the bounds on capacity increase and lead time for installing or retrofitting new assets. This is needed to set a bound on expansion possible on a single stretch at a plant location subject to technology and space. Moreover, as a plant's capacity is non-linear with cost function, it is essential to linearize capacity-cost relation across certain intervals of capacity. This study considered expansion and installation with bounded values for using a constant unit cost value for the capacity incremented. Thus, a lower and upper bound for each technology need to be defined as in equations (5.12) to (5.15).

A plant or transmission line cannot deliver the function of water production or transmission until the completion of construction of respective assets. Therefore**,** equations (5.12 and 5.13) ensures that the newly constructed capacity is available only after the completion of construction.

$$CAP\_EXPANDED^{Plant}_{r,k,l,n,t} \leq EXPANSION\_UP^{Plant}_{r,k,l,n,t} * y\_exp^{Plant}_{r,k,l,n,t\prime}$$

$$\forall \text{ r, k, l, n; } t' = t - CLT^{Plant\_Exp} \qquad (5.12)$$

$$CAP\_NEW^{Plant}_{r,k',l,n,t} \leq NEW\_UP^{Plant}_{r,k\prime,l,n,t} * y\_exp^{Plant}_{r,k\prime,l,n,t\prime}$$

$$\forall \text{r, } k'\text{,l,n;} t' = t - CLT^{Plant\_New} \qquad (5.13)$$

where $EXPANSION\_UP^{Plant}_{r,k,l,n,t}$ and $NEW\_UP^{Plant}_{r,k\prime,l,n,t}$ are the parameters given as the upper limit of an expansion possible at a plant location subject to construction limits of respective technologies.

$$CAP\_EXPANDED^{Plant}_{r,k,l,n,t} \geq EXPANSION\_LO^{Plant}_{r,k,l,n,t} * y\_exp^{Plant}_{r,k,l,n,t}$$

$$\forall \text{ r,k,l,n,t; } t' = t - CLT^{Plant\_Exp} \qquad (5.14)$$

$$CAP\_NEW^{Plant}_{r,k\prime,l,n,t} \geq NEW\_LO^{Plant}_{r,k\prime,l,n,t} * y\_exp^{Plant}_{r,\prime,l,n,t}$$

$$\forall \text{r, } k'\text{,l,n,t;} t' = t - CLT^{Plant\_New} \qquad (5.15)$$

where $EXPANSION\_LOP^{Plant}_{r,k,l,n,t}$ and $NEW\_LO^{Plant}_{r,k\prime,l,n,t}$ are the parameters given as the lower limit of an expansion possible at a plant location subject to construction limits of respective technologies. Therefore, these equations are for restricting the maximum and minimum capacities of the newly expanded plant.

This model includes the option to retrofit the existing pipeline routes with pipelines from a set of discrete values of diameter for any time period *t*. Therefore, the retrofitted capacity is related to the decision variable by equation (5.16).

$$CAP\_PIPE\_RETRO_{pi,r-r',t}^{DW} = \sum^{pi} CAP\_PIPE_{pi}^{DW\_pipe} * y\_\text{retro}\_pipe_{pi,r-r',t'}^{DW\_pipe}$$

$$\forall\, pi, t; t' = t - CLT^{DW\_Pipe} \qquad (5.16)$$

Here, $y\_exp_{r,k,l,n,t'}^{Plant}$ and $y\_new_{r,k',l,n,t'}^{Plant}$ are binary variables that determine whether to start construction of plant expansion and new plant in year *t'*, respectively. Moreover, during construction, no new decision to start a construction is possible. This is given by equations **(**5.17) to (5.18).

$$\sum_{(t-CLT^{Plant_{Exp}})}^{t} y\_\text{exp}_{r,k,l,n,t}^{Plant} \leq 1 \quad \forall \text{ k, t} > CLT^{Plant_{Exp}} \qquad (5.17)$$

$$\sum_{(t-CLT^{Plant_{New}})}^{t} y\_new_{r,k,l,n,t}^{Plant} \leq 1 \quad \forall \text{ k, t} > CLT^{Plant_{New}} \qquad (5.18)$$

For pipe retrofitting decision, the binary $y\_retro_{pi,r-r',t'}^{DW\_Pipe}$ decides whether to start a pipe retrofit of pipe size *pi*. Moreover, the pipeline retrofit process needs an option to install more than one diameter. The model included this constraint by adding a parameter *N_pipe* which controls the number of pipe sizes in a single construction period using the following two equations (5.19) and (5.20).

$$\sum^{pi} y\_retro_{pi,r-r',t}^{DS\_pipe} \leq \text{N\_pipe} \quad \forall \text{ k, t} > CLT^{DS\_pipe} \qquad (5.19)$$

$$\sum_{(t-CLT^{DS\_pipe})}^{t} \sum^{pi} y\_retro_{i,r-r',t}^{DS\_pipe} \leq \text{N\_pipe} \quad \forall \text{ k, t} > CLT^{DS\_pipe} \quad (5.20)$$

5.2.1.5 Time Gap between Successive Decisions

Although equations (5.17) **-** (5.20) ensure that no new construction occurs during year the CLT of already construction in-progress site, an additional constraint is required to ensure that a gap of ‘g’ years between two successive expansion decisions of plants or retrofits of pipelines. This is expressed by equation (5.21).

$$y\_\text{exp}_{r,k,l,n,t}^{Plant} \leq 1 - \sum_{(t"=t-g)}^{t-1} y\_exp_{r,k,l,n,t"}^{Plant} \; ; \; \forall \; r,k,l,n,t, \; t \geq g+1 \qquad (5.21)$$

$$y\_r\text{etro}_{pi,r-r',t}^{DS\_Pipe} \leq 1 - \sum_{(t"=t-g)}^{t-1} y\_r\text{etro}_{pi,r-r',t"}^{DS\_Pipe} \; ; \; \forall \; r,k,l,n,t, \; t \geq g+1 \qquad (5.22)$$

5.2.1.6 Number of Retrofits

This constraint is included to limit the number of constructions occurring at site over the whole planning horizon. This also helps to constrain imposing larger constructions than smaller ones and reduce the number of years the site is engaged with construction This is given by:

$$\sum_z^T \sum_z^{pi} y\_retro\,_{pi,r-r',t}^{DW\_pipe} \leq \text{N\_Pipe\_Retro} \quad \forall \; r \qquad (5.23)$$

$$\sum^T y\_\text{exp}_{r,k,l,n,t}^{Plant} \leq \text{N\_Plant\_Exp} \quad \forall \; r, k, l, n \qquad (5.24)$$

$$\sum^T y\_\text{NEW}_{r,k\prime,l,n,t}^{Plant} \leq \text{N\_NEW} \quad \forall \; r, k', l, n \qquad (5.25)$$

5.2.1.7 Environmental Targets

(a) Cap on CO_2 Emission:

The annual CO_2 emissions from various water production processes and transport are limited by the constraint developed in equation (5.26). This constraint specifies that the annual CO_2 emissions emitted by all existing and newly constructed water infrastructure must be less than or equal to the specified annual CO_2 target. The CO_2 emissions are related to power consumption per unit volume of water produced or transported by each process.

$$Q\_CO2_t = \sum^l \sum^k \sum^n P^{DS}_{r,l,k,n,t} * CO2^{DS}_k + \sum^l \sum^k \sum^n P^{TS}_{r,l,k,n,t} * CO2^{TS}_k$$

$$+ \sum^l \sum^k \sum^n P^{GW}_{r,l,k,n,t} * CO2^{GW} \quad \sum^{pi} \sum^{r'} \sum^r Qi^{DS}_{pi,r'-r,t} * CO2^{DS\_Transport} \quad (5.26)$$

$$Q\_CO2_t \leq \text{Annual\_Limit}^{CO2}_t \quad (5.27)$$

(b) Cap on Brine Disposals:

The production of highly saline water, termed "brine" is a major environmental challenge associated with desalination technologies. Brine has adverse environmental impact and its disposal is expensive. Therefore, to assess the volume of brine produced at each individual desalination plant; plant feed water type, desalination technology plant capacity (m^3/day) and water Recovery Ratios (RR) associated with various technologies are considered. The brine production from a plant is calculated as follows:

$$Q\_Brine^{DW}_{r,k,l,n,t} = \sum^r \sum^l \sum^k \sum^n P^{DW}_{r,l,k,n,t} * \frac{(1-RR^{DW}_k)}{RR^{DW}_k)} \quad (5.28)$$

where $Q\_Brine^{DW}_{r,k,l,n,t}$ is the volume of brine produced (m3/day); RR^{DW}_k is the recovery ratio for the respective technologies.

Therefore, to reduce the impact of brine disposal a constraint is set to limit its disposal from all production plants to an annual limit as follows:

$$Q\_Brine^{DW}_{r,k,l,n,t} \leq \text{Annual\_Limit}^{DW-Brine}_t \quad (5.29)$$

(c) Cap on GW Abstractions:

GW is considered non-renewable in a region with arid or semi-arid climatic condition. Therefore, a constraint is required to limit the annual extraction of GW based on recharge rate, government policies and strategies for sustainability. This is given by:

$$\sum^{r} P_{r,t}^{GW} \quad \leq \quad \text{Annual\_Limit}_{t}^{GW} \quad \forall \ t \qquad (5.30)$$

5.2.1.8 Other Logical Constraints

TS and WW Relation:

Unlike from DW plants where the feed water is from an infinite source, TS plants are designed to treat a predictable volume of WW generated within the population centers. Therefore, the capacities at every TS plant location (population center) should always be greater than the WW generated in the location. As there can be more than one TS plant at one plant location *l*, the sum of all TS capacities should always be greater than the WW generated for all years.

$$\sum^{k} \sum^{n} P_{r,l,k,n,t}^{TS} \quad \leq \quad GEN_{r,l,t}^{WW} \quad \forall \ r,l,t \qquad (5.31)$$

In addition,

$$\sum^{k} \sum^{n} CAP_{r,l,,n,t}^{TS\_Plant} \quad \geq \quad GEN_{l,t}^{WW} \quad \forall \ r,l,t \qquad (5.32)$$

5.2.2 Objective Function

This model minimizes the NPV of the costs associated with meeting water demand while satisfying a CO_2 reduction target, minimize brine disposal into the sea and GW usage target over a specified planning horizon. The components associated with the objective function include: capital cost for new treatment plants and pipelines, fixed and variable operating and maintenance cost, cost of brine discharge into sea from all desalination technologies, environmental costs expressed in monetary terms for carbon emission from all operations, and for GW depletion.

The objective function is defined as equation (5.33).

Min *Total_Cost_* = $[CAP\_COST^{DW\_Plant} + CAP\_COST^{TS\_Plant} + CAP\_COST^{DW\_pipe}] + [OP\_COST^{DW\_plant} + OP\_COST^{TS\_plant} + OP\_COST^{GW} + OP\_COST^{DW\_Pipe}] + [ENV_{COST}{}^{DW_{plant}} + ENV\_COST^{TS\_plant} + ENV\_COST^{GW} + ENV\_COST^{DW\_Trans}]$ (5.33)

The related equations of the objective function are explained through equations (5.34) to (5.45).

5.2.2.1 Capital Cost

All capital cost terms are annualized capital costs calculated using capital recovery rate(CRR) for a nominal discount rate (*i*) to be recovered over the entire planning horizon(*T*).

$$\text{CRR} = \left[\frac{\boldsymbol{i}.(\mathbf{1}+\boldsymbol{i})^{\boldsymbol{T}}}{(\mathbf{1}+\boldsymbol{i})^{\boldsymbol{T}}-\mathbf{1}}\right] \quad (5.34)$$

In the capital cost, following terms are included:

(a) Capital cost for DW plants:

$$CAP\_COST^{DW\_Plant} = \text{CRR} * \frac{1}{(1+i)^{t-CLT}} *[\sum^{r}\sum^{k}\sum^{l}\sum^{n}\sum^{t} CAP\_NEW_{r,k\prime,l,n,t}^{DW\_Plant} + \sum^{r}\sum^{k}\sum^{l}\sum^{n}\sum^{t} CAP\_EXP_{r,k,l,n,t}^{DW\_Plant}] * [Cap\_unit\_cost_{k}^{DW\_Plant}] \quad (5.35)$$

(b) Capital cost for TS plants:

$$CAP\_COST^{TS\_Plant} = \text{CRR}*\frac{1}{(1+i)^{t-CLT}} *[\sum^{r}\sum^{k}\sum^{l}\sum^{n}\sum^{t} CAP\_NEW^{TS\_Plant}_{r,k',l,n,t} + \sum^{r}\sum^{k}\sum^{l}\sum^{n}\sum^{t} CAP\_EXP^{TS\_Plant}_{r,k,l,n,t} \;] * [Cap\_unit\_cost^{TS\_Plant}_{k}] \qquad (5.36)$$

(c) Capital cost for pipelines:

The capital cost of pipelines includes the costs incurred in installing pipelines for the entire length of distance between two points; plant location and distribution point in the adjacent region.

$$CAP\_COST^{DW\_pipe} = \left[\sum^{pi}\sum^{r'}(\sum^{r}\;\sum^{t} y\_retro\_pipe^{DW\_Pipe}_{pi,r-r',t}) * L^{DW\_pipe}_{r,r'} * CAP\_unit\_cost^{DW\_Pipe}_{pi}\right] * \text{CRR}*\frac{1}{(1+i)^{t-CLT}} \qquad (5.37)$$

5.2.2.2 OM Cost

The model assumes that the annual operation and maintenance cost production of type of water is proportional to its production in that year. Therefore, the total operating costs can be calculated as:

$$OM\_COST^{DW\_plant} = \sum^{t}\sum^{r}\sum^{l}\sum^{k}\sum^{n} P^{DW\_Plant}_{r,l,k,n,t} * OP\_Unit\_cost^{DW}_{k} * \frac{1}{(1+i)^{t}} \qquad (5.38)$$

$$OM\_COST^{TS\_plant} = \sum^{t}\sum^{r}\sum^{l}\sum^{k}\sum^{n} P^{TS\_Plant}_{r,l,k,n,t} * OP\_Unit\_cost^{TS}_{k} * \frac{1}{(1+i)^{t}} \qquad (5.39)$$

$$OM\_COST^{GW} = \sum^{t}\sum^{r}\sum^{l}\sum^{k}\sum^{n} P^{TS\_Plant}_{r,l,k,n,t} * OP\_Unit\_cost^{GW} * \frac{1}{(1+i)^{t}} \qquad (5.40)$$

$$OM\_COST^{DW\_Pipe} = \left(\sum^{pi}\sum^{r'}\sum^{t} Qi^{DW\_pipe}_{dia,r-r',t} + \sum^{dia}\sum^{r'}\sum^{t} Qe^{DW\_pipe}_{dia,r-r',t}\right) * OP\_unit\_cost^{DW\_Trans} * \frac{1}{(1+i)^t} \quad (5.41)$$

The $OM\_Unit\_cost^{GW}_{k}$ is related to the power consumption in pumping water from wells.

5.2.2.3 Environment Cost

The CO_2 constraint in equation (5.42) also considers the potential of CO_2 reduction by assigning carbon tax for carbon emissions.

$$ENV_{COST}{}^{DW_{plant}} = \sum^{t}\sum^{r}\sum^{l}\sum^{k}\sum^{n} P^{DW_{Plant}}_{r,l,k,n,t} * ENV\_unit\_cost^{CO2} * CO2\_Emi^{DW\_Plant}_{k} * \frac{1}{(1+i)^t} \quad (5.42)$$

$$ENV\_COST^{TS\_plant} = \sum^{t}\sum^{r}\sum^{l}\sum^{k}\sum^{n} P^{TS\_Plant}_{r,l,k,n,t} * ENV\_unit\_cost^{CO2} * CO2\_Emi^{TS\_Plant}_{k} * \frac{1}{(1+i)^t} \quad (5.43)$$

$$ENV\_COST^{GW} = \sum^{t}\sum^{r}\sum^{l}\sum^{k}\sum^{n} P^{GW}_{r,l,k,n,t} * \frac{1}{(1+i)^t} * (ENV\_unit\_cost^{CO2} * CO2_{Emi}{}^{GW} + ENV\_unit\_cost^{GW}) * \frac{1}{(1+i)^t} \quad (5.44)$$

$$ENV\_COST^{DS\_Trans} = \left(\sum^{\boldsymbol{pi}}\sum^{r'}\sum^{t} Qi^{DW}_{dia,r,r',t} + \sum^{\boldsymbol{pi}}\sum^{r'}\sum^{t} Qe^{DW}_{dia,r,r',t}\right) * CO2\_Emi^{\boldsymbol{DW\_Trans}} * ENV\_uit\_cost^{CO2} \; C02\_Emission\_unit^{dw} * \frac{1}{(1+i)^t} \quad (5.45)$$

5.3 Chapter Summary

This chapter explains the methodology involved in developing a MILP model for long term water capacity planning for vast area in arid and semi-arid region which has multiple sources of water supply, and multiple regions of water supply. The formulation of the mathematical model starting from the problem statement of the model to development of complete MILP model involving model equations are explained in detail in this chapter. At the end, this chapter briefly explains the objective function and its component equations.

Chapter 6: Implementation of Abu Dhabi Capacity Planning Model

The chapter outlines the implementation of the water capacity planning MILP model developed in Chapter 5. A plausible future was selected to examine the economic and environmental impact on the EAD's water sector when forced to comply with minimized total cost, CO_2 annual emission, annual brine discharge and GW abstraction. The study is based on a 30-year time horizon, starting in 2021 and ending in 2050.

6.1 Background and Scenario Setting

As a case study, mixed integer optimization approach is used to solve the issue of the capacity expansion of existing water treatment facilities and inter-regional pipeline transmission system, and allocation of water resources of the EAD, for the period 2021– 2050 has been solved by programming the model into GAMS. A scenario of Abu Dhabi's business-as-usual future as presented in chapter 4 (Mohamed et al., 2020) is studied and solved. In this study, the EAD is divided into three regions; Western region, Abu Dhabi region, and Al Ain region (Figure 2). All three regions have population centers where demand and supply of water is based on the population size, economic development, and other local climatic conditions. As described in the Chapter 5 (Section 5.1), water demands are classified into three main classes. They form the set of demand types for the EAD. Table 10 summarizes how various water demands can be satisfied in each region.

Potable demand of each region is satisfied exclusively by DW produced at seawater DW plants located at strategic locations within the EAD, and at an external location, namely, Fujairah, from where DW is imported through transmission lines.

Therefore, for DW; regional production, inter-regional transmission and external import from outside plants are possible. The demand for nonpotable water in the EAD is satisfied mainly by GW and TS. In the model, TS is allocated only for nonpotable use (Section 5.1). In the EAD, all population centers in each region are connected to a sewerage system, and the wastewater is treated to reusable quality at respective wastewater treatment plants to produce TS water. All the WWT plants are installed in the population centers of each region. The distances, pumping distances and elevations between the population centers and WTPs are not included because the sewer network operation has been excluded in the cost calculation. The population centers of each region is assumed to be at sea level, and therefore, elevation difference is not considered in the inter-regional transport of water.

Table 10: Demand types and supply options at regional level in Abu Dhabi

Methods of Meeting Different Types of Demands (Kizhisseri et al., 2021)			
Regions	**Potable**	**Irrigational**	**Non-Potable**
Abu Dhabi	DW production, Inter-regional DW import	GW, DW production	GW, TS Production, DW production
Western	DW Production	GW, DW production	GW,TS, DW production
Al Ain	Inter-regional DW import, External DW import	GW, Inter-regional DW import, External DW import	GW, TS, Inter-regional DW import, External DW import

6.2 Key Data in the Study Area

The following key data sets used for the case study are included based on a detailed survey of the water system of Abu Dhabi: types of demands, water supply sources and types, types of technologies used in water production; capacity mix of existing water treatment plants; capacity sizes of inter-regional pipelines; and other key parameters and heuristic assumptions. However, local distribution and storage infrastructure are not considered in this study because of the complexity in obtaining and determining the data relevant to local distribution networks, and its relatively low contribution to the overall cost of infrastructure and operation. Therefore, the scenario solved for is developed based on several considerations that could characterize Abu Dhabi's plausible future.

6.2.1 Projected Water Demands

The region-wise demands for the whole planning horizon was forecasted using Abu Dhabi dynamic water budget model, developed in the Chapter 3 (Kizhisseri et al., 2021). The projected demands are shown in Table 11.

Table 11: Region-wise demands for the planning horizon

Year	Potable Demand (m³/day)			Irrigational Demand (m³/day)			Non-Potable Demand (m³/day)		
	Western	**Abu Dhabi**	**Al Ain**	**Western**	**Abu Dhabi**	**Al Ain**	**Western**	**Abu Dhabi**	**Al Ain**
2021	419163	2362553	1028854	690411	2439452	1472877	596147	1073065	715376
2022	436562	2460620	1071561	690411	2439452	1472877	611888	1101398	734265
2023	453961	2558688	1114267	690411	2439452	1472877	627628	1129731	753154
2024	471360	2656755	1156974	690411	2439452	1472877	643369	1158063	772042
2025	488759	2754822	1199681	690411	2439452	1472877	659109	1186396	790931
2026	506158	2852889	1242387	690411	2439452	1472877	674850	1214729	809820
2027	523557	2950957	1285094	690411	2439452	1472877	690590	1243062	828708
2028	540956	3049024	1327801	690411	2439452	1472877	706331	1271395	847597
2029	558355	3147091	1370507	690411	2439452	1472877	722071	1299728	866485
2030	575754	3245158	1413214	690411	2439452	1472877	737812	1328061	885374
2031	591262	3332567	1451279	690411	2439452	1472877	751841	1353315	902210
2032	606770	3419976	1489344	690411	2439452	1472877	765871	1378568	919045
2033	622278	3507384	1527409	690411	2439452	1472877	779901	1403822	935881
2034	637786	3594793	1565474	690411	2439452	1472877	793931	1429075	952717
2035	653294	3682202	1603539	690411	2439452	1472877	807960	1454329	969552
2036	668802	3769610	1641604	690411	2439452	1472877	821990	1479582	986388
2037	684310	3857019	1679670	690411	2439452	1472877	836020	1504836	1003224
2038	699818	3944428	1717735	690411	2439452	1472877	850050	1530089	1020059
2039	715326	4031836	1755800	690411	2439452	1472877	864079	1555343	1036895
2040	730834	4119245	1793865	690411	2439452	1472877	878109	1580596	1053731
2041	746342	4206654	1831930	690411	2439452	1472877	892139	1605850	1070566
2042	761850	4294062	1869995	690411	2439452	1472877	906168	1631103	1087402
2043	777358	4381471	1908060	690411	2439452	1472877	920198	1656357	1104238
2044	792866	4468879	1946125	690411	2439452	1472877	934228	1681610	1121074
2045	808374	4556288	1984190	690411	2439452	1472877	948258	1706864	1137909
2046	823882	4643697	2022255	690411	2439452	1472877	962287	1732117	1154745
2047	839390	4731105	2060320	690411	2439452	1472877	976317	1757371	1171581
2048	854898	4818514	2098385	690411	2439452	1472877	990347	1782624	1188416
2049	870406	4905923	2136450	690411	2439452	1472877	1004377	1807878	1205252
2050	885914	4993331	2174515	690411	2439452	1472877	1018406	1833131	1222088

6.2.2 Existing Water Treatment Facilities

All existing infrastructure in the Abu Dhabi for water production and pipeline transmission are considered. Different technologies and processes in use are considered for producing water of the required quality and quantity from various sources of raw water. Both DW and TS plants in Abu Dhabi are based on different types of technologies and process. The three prominent technologies for DW production in use are Multiple Effect Distillation (MED), Multi-stage Flash (MSF) distillation and Reverse Osmosis (RO). Also, DW plants in the EAD are installed as cogeneration plants producing both electricity and water. They are run using fossil fuel (i.e., natural gas), which is more than 99% of the total fuel consumption (Abu Dhabi Water and Electricity Company, 2018).

In Abu Dhabi, wastewater is treated in three consecutive levels: namely, primary (physical operation to remove suspended solids and organic matter), secondary (biological treatment to convert organic matter to settleable solids), and tertiary (to remove nutrients and microorganisms) treatments. In the EAD, major TS plants are working on a conventional biological process, that is, Activated Sludge Process (ASP). The options of Sequential Biological Reactors (SBRs), Moving Bed Bioreactors (MBBRs), and Membrane Bioreactors (MBRs) are other possible and tried options.

Data of all existing DW and TS plants were compiled from the published statistics by (Abu Dhabi Water and Electricity Company, 2018; ADDC, 2019; Statistics Centre - Abu Dhabi, 2018). Table 12 Shows the technology-wise capacity of all existing DW and TS plants.

Table 12: Initial capacity of DW and TS Plants in the EAD

Region *(r)*	Plant Location *(l)*	Technology *(k)*	Plant# *(n)*	Plant Capacity M^3/day
(a) Desalination Plants				
Western	Shuweihat S1	MSF	MSF_1	454000
Western	Shuweihat S2	MSF	MSF_2	454000
Western	New Mirfa	MSF	MSF_1	102150
Western	New Mirfa	RO	RO_1	136200
Abu Dhabi	Umm Al Nar	MSF	MSF_1	182508
Abu Dhabi	Umm Al Nar East	MSF	MSF_2	101696
Abu Dhabi	Sas Al Nakhel	MSF	MSF_1	400882
Abu Dhabi	Sas Al Nakhel	MED	MED_1	31780
Abu Dhabi	Taweelah B	MSF	MSF_1	315984
Abu Dhabi	Taweelah BExt	MSF	MSF_2	103512
Abu Dhabi	Taweelah BExt	MSF	MSF_3	314168
Abu Dhabi	Taweelah A1	MSF	MSF_4	145280
Abu Dhabi	Taweelah A2	MSF	MSF_5	227000
Abu Dhabi	Taweelah A1	MSF	MSF_1	236080
Fujairah*	Fujairah F1	MSF	MSF_1	286020
Fujairah*	Fujairah F1	RO	RO_1	167980
Fujairah*	Fujairah F2	MED	MED_1	454000
Fujairah*	Fujairah F2	RO	RO_2	136200
(b) Wastewater Treatment Plants				
Western	Madinat Zayed	ASP- Conv	ASP_1	30000
Western	Liwa	ASP- Conv	ASP_1	10000
Western	Ruwais	ASP-Conv	ASP_1	45000
Western	Mirfa	ASP-Conv	ASP_1	16000
Western	Sila	ASP-Conv	ASP_1	5000
Western	Ghayathi	ASP-Conv	ASP_1	15000
Abu Dhabi	Wathba	ASP-Conv	ASP_1	300000
Abu Dhabi	Wathba	ASP-Conv	ASP_2	300000
Abu Dhabi	Mafraq	ASP-Conv	ASP_1	270000
Al Ain	Al Saad	ASP-Conv	ASP_1	80000
Al Ain	Al Hammah	ASP-Conv	ASP_2	130000

Sources : (Abu Dhabi Water and Electricity Company, 2018; ADDC, 2019; Statistics Centre - Abu Dhabi, 2018))

This study considered that existing plants can be expanded from a set of technologies possible for installation at each location. As more data are required on the site feasibility, in this case study, only those existing technologies popular in the

UAE were considered for capacity expansion by the model. Therefore, for DW plants, MSF, MED and RO are the options available. For WTP, the options of ASP, MBBR and MBR are included in the selection by the model during optimization.

6.2.3 Water Transmission System

In the EAD, DW is imported between the regions and from outside the regions. Both TS and GW are restricted to local use. The water transmission system is used to supply water to the land-locked region (Al Ain) and Abu Dhabi region, where the demand is higher than the available production capacity within the region for various reasons. Al Ain region imports DW from DW plants outside Abu Dhabi, such as Fujairah, and those located in the adjacent region, namely, Umm Al Nar and Taweelah. However, the exact distance of the pipeline route is unknown. Therefore, the shortest distance between, respective, supply origin (DW plants) and the key distribution point in the connecting region is considered an approximation to the pair-wise distance to calculate the pumping distance. Moreover, it is assumed that no significant difference exists in the elevations of the connecting points. This study considers that water flows in the pipelines only in one direction, although, in reality, the option of reverse flow exists for an emergency. In most of the recently installed pipelines, ductile iron (DI) pipes have been used to connect regions with diameter sizes ranging from 800 mm to 1600 mm. Therefore, in this optimization, the model is given the option of selecting pipe sizes from the following diameter sizes (1000 mm, 1200 mm, 1400 mm, and 1600 mm) during the optimization process. The maximum capacity of each pipe diameter is calculated based on the assumption of a velocity of 2 m/s and an operation time of 20 hours daily, consistent with requirements by (ADDC, 2019). The list of existing pipeline networks within the regions and those connecting external DW plants to Al Ain is shown in Table 13.

Table 13: Initial capacity of inter-regional DW transmission system in the EAD

Transmission Line Regions		**Flow Direction**	**Pipe Diameters***	**Pipe Capacity** M^3/day**
Link-1	**Link-2**			
Shuweihat	Abu Dhabi	Shuweihat ➡ Abu Dhabi	2 x 1600 mm	868146
Umm Nar	Al Ain	Umm Al Nar ➡ Al Ain	1 x 1000 mm	169560
Taweelah	Al Ain	Taweelah ➡ Al Ain	2 x 1200 mm	488332
Fujairah	Al Ain	Fujairah ➡ Al Ain	3 x 1600 mm	1302219

*compiled from (Abu Dhabi Water and Electricity Company, 2018; ADDC, 2019)
** Calculated using the daily Operating time of 20 hrs and velocity 2 m/s

6.2.4 Other Parameters

Many constraints in the model contain parameters and the accuracy of the results of the model depends on these parameters. In this study, most data were obtained from the available literature and estimated from the publicly available sources, while a few were estimated based on heuristics.

6.2.4.1 Cost Parameters

In this case study, the unit cost is measured in US dollars ($) and converted to the present value corresponding to 2020. The cost components considered are grouped under three categories: (1) unit capital cost, (2) unit OM costs, and (3) unit environmental costs.

Unit capital cost is the cost for a new construction or expansion of infrastructure of unit m^3 capacity. The unit capital cost of construction depends on the technologies, size of the infrastructure to constructed or expanded, and site of the construction. Considering these factors, the most possible accurate average values were found by linearizing the cost functions for all types of infrastructure for the capacity ranges considered.

(a) Unit capital costs:

The study focused on desalination technologies prevalent in the Middle East and their per unit capital cost or expansion were estimated. In this study, the cost data from several sources were used to derive the average cost of different sizes of plants. The data required are obtained from several sources: (Ibrahim Kizhisseri et al., 2020; Global Water Intelligence, 2020). The DEEP and WTCost software were also deployed to verify the cost parameters of DW plants (Moch & Chapman, 2004). The capital costs of the plants vary based on the capacity. However, the capacity relation, which is nonlinear, has been linearized to find the unit costs for plants for different sizes considered in the case study.

The unit capital cost of the WWT plants depended on the plant capacity, the treatment process, and design criteria. Several references have developed cost functions for different treatment processes. The data from various sources were combined to estimate the average unit costs of various treatment processes and sizes of plants considered for this case study (Abdulbaki et al., 2017; Gonzalez-Serrano et al., 2005; Hernandez-Sancho et al., 2011).

The capital costs of various technologies of DW and TS plants considered in the case study are given in Table 14.

Table 14: Unit capital cost of water treatment plants

Treatment Plant Type	Technology	*Unit Capital cost/ m^3/day Capacity $/$m^3$
DW	MSF	1933
DW	MED	2443
DW	RO	1404
TS	Conventional-ASP	420
TS	MBBR	660
TS	MBR	750

*Compiled and estimated from multiple sources: (Chaudhry, 2003; Hernandez-Sancho et al., 2011; Ibrahim Kizhisseri et al., 2020; Lamei et al., 2008; Marchionni et al., 2015; Moch & Chapman, 2004)

As water transportation from one location to another is dependent on many factors, such as pumping distance, pumping elevation difference, and soil type, a comparison of the cost of pipeline construction from one location to another is difficult. Considering this, the studies that focused on developing cost relation for long-distance water pipeline cost estimation based on data from different long-distance pipeline projects. Capital costs were correlated with the distance of transport and capacity. The capital costs of installing pipelines with DI pipes and its associated fittings and equipment have been estimated from the cost functions (Chee et al., 2018; Lamei et al., 2008; Lockwood et al., 1967; Marchionni et al., 2015; Water Globe

Consultants, 2016). The unit cost was derived from the overall capital cost by dividing it with distance of pipeline. Table 15 shows the estimated costs for various diameter sizes considered in the study.

Table 15: Unit capital cost of installing DW pipelines

Pipe Type	**Diameter Size(mm)**	***Unit Cost for Installing per unit length $/m**
DI Pipe	1000	672.5
DI Pipe	1200	927.8
DI Pipe	1400	1225.4
DI Pipe	1600	1565.2

*Compiled and estimated from multiple sources : (Chee et al., 2018; Lamei et al., 2008; Lockwood et al., 1967; Marchionni et al., 2015)

(b) Unit OM costs:

The unit OM cost of DW plants is the cost of production of 1 m^3 of desalinated water using the respective technologies and represented by $/$m^3$ of water produced. The OM cost is the function of plant capacity and operation levels of plants. The correlation plots are reported by: (Chaudhry, 2003; Frioui & Oumeddour, 2008; Karagiannis & Soldatos, 2008; Malek et al., 1996; Moch & Chapman, 2004; Papapetrou et al., 2017; Sommariva & Syambabu, 2001; Tofigh & Najafpour, 2012; Wittholz et al., 2008). In addition, the simulation of various process condition in the DEEP software was used to estimate and compile the unit OM costs of various desalination technologies considered in this study. The unit OM costs of various DW plant types are shown in Table 16.

Table 16: Unit OM cost of water treatment plants

Treatment Plant Type	**Technology**	***Unit OM cost/ m^3 produced ($/$m^3$)**
DW	MSF	0.26
DW	MED	0.14
DW	RO	0.64
TS	Conventional-ASP	0.21
TS	MBBR	0.20
TS	MBR	0.30

*Compiled and estimated from multiple sources : (Chaudhry, 2003; Frioui & Oumeddour, 2008; Karagiannis & Soldatos, 2008; Malek et al., 1996; Moch & Chapman, 2004; Papapetrou et al., 2017; Sommariva & Syambabu, 2001; Tofigh & Najafpour, 2012; Wittholz et al., 2008)

Data on TS plants based on different processes were compiled from different sources of literature. The major wastewater processes prevalent in the region for municipal wastewater treatment are found to be the conventional ASP and membrane bioreactor. The cost curve for the conventional system of wastewater treatment by ASP is available from (Abdulbaki et al., 2017; Gonzalez et al., 2016; Hernandez-Sancho et al., 2011). The cost data function was linearized to estimate average OM cost for TS plants for installation sizes considered in this case study. The unit OM costs for TS plants are listed in Table 16.

The unit cost of transporting 1 m^3 water per kilometer is found from various correlations (Abdulbaki et al., 2017; Lamei, 2009). It was approximated to be $5 per 100 km transportation.

(c) Environmental costs:

Environmental cost is included to quantify various environmental impacts arising from the use of various water supply sources and the costs incurred in environmental compliance monitoring. Environmental cost is a monetized measure of environmental damages owing to production technologies by emitting GHG, disposal of the wastes produced, and causing depletion of a natural resource. In this case study, environmental costs are estimated in terms of $/$m^3$ of water produced. The carbon cost for the emission of GHG at the treatment plants of DS and TS and during the transportation of water are used to measure global warming potential. As the CO_2 emissions are directly dependent on the fuel used, the CO_2 emissions from DS plants in Abu Dhabi are considered in terms of carbon footprint for each type of technology and process. The carbon footprint gives an estimate of the amount of GHG emitted into the atmosphere and expressed as kilograms of CO_2 equivalents (kg-CO_2-e). Several authors have used a monetary cost for this emission (Abu Dhabi Quality and Conformity Council, 2015; Morris et al., 2008; United Nations Environment Programme, 2008). In this study, a value of 0.025 $ / kg-e CO_2 was used as a base value.

Considering that GW in Abu Dhabi is a nonrenewable source of water with less than 4% of GW used is recharged, consistent with the economic value for GW reserves in Abu Dhabi by (RTI International, 2015), an environmental cost in terms of $/$m^3$ for GW used is assigned. The economic evaluation considers various aspects such as sustainability and cost–benefit analysis applying the hydro-economic model. This has been identified as a meaningful metric to be used in policy frameworks if policymakers are interested in setting a price on the GW to reflect the scarcity value and encourage the efficient use of available water resources. An estimated value of 1.15 $\$/m^3$ is implemented in this study.

Another environmental aspect included in the model is brine disposal from DS plants and its handling. The impacts of brine discharge from DW plants to sea are numerous, such as an increase in salinity levels and other metals, contribution to global warming, increase in the temperature of the receiving water body, and impact on aquatic life. However, no equivalent monetary costs are available to quantify brine disposal impacts. Therefore, in this study, we have used per unit cost incurred in operating brine disposal facilities. The unit cost in $\$/m^3$ of brine discharge is obtained from (Y. Saif & Almansoori, 2014) and its implementation in the model allows optimizing overall brine disposal. The brine disposal rates considered in this study are \$0.0015, \$0.0015, and \$0.04 per m^3 of brine discharged from MED, MSF, and RO plants, respectively.

6.2.4.2 Bounds on New Installations

The capacity expansion at a production site is subject to space availability, technology limitation and so on. For those assets without available data on expansion limits, a heuristic assumption was made to set the bounds. A lower limit for an increase in capacity at a production site is set be 20% of the initial capacity, while an upper limit is set be 50% during an expansion. Another bound set is on the number of years of the time gap between two successive expansions or installations at a site is kept at 8 years, as a heuristic assumption. Besides, the maximum number of times

(*N_Plant_Exp and N_Pipe_Retro*) that an asset can undergo expansion is limited by assigning a value of 3 for the entire planning horizon. A CLT of 2 years is applied for all construction works.

6.3 GAMS Outputs

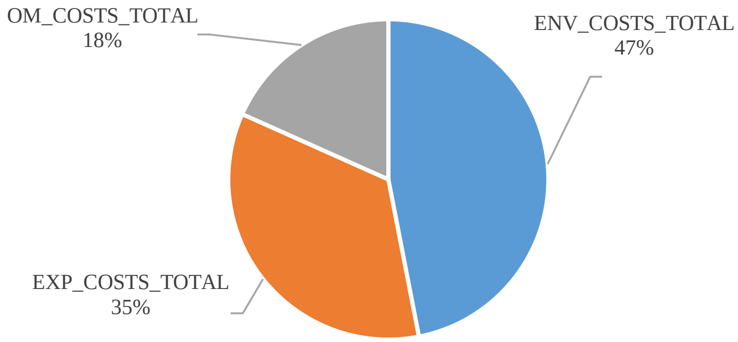
The MILP model for solving multi-period, multi- regional problem of water resources planning in Abu Dhabi has been programmed into GAMS 23.1, and solved using the solver Cplex 12.1. The parameters required by the model (discussed under Section 4.2) were retrieved via import option in GAMS add-on tools which enables GAMS to retrieve data from Excel files and use the data as input parameters to the model.

The scenario formulated for the case study has a total of 7655 EQUATIONS, 5277 continuous variables, and 1350 binary variables. The optimal solution was obtained after a CPU time of around 650 seconds while run on a core i7 computer.

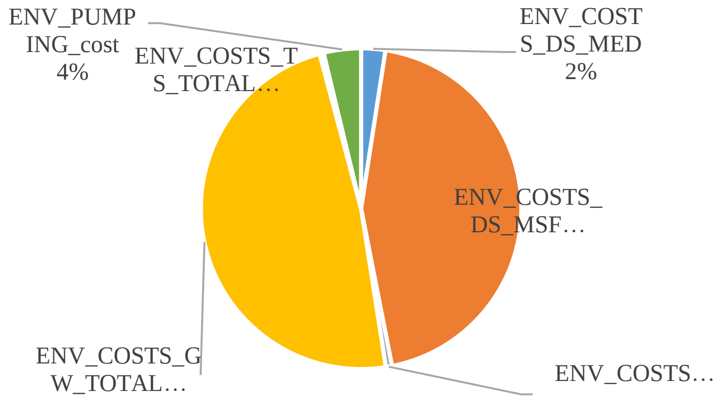
Based on the model base run, the optimal capacity expansion pathway of the water sector infrastructure in Abu Dhabi for the BAU future is obtained. This includes the composition of water supply sources, the technology composition for producing different types of water, capacity of each type of plants for each year, decisions on the installation of assets - for both plants and pipeline networks, yearly emissions of CO_2, yearly brine discharge, and yearly GW abstractions. Sensitivity analysis was performed to understand the effects of varying values of various parameters on the optimal solution. The results are discussed in detail as follows.

6.3.1 Overall Costs and Its Breakdown

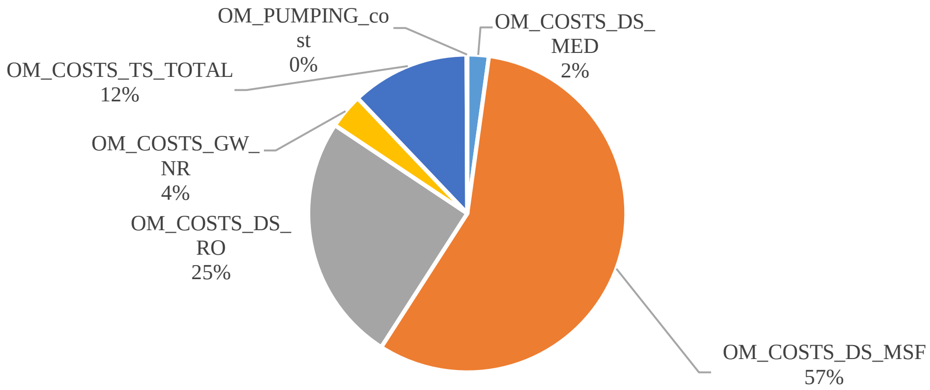
The optimized solution of the problem is the total cost for the entire planning period. The model estimated the NPV as 126.76 billion dollars (B$). The breakdown of the total cost is given (Figure 15). The major cost incurred is in the form of environmental cost which is about 47% of the total cost. The three types of costs are given in figures (Figure 15 (b) - (d)). A large environmental cost is incurred because of the conversion of the carbon footprint and depletion value for GW into monetary values. These indicators are very significant especially in a place like Abu Dhabi because the GW reserve is non-renewable. A high carbon cost is incurred by the water production through thermal cogeneration plants using MSF and MED followed by the capital cost required for capacity expansions of DW plants. Given that the total cost depends on the various unit costs, we have studied their effects on total costs and discussed under sensitivity analysis in Section 6.4.



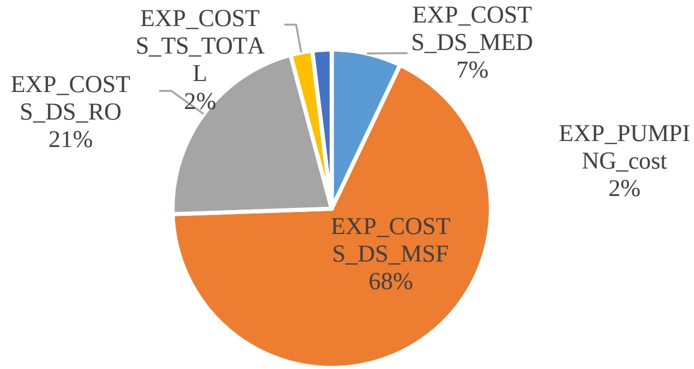
(a) Overall cost breakdown



(b) Environmental cost breakdown



(c) OM cost breakdown



(d) Investment cost breakdown

Figure 15: Breakdown of the optimal total cost for the case

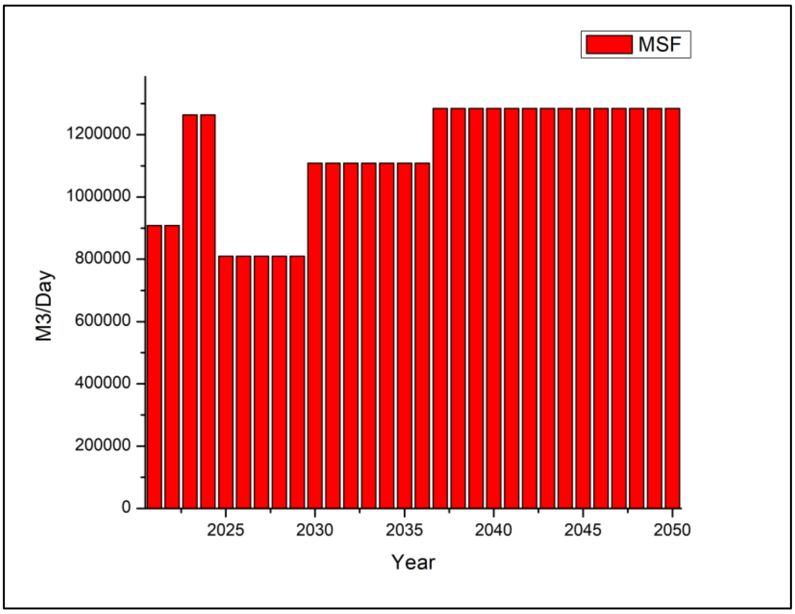
6.3.2 Capacity Expansion

The optimal solution for an increase in capacity of DW plants at different locations for the entire planning period and technology as solved by the proposed model is given in Figure 16. All the DW plant sites should undergo capacity increase by choosing an optimal technology and year, satisfying all the constraints in the model for the selected scenario. The capacity of a plant is considered a non-decreasing function. However, in some plant locations, a decline in capacity can be noted in the planning horizon because of the decommissioning of the retiring plants incorporated into the model. At the site, Shuweihat, as shown in the Figure 16 (a), the MSF plants will have to undergo capacity expansions in the years 2023, 2030 and 2037. The model also has considered the retirement of the plant units at this site in the year 2025.Similary, at Mirfa where both RO and MSF technologies are in place, the capacity expansion plan as solved by the model has opted more RO than MSF. It can be seen that the capacity of MSF at Mirfa has to come down to 61290 m^3/day from 102150 m^3/day while the RO will show an increase to 681000 m^3/day in 2050 from 136200 m^3/day in 2020 (Figure 16 (b)). At the site Umm Al Nar where capacity expansion was given with choices of MSF and MED, it was seen that the model opted for MSF technology. The MED capacity is almost halved while MSF capacity is to increase by about five times by 2050 (Figure 16 (c)). At Taweelah where the options are for RO and MSF, a trend in which RO is opted over MSF is evident (Figure 16 (d)). At Fujairah site, the options of technology selection were RO, MSF and MED for the capacity expansion. However, the model opted RO over both the MED and MSF. This means RO capacity will increase largely but MED and MSF capacity will be reduced with planned decommissioning of the existing units (Figure 16 (e)).

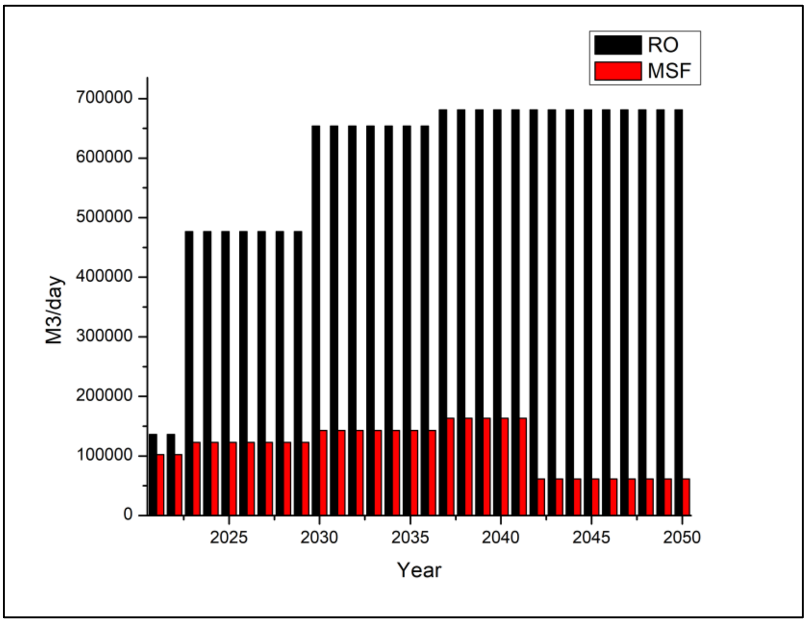
The overall technology-wise capacity for whole Abu Dhabi water demands in the initial year 2020 and 2050 as solved by the model is given in Table 17. The technology-wise contribution of capacity in 2050 will be MSF- 9520309 m^3/day, RO- 2201900 m^3/day, and MED- 433116 m^3/day. Another key observation is that RO contribution would increase from 5.1% in 2021 to 18.1% in 2050. It can be seen that the model has opted for capacity expansion by choosing more RO. The relatively smaller selection of MSF and MED is because of their high capital cost and carbon footprint. Naturally, the model has selected RO as the first option because it is the least expensive. Besides, MED and MSF are less energy consuming but have higher carbon footprint and lower recovery rate. In contrast, RO is energy expensive but has higher recovery. Therefore, the model selects more RO to satisfy all the model constraints while minimizing the total cost.

Table 17: Technology wise capacity of DW plants

Technology	**Technology Wise Capacity for DW Production (% contribution to overall)**	
	2021	**2050**
MED	721860 (8.3%)	433116 (3.6%)
MSF	7510976 (86.6%)	9520309 (78.3%)
RO	440380 (5.1%)	2201900 (18.1%)

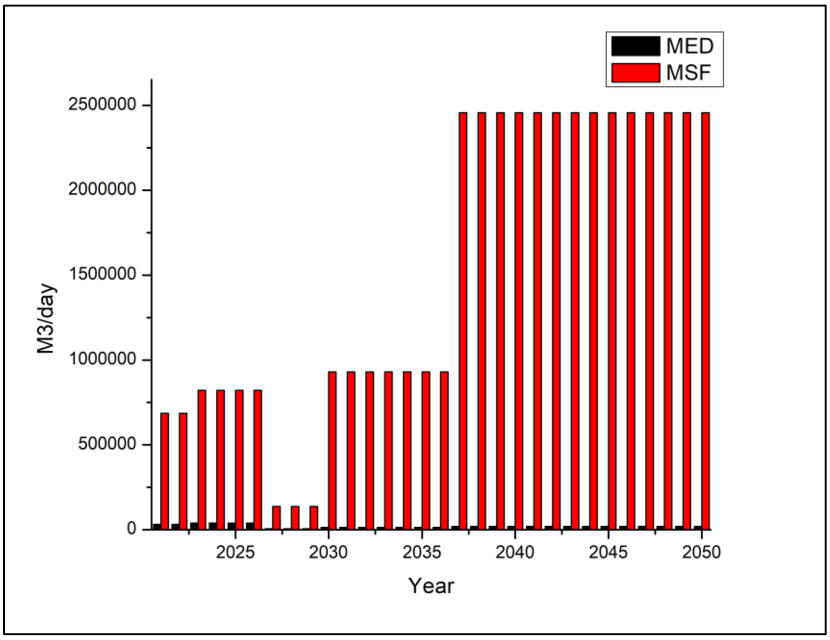


(a) Capacity required for different years at Shuweihat

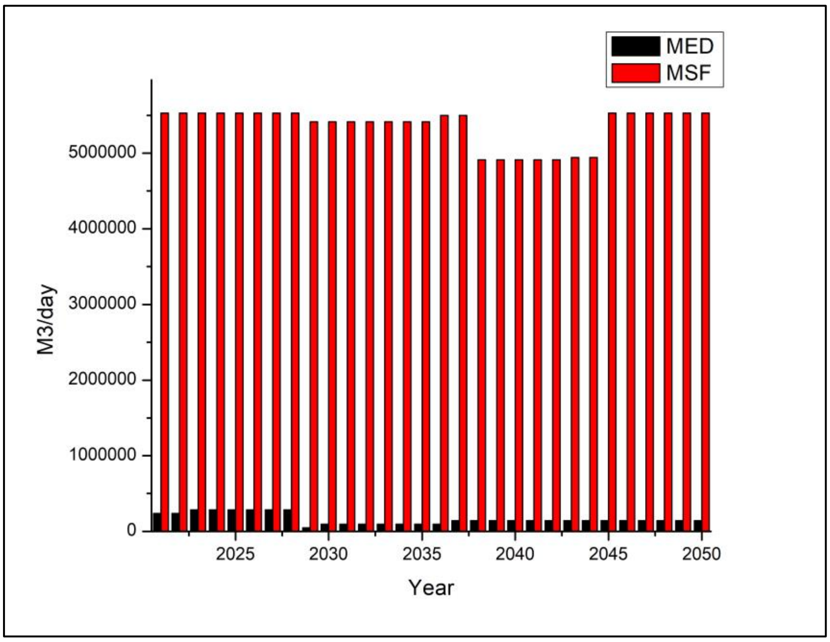


(b) Capacity required for different years at Mirfa

Figure 16: DW capacity expansion and the technology mix over years at all DW plant locations.

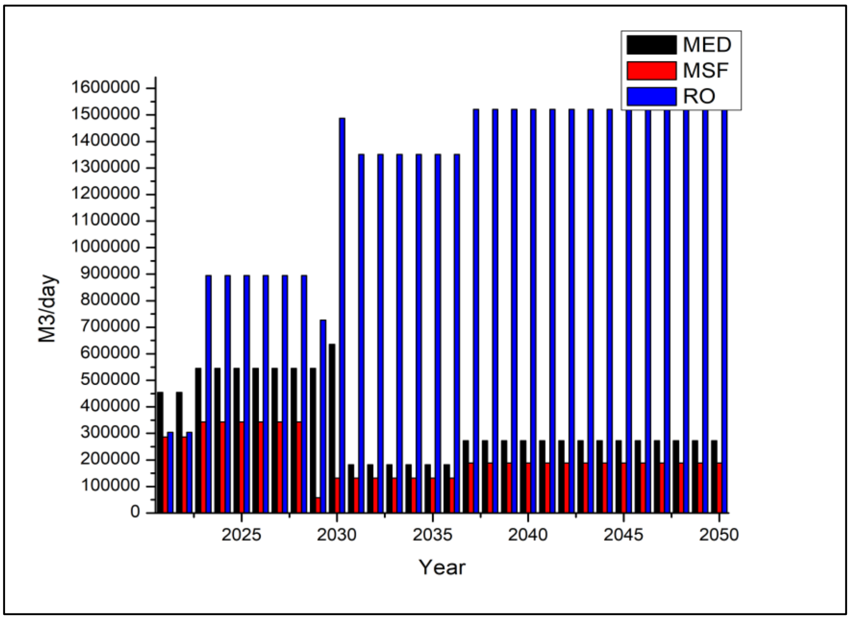


(c) Capacity required for different years at Umm Al Nar



(d) Capacity required for different years at Taweela

Figure 16: DW capacity expansion and the technology mix over years at all DW plant locations (Continued)



(e) Capacity required for different years at Fujairah

Figure 16: DW capacity expansion and the technology mix over years at all DW plant locations (Continued)

Other observations that can be made from the model are related to the wastewater treatment plants. The year-wise capacities of WTPs at all plant locations for selected years (every tenth year in planning horizon) are shown in Figure 17. For WW treatment, the expansion of TS plants based on ASP is the optimal option at all sites, which is likely because of the large capital costs needed for MBR and MBBR plants although the unit OM costs are comparable with conventional ASP. Besides, ASP has a lower carbon footprint than the other two technologies included in the model. Naturally, the model would have selected ASP because it is the least expensive of the available processes and has low carbon emission.

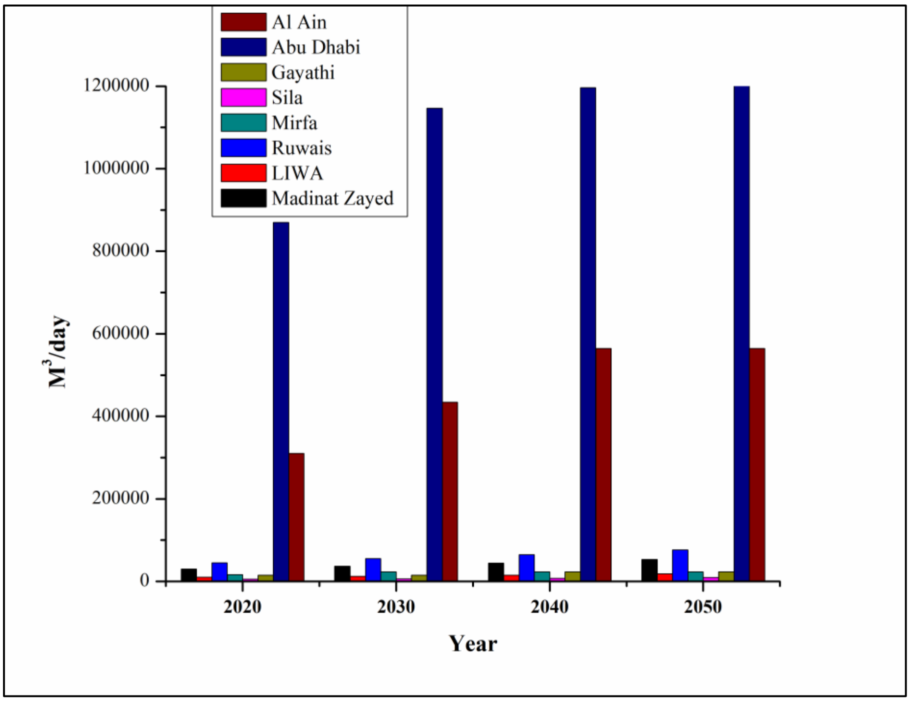


Figure 17: Capacity expansion for the TS plants at all locations

The contribution of GW in meeting water demands is shown in Figure 18. The GW in the EAD is used without any treatment. Therefore, the capacity of GW production is not limited by plant capacity. However, the GW abstraction is limited by a maximum yearly limit in the model and it determines the sustainability of GW reserve in the EAD. The maximum limit on GW abstraction was set so that the GW reserve will last for at least another 150 years. Based on this, the model has chosen GW as the best supply option for irrigation and nonpotable demands. The use of GW opted by the model is constant for most years, except for a few years when there is maximum use because some DW plant decommissioning the surplus DW being supplied to irrigational will be interrupted. This is compensated in the optimal solution by the model with the increase of GW usage for such years. GW abstractions are still the best choice for irrigation demand even after imposing an environmental cost because of the large investment and environmental costs associated with all DW technology types.

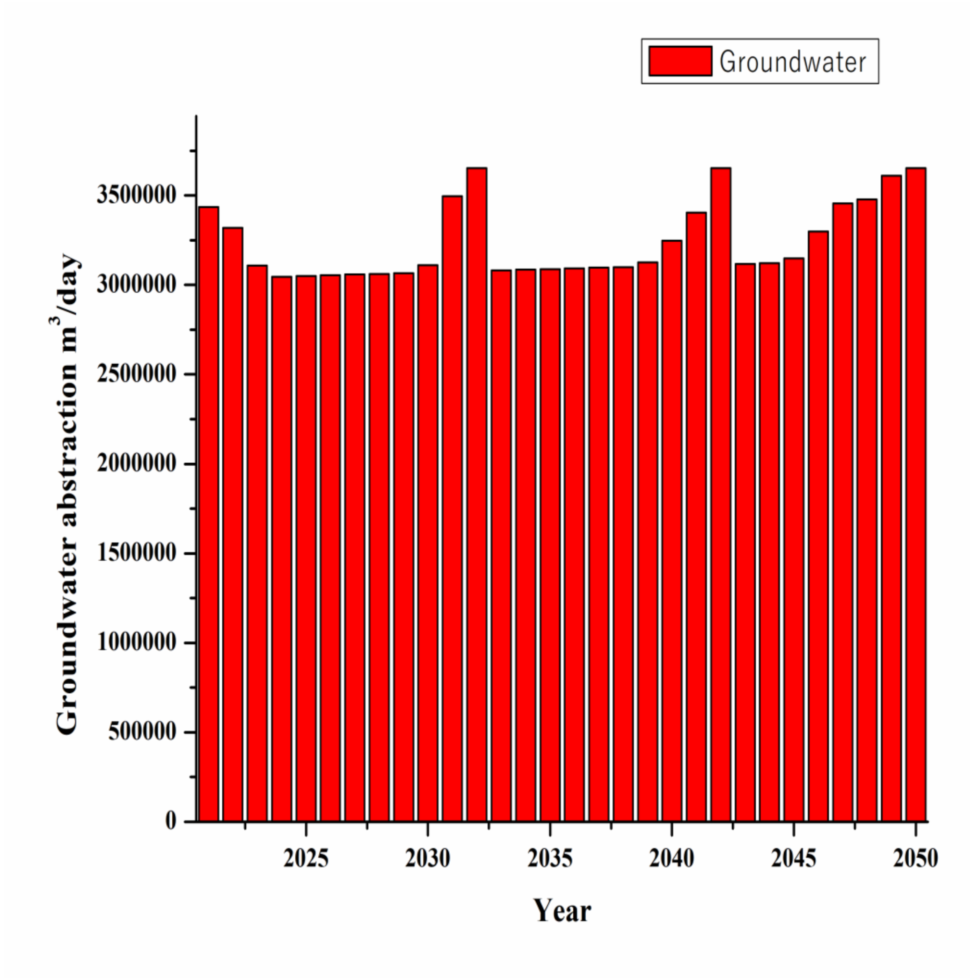


Figure 18: GW utilization trajectory for the planning horizon

Table 18 shows the capacity expansion requirement for DS water transportation. The optimal solution suggests that the new installations are required between the following regions: Shuweihat–Abu Dhabi, Umm Al Nar–Al Ain, Taweelah–Al Ain, and Fujairah–Al Ain, at different times of the planning horizon and diameter sizes.

Table 18: Inter-regional DW transmission line expansion plan

Transmission Line Regions		**Year of Retrofit Start**	**Year of Completion**	**Flow Direction**	**Pipe Diameters**
Link-1	**Link-2**				
Shuweihat	Abu Dhabi	2039	2041	Shuweihat to Abu Dhabi	1 x 1000 mm
Umm Al Nar	Al Ain	2036	2038	Umm Al Nar to Al Ain	1 x 1000 mm
Taweelah	Al Ain	2038	2040	Taweelah to Al Ain	1 x 1000 mm
Taweelah	Al Ain	2046	2048	Taweelah to Al Ain	1 x 1000 mm
Fujairah	Al Ain	2034	2036	Fujairah to Al Ain	1 x 1400 mm

6.3.3 Environmental Indicators

(a) CO_2 Emission Trajectory

The model has solved the problem of the capacity expansion considering the constraint to minimize carbon emission. Although an annual carbon limit can be imposed, it was not imposed for this case study scenario. However, the model has solved for an optimal solution by selecting optimal capacities for technologies and operation of a water system of Abu Dhabi by minimizing carbon emissions. The trajectory of carbon emission from various operations for the entire planning period is shown in Figure 19. The optimal solution showed that the overall carbon emissions would reach 250159846.7 kg CO_2-e in 2050 if no carbon capture technologies were implemented.

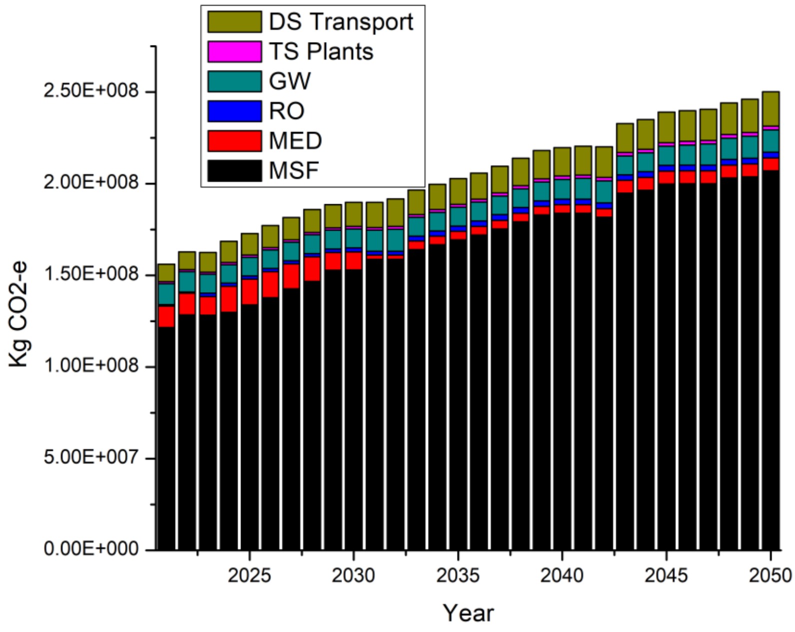


Figure 19: Carbon emission from various technology based plants, operation and transportation

(b) Brine Discharge:

The discharge of highly saline brine from the desalination plants is considered an environmental concern in the EAD. The brine from the DW plants supplying water to the EAD is discharged into two water bodies. The DW plants in the Western and Abu Dhabi regions discharge brine to the Arabian Gulf. While the DW plants located in Fujairah, a location outside the EAD, discharge brine into the Gulf of Oman. Therefore, the brine discharge into both these water bodies should be reduced in the optimal solution. The technology-wise brine discharge are shown in Figure 20. The optimal solution shows that major brine comes from the MSF because of a lower recovery rate and high percentage of capacity contribution in DW production in the UAE. The increase in RO installations in the optimal solution is because of the higher recovery rate compared with both MED and MSF. Therefore, an improved recovery rate at all plants can reduce brine discharge, thus lessening impact on the marine environment.

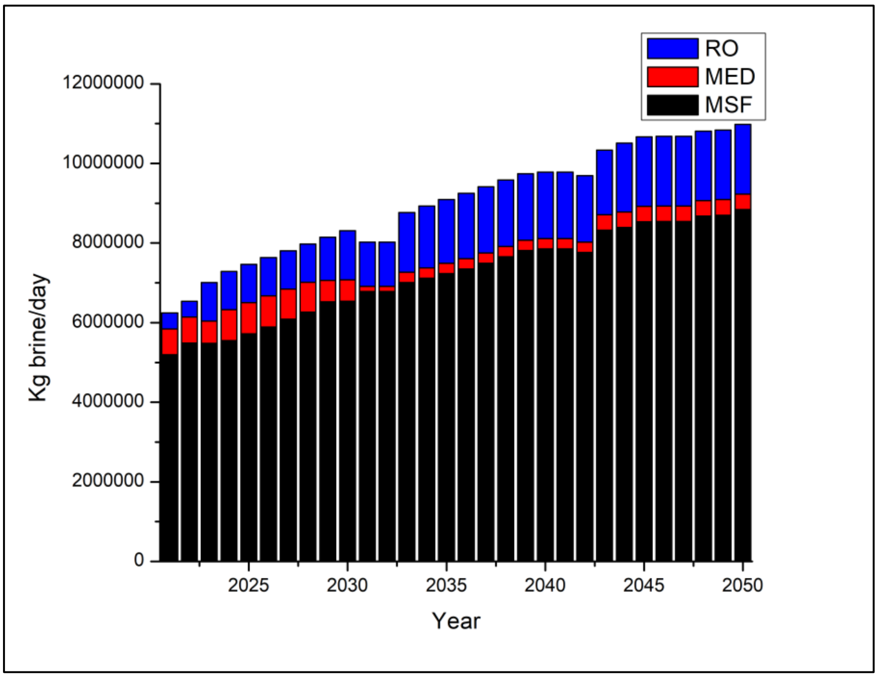


Figure 20: Technology-wise contribution to brine discharge over years

6.4 Sensitivity Analysis of Key Parameters

Sensitivity analysis was performed to determine the effects of changing parameters of the model. The data for the base run along with the model outputs for various sensitivity analysis cases are put in Table 19.

For the baseline run, in the model, an environmental cost of 1.15 \$/ m^3 was assigned for GW. However, for the sensitivity analysis, the range of environmental cost considered is 0–\$1.25/m^3. The results showed that while no cost was assigned for GW, the total cost was reduced to 60% (74.11 B\$) compared with the baseline cost of \$126.76 billion (Table 19), which implies that allocating the environmental cost affects the total cost. Besides, other observations while varying the GW environmental cost are in the selection of technologies for DW plants. For a cost of \$0.5 /m^3 or less, the MED technology is excluded from the solution and replaced with MSF. Thus, a cost more than \$0.5/m^3 affects the selection process of optimal DW technology.

The impact of allocating carbon tax or cost based on carbon emissions during various stages of water production and supply are studied. The idea of allocating a monetary cost for the GHGs is in practice, although it is a debated subject. In the base run, a marginal cost of \$0.025 / kg-CO_2-e is assigned. However, to understand how it affects the optimal solution, a range of cost from \$0.025 / kg-CO_2-e to \$0.25 / kg-CO_2-e was selected, consistent with the value ranges used by (Moore & Diaz, 2015; Y. Saif & Almansoori, 2014). For this range, the overall cost varied between \$99.19 billion and \$378.5 billion. This shows how significant is the assigning carbon cost as the total cost tripled in the range studied (Table 19).

Thus, the sensitivity study indicates that various environmental costs and its values play a significant role in the optimal solution. The sensitivity analysis values showed that assigning a lower economic value for GW (less than 0.3 \$/m^3) has no much significant impact on the overall cost of water planning and infrastruction expansion. However, when the GW was given a value more than 0.3 \$/m^3, the results showed that DW are also opted for irrigational demand. This is because the overall of cost of DW becomes comparable with GW cost. The carbon cost when assigned with a value greater than \$0.1 / kg-CO_2-e showed a high impact on the overall cost as well as on the selection of technologies for desalination. This indicates that when the carbon cost assigned is increased, the technologies with high carbon emissions are least opted. Therefore, choosing an appropriate environmental cost value for both GW economic value and carbon footprint for all water technologies is essential. The impact of change in the capital cost of various process technologies were studied by changing the base run value of the capital costs (Table 19). A range of −10% to +10% variation was studied. The results showed that the total cost did not vary significantly over the range studied and only a change of about 3% variation was noted. Thus, the change in capital cost does not affect the optimal solution. Besides, it did not affect the selection of technologies as the capital cost variation was implemented for all technologies. Therefore, unit capital cost of treatment plants of various technologies has less impact on technology mix for supply of water supply.

Similar to capital costs, variations in OM costs in the range −10% to +10% change from the base run value of OM costs were studied (Table 19). The results showed a low impact on the total cost; for instance, less than 2% increase for a 10% increase in the unit OM cost. The change had an insignificant impact on the process selection of water treatment technologies.

Table 19: Impact of parametric values on costs and capacity selection for the baseline and sensitivity analysis scenarios

Variation in Parametric Values	**Total Cost B$**	**Technology Wise Overall Capacity in 2050 (M3/day)**				
		MSF	**MED**	**RO**	**GW**	**ASP**
1. GW cost ($/m3)						
0	74.11	9896506	0	2201900	3652967	2060612
0.1	83.11	9896506	0	2201900	3652967	2060612
0.2	101.23	9896506	0	2201900	3652967	2060612
0.3	87.63	9896506	0	2201900	3652967	2060612
0.5	101.23	9520309	433116	2201900	3652967	2060612
0.75	111.14	9520309	433116	2201900	3652967	2060612
1	121.08	9520309	433116	2201900	3652967	2060612
Base run (1.15)	126.76	9520309	433116	2201900	3652967	2060612
1.25	130.6	9520309	433116	2201900	3652967	2060612
2. Carbon emission cost ($/KgCO2-e)						
0	99.19	9587305	433116	2119441	3652967	2060612
Base run (.025)	126.76	9520309	433116	2201900	3652967	2060612
0.05	158.36	9503674	448087	2201900	3652967	2060612
0.1	216.57	8325090	1626671	2201900	3652967	2060612
0.15	270.76	8325090	1626671	2201900	3652967	2060612
0.2	324.37	8325090	1626671	2201900	3652967	2060612
0.25	378.5	8325090	1626671	2201900	3652967	2060612
3. Percentage variation in Capital cost from model base run						
-2%	126.08	9520309	433116	2201900	3652967	2060612
-5%	125.25	9520309	433116	2201900	3652967	2060612
-10%	123.36	9520309	433116	2201900	3652967	2060612
Base run	126.76	9520309	433116	2201900	3652967	2060612
2%	127.43	9520309	433116	2201900	3652967	2060612
5%	128.45	9520309	433116	2201900	3652967	2060612
10%	130.58	9520309	433116	2201900	3652967	2060612
4. Percentage variation in OM cost from model base run						
-2%	126.37	9520309	433116	2201900	3652967	2060612
-5%	125.8	9520309	433116	2201900	3652967	2060612
-10%	124.84	9520309	433116	2201900	3652967	2060612
Base run	126.76	9520309	433116	2201900	3652967	2060612
2%	127.14	9520309.649	433116	2201900	3652967	2060612
5%	127.72	9520309.649	433116	2201900	3652967	2060612
10%	128.68	9520309.649	433116	2201900	3652967	2060612

6.5 Chapter Summary

In this chapter, the MILP optimization model developed in chapter 5 was implemented for Abu Dhabi water planning until 2050. The problem setting that involved the estimation of all MILP model parameters, and other model inputs are explained. Then, the model was solved for a scenario, and its results from the model are discussed. A sensitivity analysis was also carried out to find out the sensitivity various parameters on key model outputs. The model developed in this chapter is first of its kind to be developed for an arid or semi-arid condition for multi-period integrated water management and planning. This can be used as a decision making tool for developing long-term water strategies for large geographical land area.

Chapter 7: A Decision Support System for Sustainable Water Planning in Arid Regions

The use of decision support systems in the field of water resource management and planning is now widely implemented, but its use in sustainable water planning of a nation or state in arid and semi-arid areas, such as Middle Eastern countries, remains limited (Giupponi & Sgobbi, 2013b, 2013b; K. Zhang et al., 2014). Therefore, the main idea of this chapter is to present a graphical interface that incorporates the ADWBM and ADWCPM to assist water planners and decision makers in water planning is developed.

7.1 Methodology

In this study, a DSS for sustainable water planning is developed for the Emirate of Abu Dhabi (EAD), UAE and is named as "Sustainable Water Budgeter for Abu Dhabi" (SuWaB-AD). The tool development involved integration of two major component models to be used as a user-interactive tool as given in the Figure 21 : (i) the ADWBM developed in (Chapter 3) to develop future water scenarios by forecasting water demands, available water resources, and the annual water balances for the whole planning horizon; and (ii) the multi-period capacity planning optimization model developed in (Chapter 5) which takes the water demands forecasted by the ADWBM, water allocation arrangements for all demand zones, system efficiencies and environmental requirements. The overall design focused on developing a user-friendly tool with interface so that these models can be used and run by even a non-expert to generate the results in the form of graphs, charts, and tables. The DSS SuWaB-AD allows a 30-year planning, and its outputs are centered on user inputs to run the models incorporated within it.

The output of the model from GAMS is exported to a Microsoft Excel file where it is automatically formatted into tables and figures. In addition to the Excel Output file, GAMS also generates an output file which contains raw data results and specific model statistics.

7.2 Development of DSS: SuWaB-AD

The architecture of SuWaB-AD is designed in an interconnected modular framework. The general concept, interaction, and data flow between the modules are depicted in Figure 21. The SuWaB-AD consists of three main components; namely, user interface, models, and database.

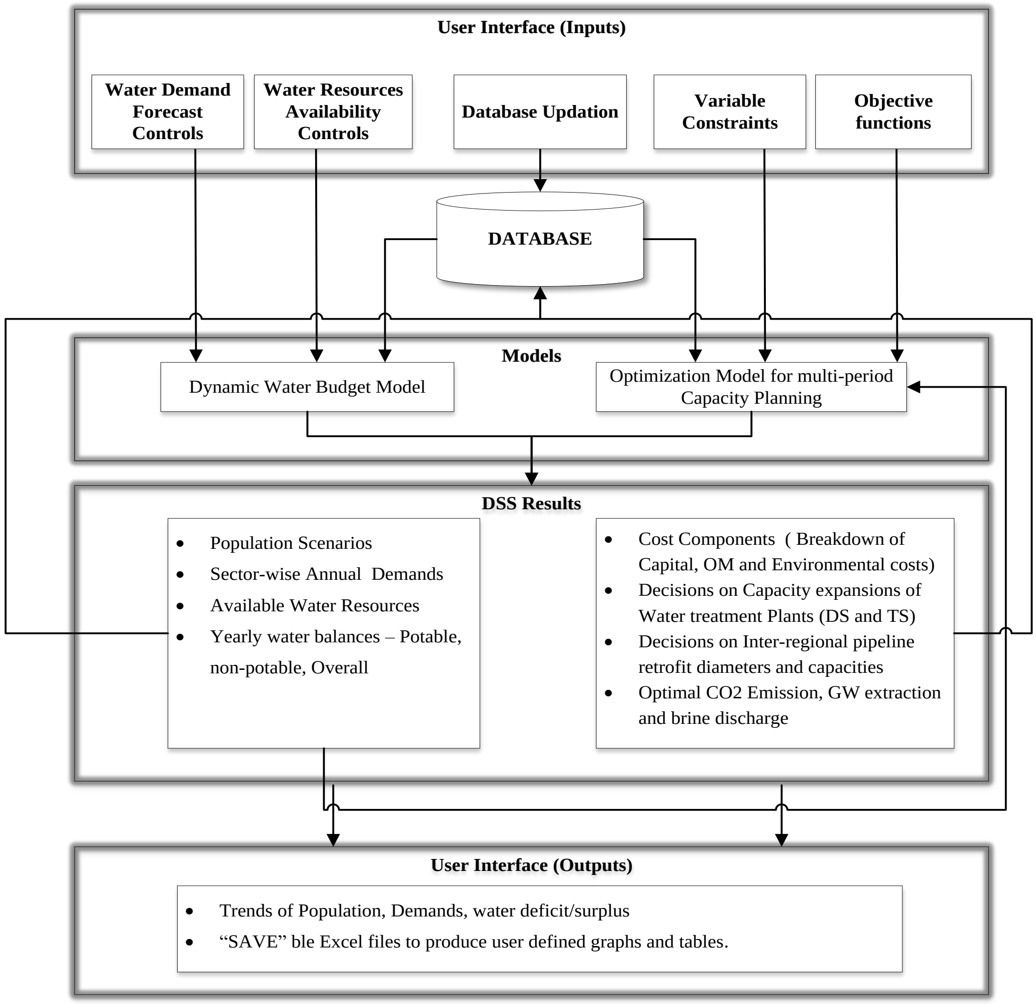


Figure 21: Conceptual Design of the SuWaB-AD Decision Support Tool

7.2.1 User Interface of the SuWaB-AD

For easy navigation, the SuWaB-AD is designed with a user-friendly interface screens to interact with the DSS modules through a control screen for inputting data and viewing outputs. Data inputs to the DSS comprise parameter values, the constraints, the targets or objective functions in the forecasts and optimization, for running the respective models. The GUI was created with "MATLAB app designer" and allows the user to enter data into the specified fields and import data from external sources. Here, some of data inputs need to be supplied to the models as tables or arrays. This feature is made possible by the import function in MATLAB to load data from spreadsheet files. Every time the application is run, all the required information from the input files and fields as well as other numerous parameters for the model run are used by the system. The SuWaB-AD inputs are organized in such a way that all the inputs belonging to a particular category of action are grouped together. All output files are written to respective tables in a database as well. After the model is RUN, all outputs from the DSS are made available to view key results, and SAVE is allowed for these data for further perusal and interpretation by the user The three programming platforms used to interact and navigate through the DSS modules are MATLAB App Designer, GAMS, and Microsoft Excel. The GUI of the welcome screen allows the user to navigate to the respective modules for use (Figure 22).

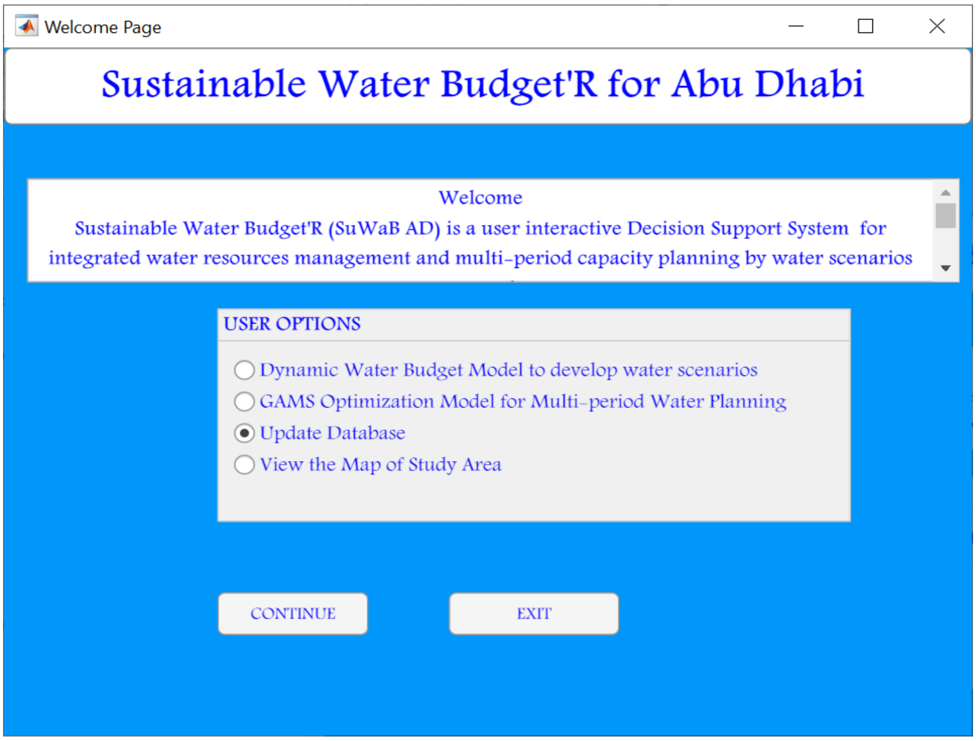


Figure 22: Welcome page design for the DSS

7.2.2 Models of the SuWaB-AD

7.2.2.1 ADWBM Module

In the SuWaB-AD, ADWBM is included to help the water planners to build scenarios and evaluate the future water situation in the Abu Dhabi based on judgmental forecasts of water demands and supply by setting targets on allocation rates, and policy implementation for different population projections. The ADWBM module comprises three subsections: population forecast, water demand forecast and water availability forecast. The DSS architecture is designed so that all the required data inputs into these subsections in ADWBM can be supplied by the user through respective GUI forms. These data are then processed by built-in program codes and baseline data to generate outputs representing future water condition of the scenario simulated. The interface pages are designed to enter correct data types for all the input fields of the ADWBM module. All the key interface pages for using ADWBM for scenario development are shown in (Figure 23 - Figure 26). Figure 23 shows the population forecast subsection. In the Figure 24, a sample of GUI for sector-wise demand forecast is included. Figure 25 shows the steps involved in projecting future water availability. The results from ADWBM can be visualized using the GUI in Figure 26.

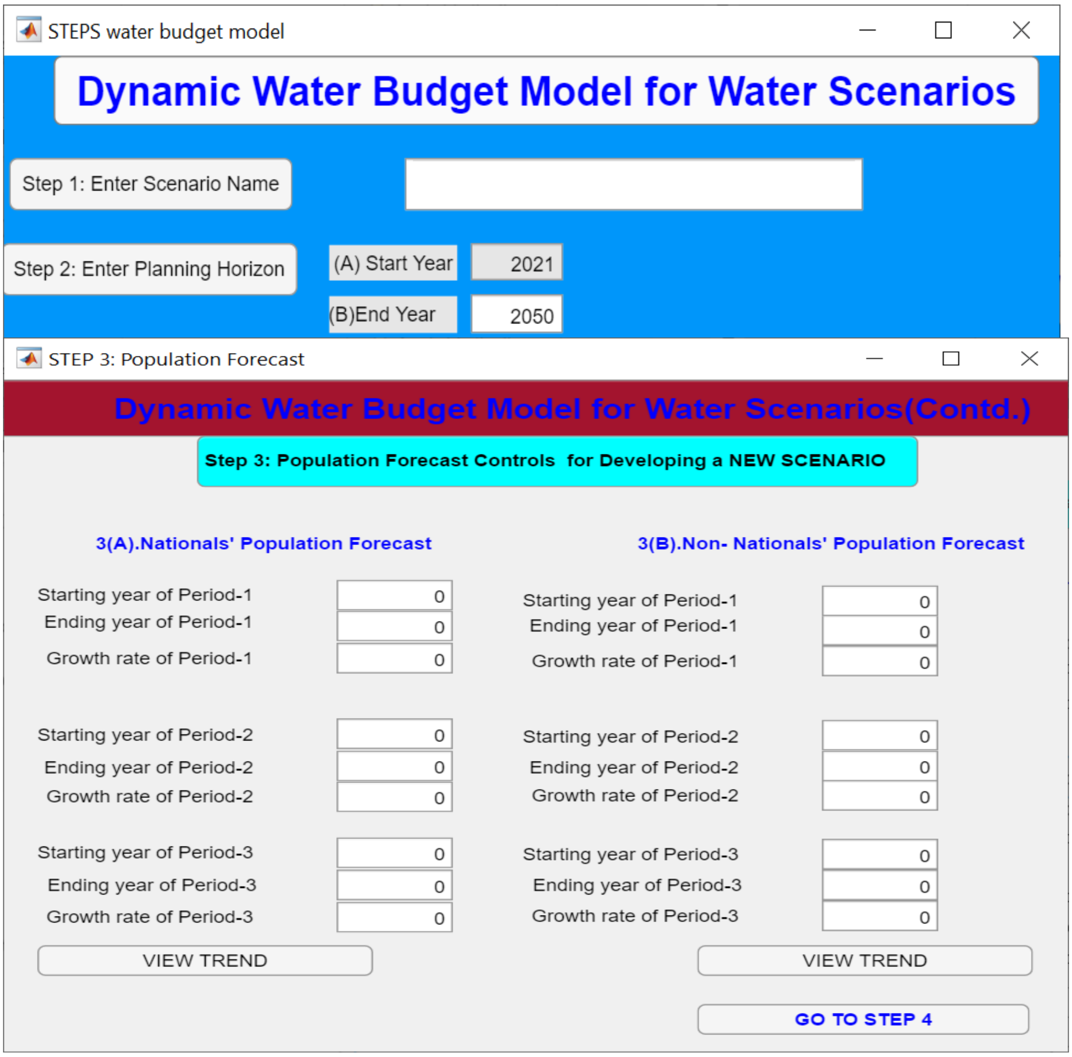


Figure 23: Population forecast pages

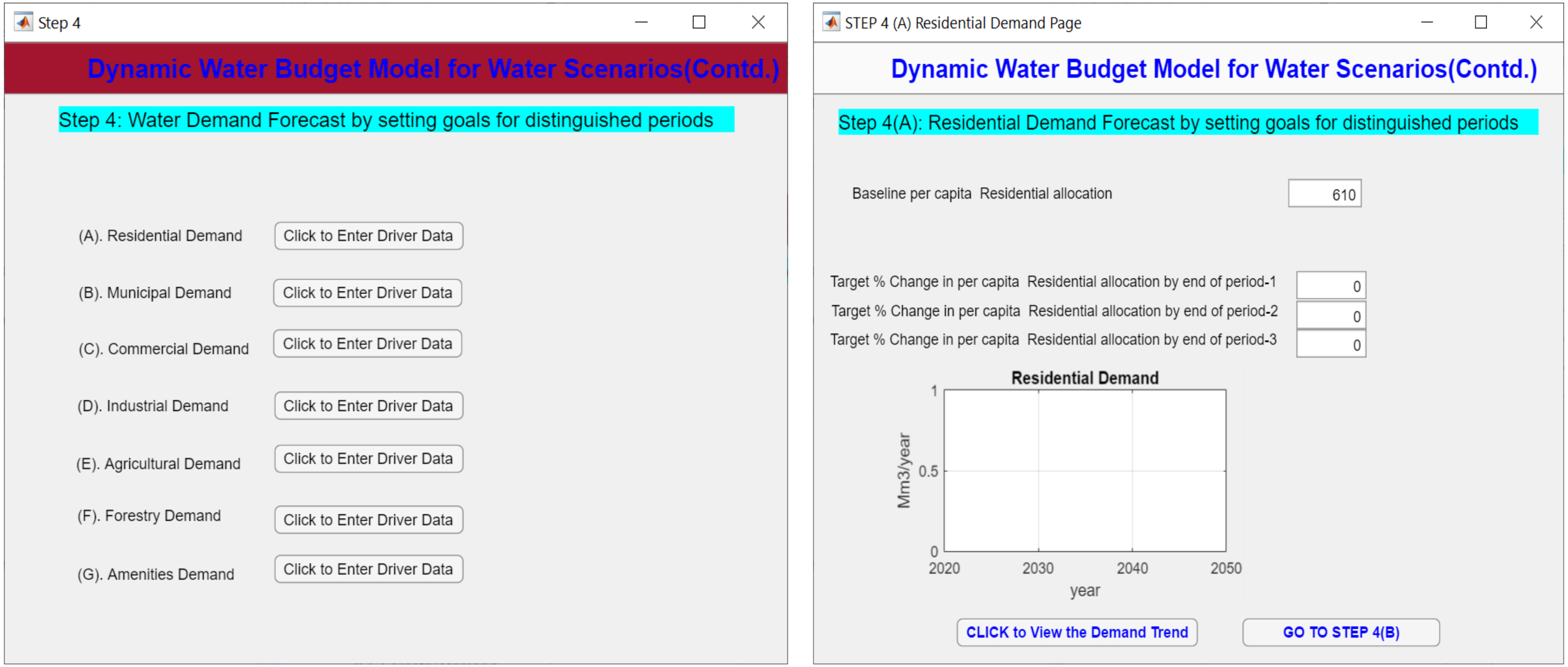


Figure 24: GUI for water demand forecast using ADWBM

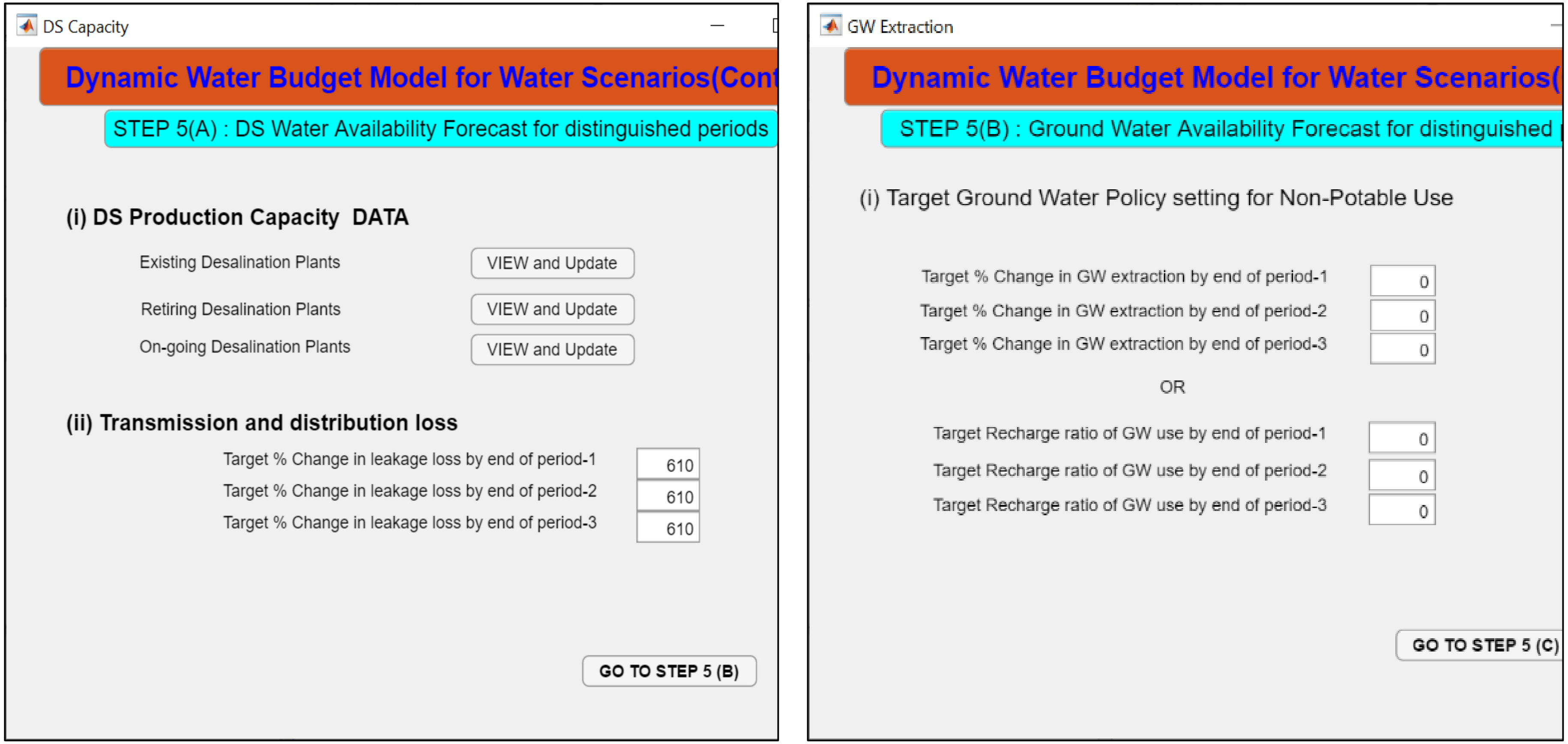


Figure 25: GUI for water supply availability forecast using ADWBM

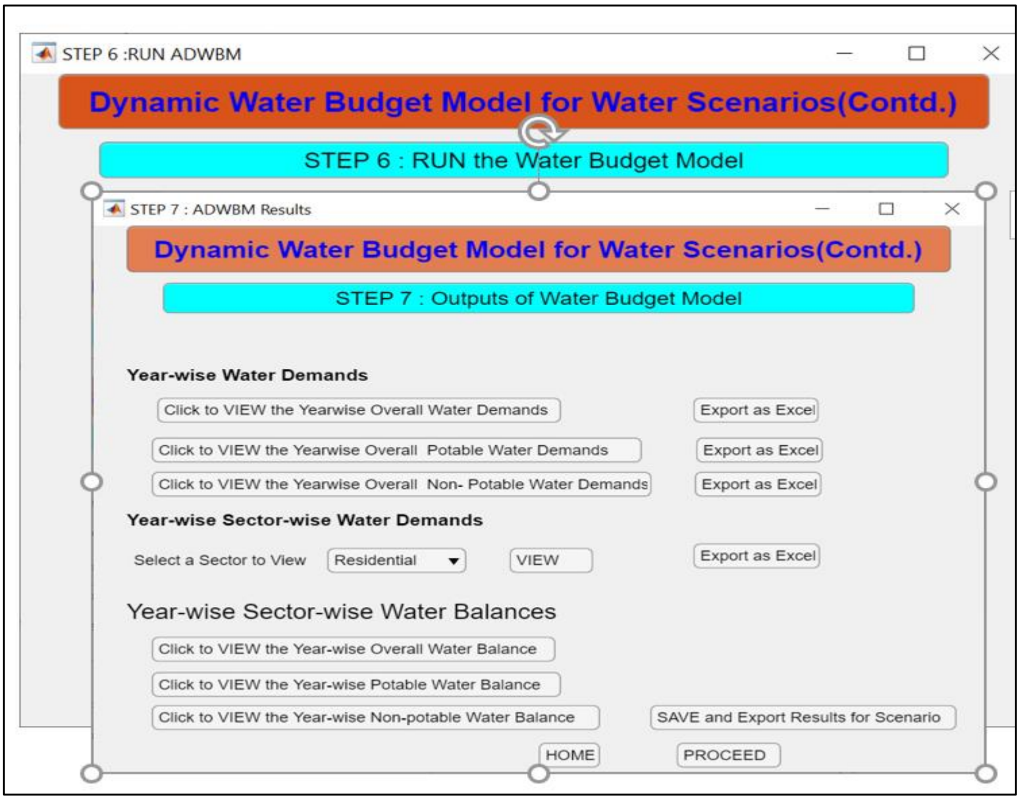
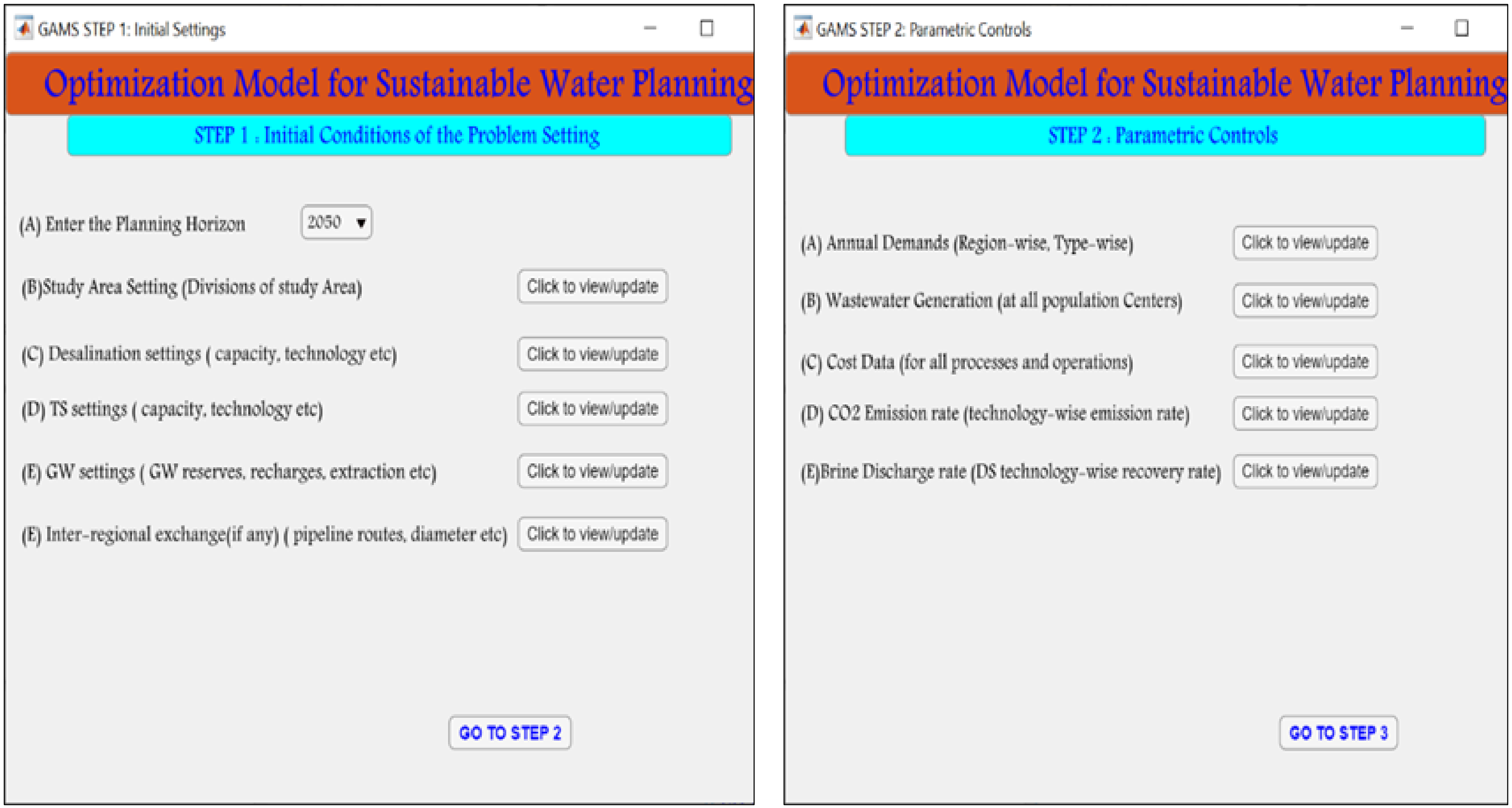


Figure 26: GUI for viewing ADWBM outputs

7.2.2.2 ADWCPM Module

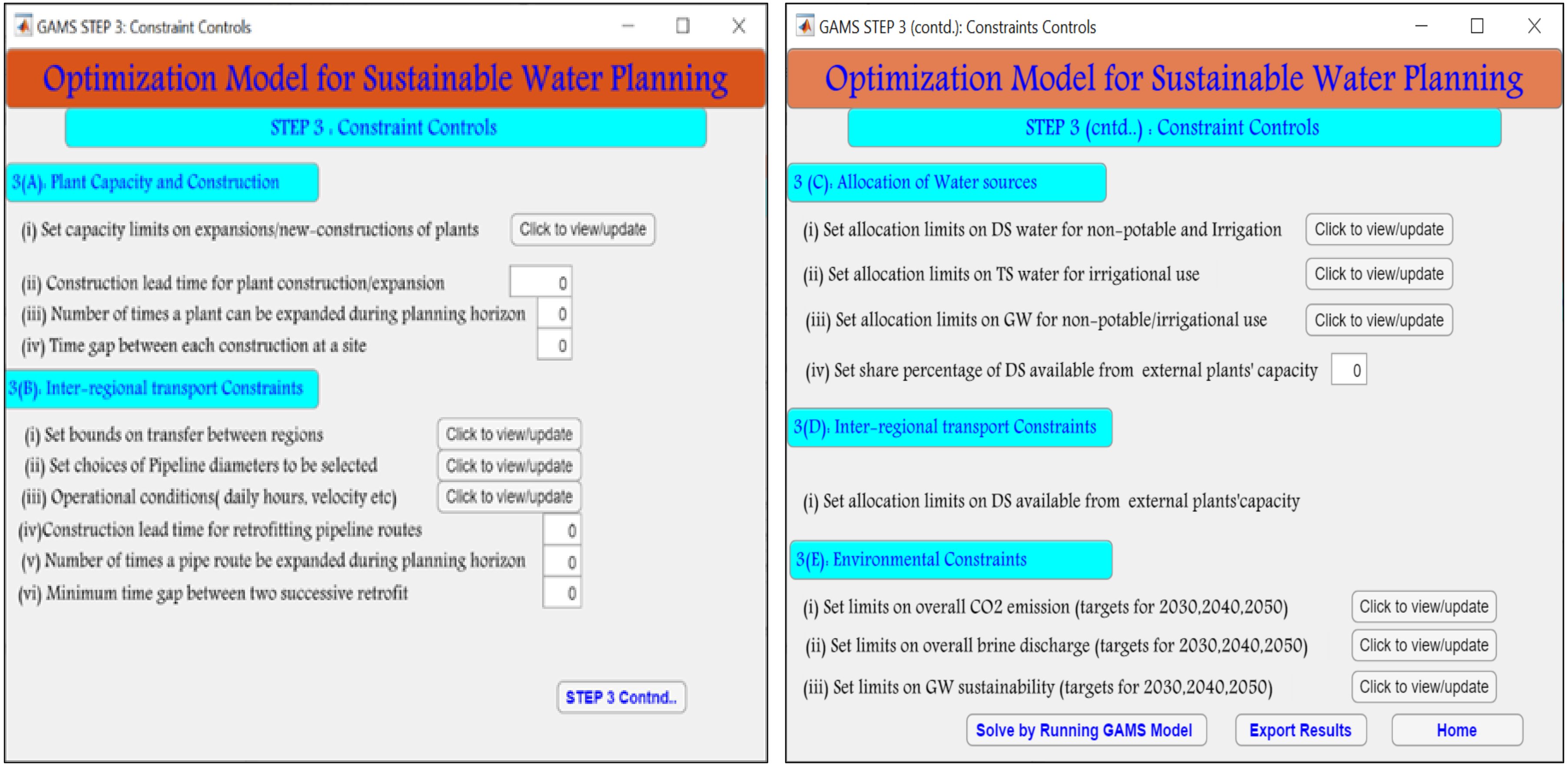
In the SuWaB-AD, the ADWCPM model is an optimization model coded in GAMS as a MILP capacity expansion problem which when supplied with constraints on supply and operating settings in addition to environmental constraints can find an optimal solution for water planning based on water demands as forecasted by the ADWBM. The key user controllable inputs that are incorporated in the SuWaB-AD are discussed in Chapter 5. The actions that a user can perform are to change input, edit, view these values before a solution is sought from the DSS. The GUIs designed for the ADWCPM module are shown in Figure 27.



(a) Inteface for intial conditions input

(b) Interface for parameters input

Figure 27: User interface pages for ADWCPM



(c) Inteface for constraints input

(d) Inteface for constraints imput (continued)

Figure 27 : User interface pages for ADWCPM (continued)

A user can RUN these models simultaneously in such a way that the user can opt to use ADWBM to develop water scenarios followed by ADWCPM to optimize the water plans for the planning period. The selective outputs of ADWBM are supplied to the optimization module for further use in calculations. During the ADWBM running, data generated for running MILP in the ADWCPM are transferred to the database in the DSS. The ADWBM allows the users to evaluate the water balances in the context of user inputs for the water scenario simulated. Based on these water balance trends, along with the user inputs in the MILP module, a user can RUN the SuWaB-AD for the optimal planning solution for the scenario simulated.

7.2.3 Database for the SuWaB-AD

The DSS database stores data for running the mathematical models, namely ADWBM and ADWCPM. The built-in data include the different baseline consumption rates by various demand sector categories, initial population data, policy and target levels for demand sectors, data on investment, operation and environment costs, initial capacities of water supply infrastructures, initial water supply resources data, other environmental and climatic data, and other parameters required for planning. The details of the database components are categorized and discussed in chapter 5. All the data for the study area can be stored in the database of the model in the form of spreadsheet rows and columns. The GUI design allows a user to update model database with fresh values or customize the data for the study area. The database files used in this study are all in the Microsoft Excel table format. Specific data in these tables can be edited through the GUI, making it unnecessary for the users to have direct access to database.

7.3 Application of SuWaB-AD

To illustrate the application of SuWaB-AD for water decisions, the tool was used in scenario building and sustainable long-term capacity planning for the Emirate of Abu Dhabi, incorporating the government's policies, strategies, and visions. The objectives were to use to predict future water balances using the ADWBM module in the DSS, and to find an optimal sustainable capacity planning solution for the scenario simulated using the ADWCMP module in the DSS.

7.3.1 Simulation of a Water Scenario using ADWBM Module

The SuWaB-AD DSS was used to simulate a water scenario named the Sustainable Environment Scenario (SES). The scenario was formulated by considering the different strategies required in Abu Dhabi for a sustainable future, such as supply and demand side measures and population growth control. The planning period considered was 2021–2050. In general, based on the ADWBM simulation, the results can be viewed as tables and graphs for variables such as sector-wise water demands; abstractions of GW; use of treated sewage effluent; production and loss of DW; and water supply/demand balances (potable, non-potable), which are dependent on human actions and governmental policies, strategies, and visons. However, this study discusses only the specific topics that form the core of the scenario building and future capacity planning.

7.3.1.1 Population Growth for the SES

Population is one of key drivers of water demand in Abu Dhabi. This subsection in the ADWBM module permits forecasting the population for nationals and non-nationals, separately, by dividing the planning horizon into more than one distinguished periods of growth. In this scenario building, two periods were used: medium term (P1, for years 2021–2030) and long-term (P2, for years 2031–2050). The GUI shown in Figure 23 was used to input the values shown in Table 20 as published in (Mohamed et al., 2020); to forecast the population under the SES. The average annual growth rates for these periods are used based on the assumption that a medium population growth represents a balanced and sustainable environment, and steady economy. The forecasted population by SuWaB-AD using the module included in ADWBM (Kizhisseri et al., 2021) for the SES is shown in the Figure 28**.** The population forecast forms the basis of water demand calculation of all the population dependent demand sectors.

Table 20: User data inputs for population forecast under SE scenario

Input Field Names	**Input Values**
Planning Horizon (years)	2021-2050 (P1&P2)
Number of distinguished periods within the planning horizon for setting targets	2 subperiods: (P1&P2): P1:Years 2021-2030, P2:Years 2031-2050
Start year of each distinguished period	P1: 2021, P2:2031
End year of each distinguished period	P1:2030, P2:2050
Population growth rate of nationals in each distinguished period	P1:3, P2:3.5
Population growth rate of non-nationals in each distinguished period	P1:5.3, P2:3

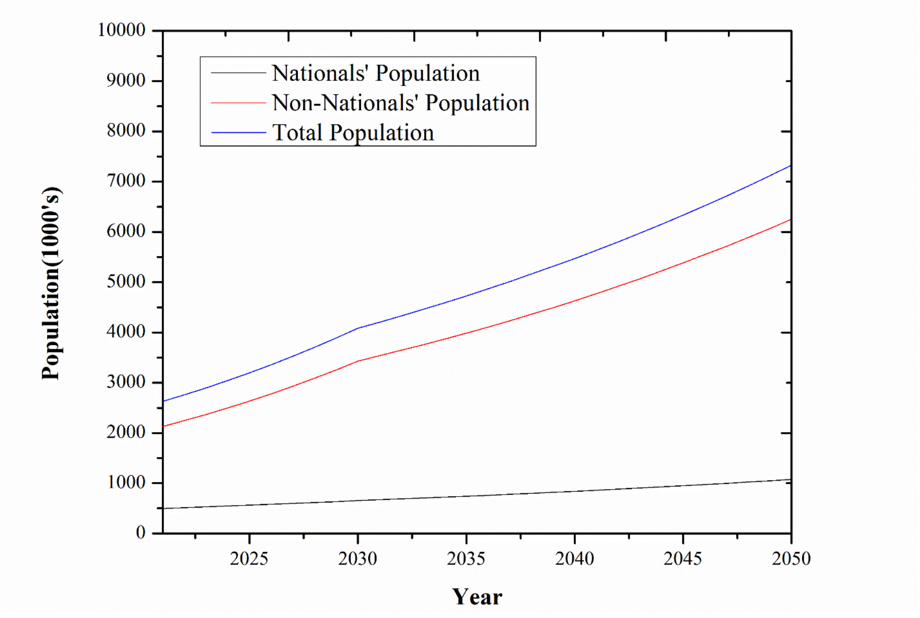


Figure 28: Population forecast under SE scenario

7.3.1.2 Waters Demands for the SES

The ADWBM allows a targeting demand forecast in the model that sets the reduction targets in demand drivers of the demand sectors based on regulations and policy for every distinguished period (or years). Therefore, to establish targets for consumption rates in the distinguished periods, various published documents by the government and stakeholders were gathered and judgments were made for estimations to forecast the demand under this scenario. For the SES, different factors were considered and can be summarized as follows.

(a) Conservation regulations:

Conservation regulations could decrease water consumption by all population-dependent demand sectors (residential, commercial, and municipal). Therefore, a reasonable possible reduction in the baseline per capita water allocation to these sectors was assumed and implemented in the scenario development. In the SES, a reduction of 10% per capita consumption by 2030 and another 10% reduction by 2050 is assumed to be achievable in all potable sectors,

(b) Agricultural, Forestry, and Amenities Sectors:

The population-independent demand sectors such as agriculture, forestry, and amenities is assumed to be essential for a balanced food security and green environment. Therefore, working toward optimizing water use intensity and increasing efficiency in the agricultural, forestry, and amenities sectors are the targets to reduce water use by 35% by 2050.

(c) Industry Sector:

For industry sectors, the projected demands are only driven by the governmental policies and visions. However, taking into consideration economic growth in relation to population growth, a 10% increase by 2030 and another 20% by 2050 is considered under the SES. These values were included in development of the SES and were entered into the SuWaB-AD using the GUI pages shown in Figure 24. The water demand pattern of various sectors until 2050 under the SES as projected by the ADWBM within the SuWaB-AD is shown in Figure 29.

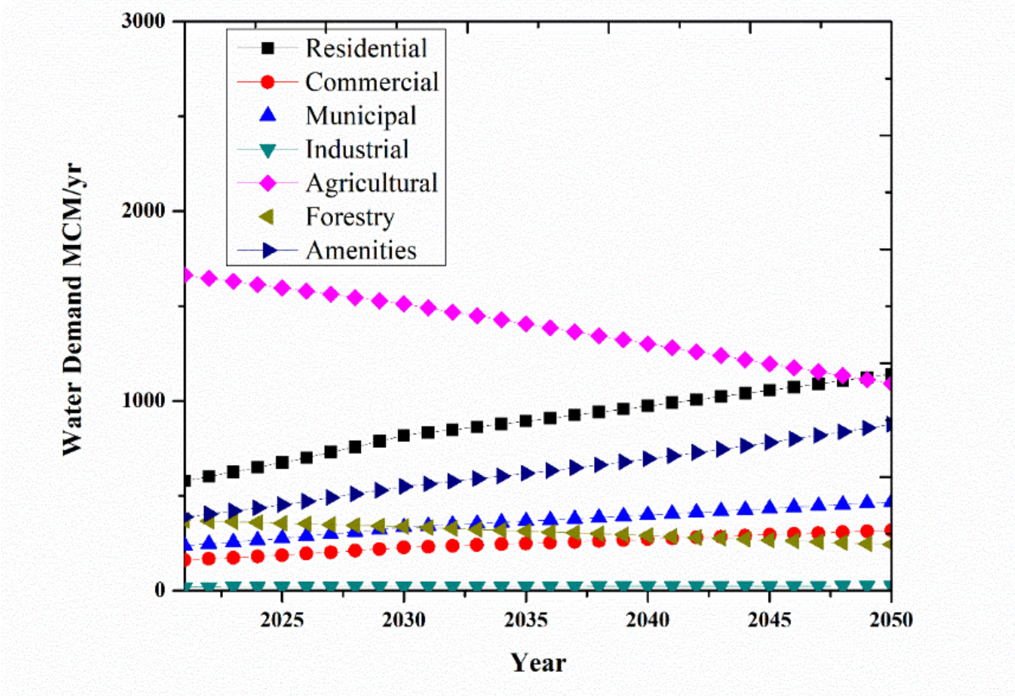


Figure 29: Sector-wise demands forecasted for SE scenario

7.3.1.3 Available Water Supply Sources for the SES

The amount of water from various sources that can be allocated to meet demands of different quality types are subject to the availability, the sustainability policies, capacity of the production facilities, loss during transmission and distribution, usability for specific purposes and other operational aspects. The ADWBM encompasses all these aspects while estimating yearly available water supply from each source. For the SES, based on the assumption that all the treated sewage is usable for non-potable purposes, the GW use for the planning horizon had to be kept under control in line with a feasible target reduction in GW extraction, as pointed out in the Environment Vision 2030 policy agenda (Environment Agency - Abu Dhabi, 2012). Therefore, under SES a GW reduction of 10% by 2030 is targeted and another 25% reduction is to be achieved by 2050. The rainfall—which is a natural source of water but very limited in Abu Dhabi—was been included as dependable source in future.

The DS capacity is proposed to deliver uniformly throughout the entire planning period. The option of importing potable water from outside the Emirate by its legal agreement with Fujairah Government is also taken into account. The changes to baseline settings of supply for developing the SES was achieved by entering values using templates shown in Figure 26. The key target values applicable for water supply sources as used in SES are shown in Table 21. These values are in line with sustainability visions of Abu Dhabi government (Abu Dhabi Council for Economic Development, 2009; Environment Agency - Abu Dhabi, 2009a, 2012, 2014).The outputs from the SuWaB-AD are shown in the Figure 30.

Table 21: User data inputs for water supply availability forecast under SE scenario

Input Field Names	**Input Values**
Target reduction in extraction rate of GW for each period	P1: 10% P2: 25%
Recyle-ratio of TS produced	P1: 90% P2: 90%
Production Plant Capacities	Base year 2020
Transmission and leakage loss percentage	P1: 10% P2: 10%

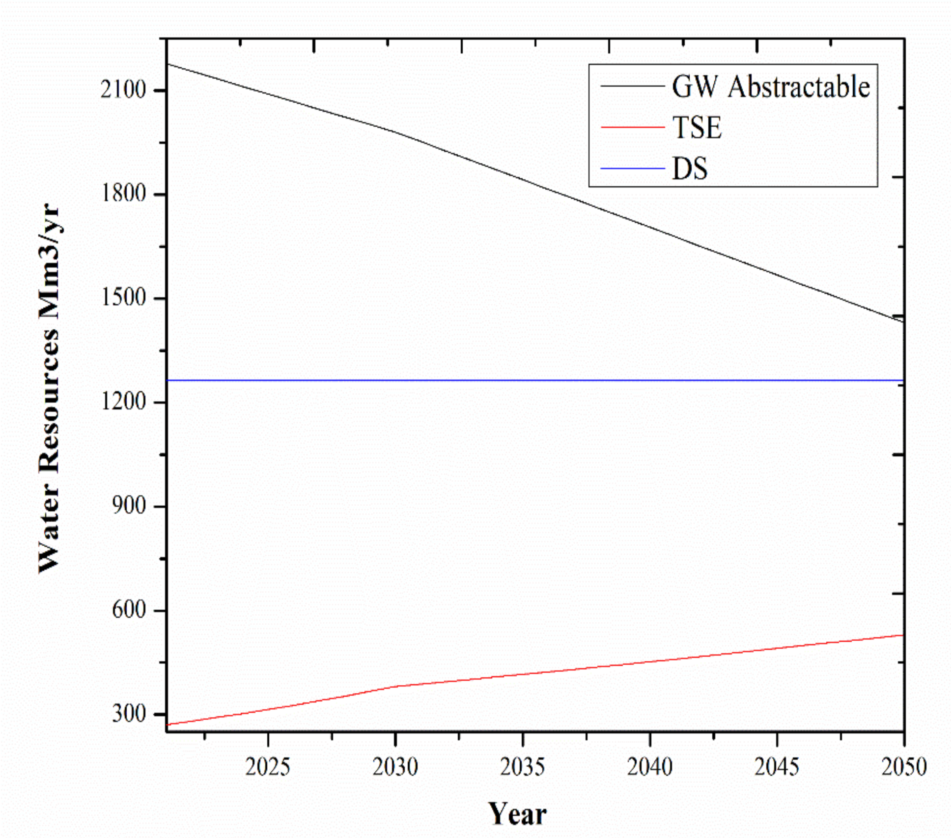


Figure 30: Available water supply under SE scenario

7.3.1.4 Yearly Water Balances for the Sustainable Environment Scenario

The SuWaB-AD results allowed users to obtain the yearly data on water balances for the entire planning horizon. Based on these data, the useful results for the capacity planning in the ADWCPM module are yearly water surpluses or deficits for potable, non-potable, and irrigation demands. The growth of water deficits for the SES obtained from the SuWaB-AD are shown in Figure 31.

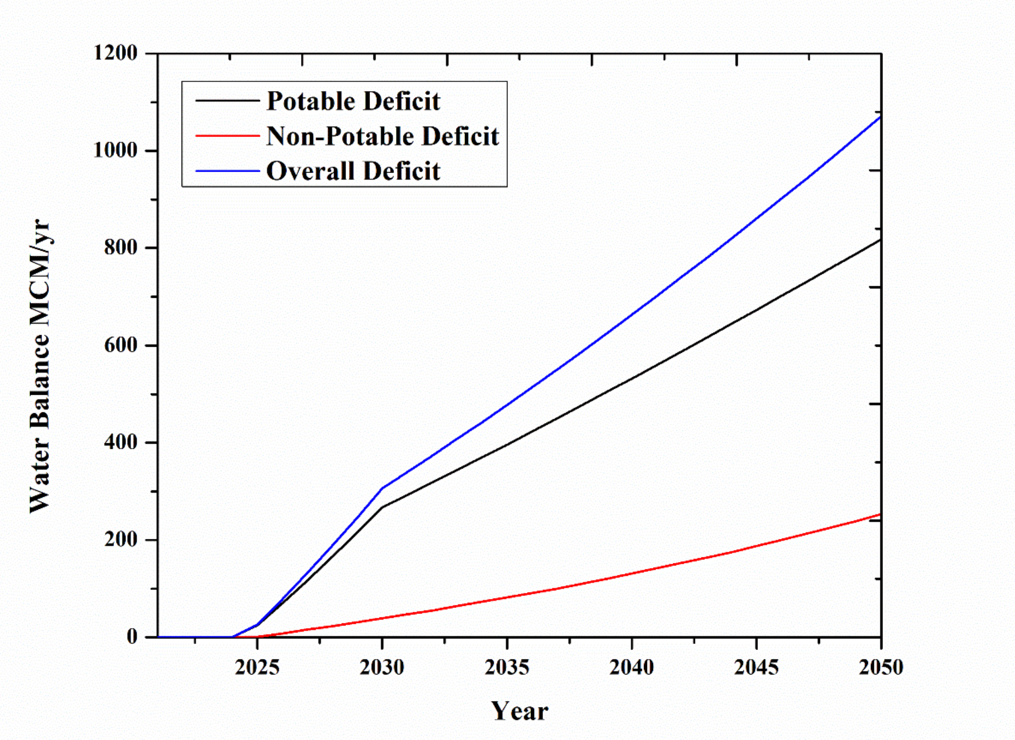


Figure 31: Growth of water deficit under SE Scenario

7.3.2 Results from ADWCPM Module

In the SE scenario, it was found that the water deficit would start in the EAD by the year 2025 (Figure 31). Because the motive was to plan sustainably for the entire planning horizon, it was necessary to have a strategy to deal with this increasing water deficit. Therefore, the SuWaB-AD interface was used to input various user controls and to generate the visually interpretable results through the ADWCPM module. The built-in ADWCPM module in SuWaB-AD works on a preprogrammed optimization model specifically developed for Abu Dhabi emirate which works on many rules for water quality requirements of each demand sectors, regional allocation, inter-regional import and export, constraints on capacity expansion limits at each production location and other operating constraints. The ADWCPM allows the user to modify certain parameters and constraints in order to seek for optimal solution under different scenarios. The key data used in ADWCM module specifically for SES are described in Table 22.

Table 22: User data inputs for the SES scenario in the ADWCPM module

User Controls for the ADWCPM Module	Data Input Details for the SES
(i) Water demands	
Yearly Potable Demands (region-wise)	Generated from ADWBM module simulation run for SE scenario
Yearly Non-potable Demands (region-wise)	Generated from ADWBM module simulation run for SE scenario
Yearly Irrigational Demands (region-wise)	Generated from ADWBM module simulation run for SE scenario
(ii) Cost data	
OM Cost of all plant production (Technology-wise) and DW Transmission	Editable in-built. Details given in Table 16
CAP Cost of Pipeline Construction (Diameter-wise)	Editable in-built. Details given in Table 15
Carbon cost per unit Kg e emitted	Editable in-built. .023 $/ Kg e CO_2 emitted
Brine discharge costs	Editable in-built Values. MSF, MED- 0.0015 $/m^3$; RO-0.04 $/m^3$
GW Environment Cost	Editable in-built. 0 $/m^3$
Interest rate	Editable in-built. 5% -for SE scenario
(iii) Capacity related parameters	
Carrying capacity of all pipeline routes	Editable in-built. Table 13
Initial plant capacity data	Editable in-built. Table 12
Planned Plant Capacity Decommission	Editable in-built.
Pair-wise length of all pipeline routes	Editable in-built. Table 13
Yearly WW generation at all population centers	Generated from ADWBM module simulation run for the SE scenario

Table 22: User data inputs for the SES scenario in the ADWCPM module (continued)

(iv) other user controllable constraints	
Bounds of each plant capacity increase for each site	Editable in-built Values. SE scenario assumption: 20-100% of initial capacity
Maximum buildable capacity for a technology, site	Editable in-built Values. SE scenario assumption: 100-250% of initial capacity
Bound on import limit to a region	Between 0%-100% of potable demand
Bounds on operating factor of different technology types	Between 50%-90% of installed capacity*
Minimum interval between successive expansions of plants	Editable in-built Values. SE scenario input: 7 years
Minimum interval between successive expansions of pipeline routes	Editable in-built Values. SE scenario input: 7 years
Construction Lead Time of Projects	Editable in-built Values. SE scenario input: 2 years
(v) User controllable objectives	
Set maximum allowable yearly CO2 emission,	Editable in-built Values. SE scenario input: Set to minimize carbon emissions. No targets set
Set maximum allowable yearly brine discharge	Editable in-built Values. SE scenario input: Set to minimize overall brine discharge
Set GW sustainability targets	Editable in-built Values. SE scenario input: 35% reduction from initial GW use rate by 2050

For the SES developed for this study, the scope was to ensure an environmental outline, and therefore the SES was solved with an optimistic vision of dependability on renewable sources of energy. This vision was drawn based on possible environment targets in Environment Vision 2030 (Environment Agency - Abu Dhabi, 2012). Solar energy is the most feasible and reliable cleaner renewable energy in the UAE (McDonnell, 2014). Furthermore, the latest development of cheaper solar-RO plants by Masdar Institute for Abu Dhabi conditions (Kaya et al., 2019) is taken into consideration while solving for optimal capacity planning under the SES. Therefore, based on these considerations, up to 30% of future RO plant expansions can be solar powered. This target was included in the solution search. The objectives were to create a sustainable and cost effective capacity expansion plan for with minimal economic and environmental costs, carbon emissions, brine discharge and GW abstraction.

The optimum capacity expansion pathway of the water sector infrastructures in Abu Dhabi for the SES future was obtained; including the water supply source composition, the technology composition for supplying various types of water, the capacity of each type of plant for each year, decisions on asset installation- all plants and pipeline networks, and yearly emissions. Because the main focus of this study was to illustrate the applicability of the SuWaB-AD as a GUI tool, only the consolidated results of key indicators are discussed.

7.3.3 Overall Costs and Breakdown

The average cost for the whole planning period is the net present value calculated by the ADWCPM. The overall accumulated cost for SES is 45.5 billion US dollars. breakdown of the total cost is given in Figure 32. Carbon cost is the only environmental cost assigned in this study, which was achieved by converting the carbon footprint into dollar values for each unit of carbon emission. This indicator is very significant, especially in a place like Abu Dhabi where the lion’s share of the water is made available by desalination processes deploying thermal technologies such as MSF and MED. The total environmental cost is about 20% of the total accumulated cost for the planning period. This is relatively low, and it can be attributed to the choice of solar energy in the expansion of RO plants. However, for further reduction in carbon emissions the emerging technologies of carbon capture and sequestration can be tried in the solution search.

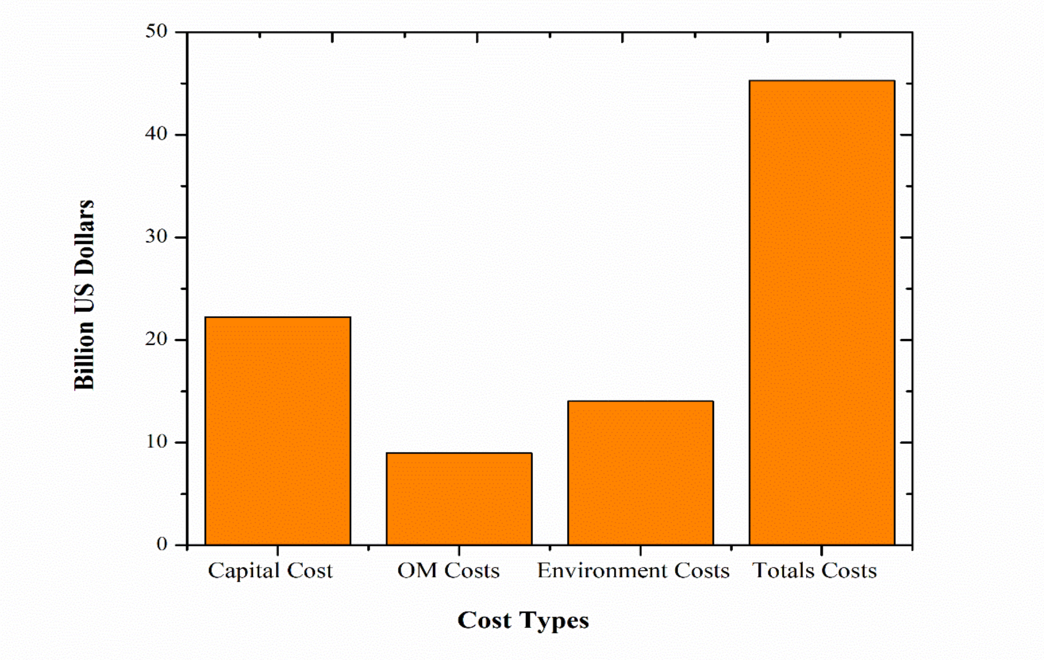


Figure 32: Breakdown of the optimal total cost for the SE scenario

7.3.4 Capacity Expansion Plan

The optimal development pathway of the water sector under the SES setting was obtained, including water production composition, plant capacity composition, capacity of each type of plant to be built each year, and decisions on pipeline retrofits for inter-regional transmission. These optimization results were then analyzed and discussed. The evolution of technology-wise optimal water production- mix for the planning period is given in Figure 33. Remarkable reductions in the technology MED are seen in the solution. The MED plants are not chosen under the SES after the planned decommissioning of the existing MED plants. Another key observation is that RO-conventional and RO-solar technologies together would contribute about 47% of total DW supply in 2050. Naturally, this finding may be because conventional RO is less expensive whereas solar RO is cleaner. Also, RO has higher recovery rate. Thus, the brine discharge is less. The relatively smaller selection of MSF and MED can be attributed to their high capital cost, higher carbon footprint, and lower recovery rate. Therefore, it can be explained that the model selected more RO in order to satisfy all the model constraints while minimizing the total cost. The optimal increase in capacities of WTPs at all population centers was also obtained, and the evolution of the treated sewage effluent contribution to the water supply over many years is also illustrated in Figure 33; as activated sludge process-conventional plants. The trend of decreases in GW abstraction is induced in the solution by the constraint set for GW—a minimum of 35% reduction by 2050. However, no further reduction in GW was observed. This finding is because no economic cost was assigned to GW in the optimization. To know the impact of assigning a cost for GW, further simulations can be carried out and analyzed. The model was also solved by considering that a retrofit in a pipeline route between two regions of Abu Dhabi is required. Results showed that two retrofits are needed in the years of 2040 and 2047, with a diameter of 600 mm to import water from the Fujairah DS plant (an external DS plant with which government of Abu Dhabi has legal agreement to import water) to satisfy the water demands of parts of eastern region of Abu Dhabi, namely Al Ain.

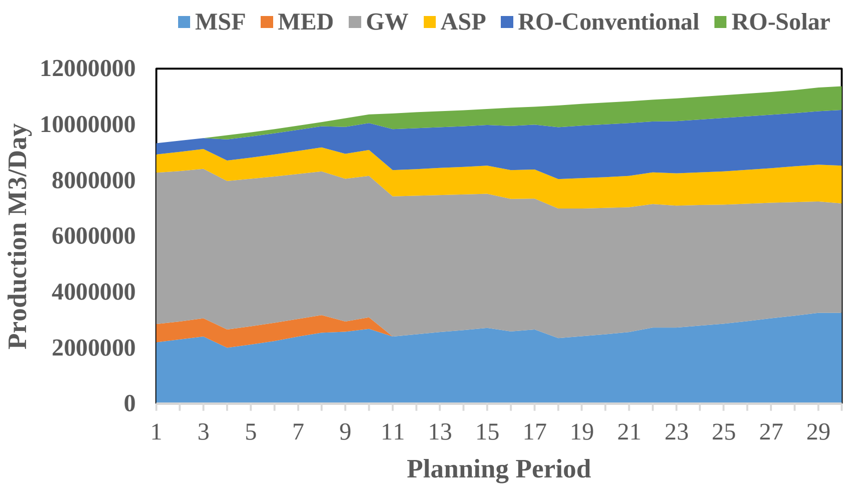


Figure 33: Production-mix water by different technologies and sources under SE scenario

7.3.5 Environmental Indicators

The model has solved the problem of the capacity expansion taking into account two environmental indicators; carbon emissions into the atmosphere and brine discharge into water bodies

7.3.5.1 Carbon dioxide Emission Trajectory

The emission of carbon dioxide from various processes and operations under the SES is shown in Figure 34. The optimal solution showed that the overall carbon emission would increase by about 14% in 2050 relative to the base year 2020. In terms of Abu Dhabi's sustainability initiative to reduce carbon emissions (Abu Dhabi Quality and Conformity Council, 2015), more efficient and cleaner scenarios must be implemented.

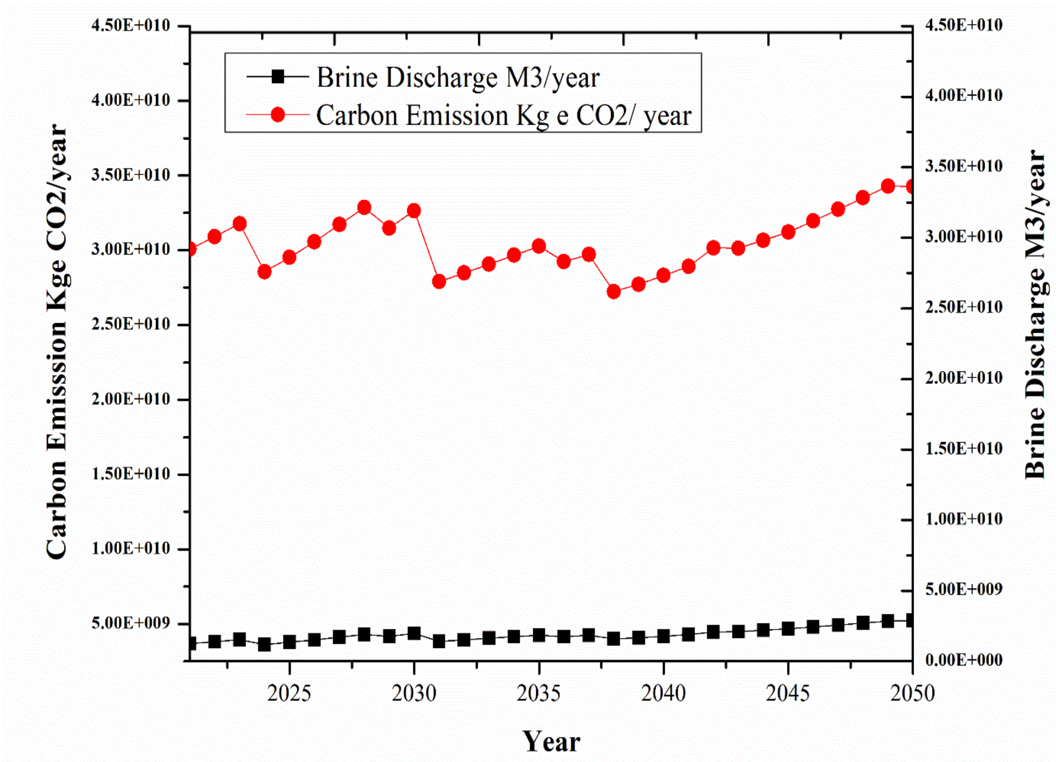


Figure 34: Carbon emissions and brine discharge under SE Scenario

7.3.5.2 Brine Discharge

The brine discharge from various DW plants supplying water for Abu Dhabi are solved by the ADWCPM module and is included in Figure 34. Improved recovery rate at all DW plants could lead to reduced brine discharge. Hence, lessening the impact on marine environment.

7.4 Chapter Summary

In this study, the tool SuWaB-AD DSS is presented. This is an integrated tool for long-term planning of infrastructures like water and wastewater treatment plants, and pipeline capacity; and helps in sustainable management and planning of natural resources like groundwater. Since it incorporates the cost and environmental aspects into the decision-making process, this method can be very useful in promoting sustainability among the decision-makers. The case study to demonstrate SuWaB-AD methodology showed that the tool can be helpful to water decision-makers worldwide. In conclusion, the primary significance of the SuWaB-AD is its usefulness to policy makers in supporting sustainability plans.

Chapter 8: Summary, Conclusions and Recommendations

8.1 Summary and Conclusions

The aim of this study was to provide a decision-support mechanism to assist water decision-makers and policymakers in preparing long-term water sustainability plans. The research was divided into five phases to achieve its goals. The first phase involved reviewing the literature of all critical issues that led to the creation of the proposed DSS (Chapter 2). The literature review focused on four areas; water balances models, scenarios analysis in water management, optimization techniques used in capacity expansion and planning, and an overall review of DSSs available in various areas of water management. According to the literature, DSSs are valuable tools for long-term water planning. The study aided in the creation of the SuWaB-AD DSS, and stressed the value of a user-interactive DSS in order to facilitate decision-making.

To accomplish the first objective a dynamic water budget model for Abu Dhabi has been developed. This model satisfies not only mass balance between the various water subsystems of Abu Dhabi but also is capable for forecasting water demands, future availability of water resources, and future water balances (year-wise surplus/deficit) as well with the use of equations incorporated in the model. This formed second phase of the research with a detailed study of Abu Dhabi water system. The ADWBM developed is a numerical tool for producing precise forecasts of water supply and demand in the EAD until 2050. The model also served as a planning tool in order to accommodate necessary steps to avoid a future shortage. ADWBM was calibrated and validated with the available actual data. The second objective was to build water scenarios for Abu Dhabi and simulate the water conditions using the

ADWBM. Therefore, a series of future water scenarios were simulated in the third phase to represent various future water conditions in Abu Dhabi (Chapter 4). This focused on the factors affecting current and potential water use in the EAD. Analysis of conservations needed to achieve a balanced water budget was identified for all scenarios. The importance of each driver in the model was calculated using a sensitivity analysis. The developed model aimed to recognize needed demand reductions for the different proposed interventions. The second objective of the research was thus fulfilled with simulation of four suites of water scenarios which followed a sensitivity analysis which identified significant demand drivers of each demand sector in Abu Dhabi.

The third objective was based on the need of an optimal planning solutions for long term water planning in arid and semi-arid regions. Thus, in the fourth phase, a multi-period MILP optimization model was developed to determine the needed capacity expansion pathway for the water sector in Abu Dhabi in order to meet future water demands with minimum cost, CO_2 emissions, and brine disposal. In addition, the model identifies the optimal capacity of water treatment plants, water transmission systems, and minimal utilization of non-renewable natural water resource (Chapter 5). The third objective of this research was thus achieved.

Another objective was to demonstrate the developed MILP for a case scenario and interpret its results. Therefore, a case study was undertaken for a planning horizon of 30 years, starting from 2021. The optimization model developed for the case scenario was run using GAMS software and solved using Cplex solver. The optimization framework considered the capacities of existing water infrastructure, decommissioning of retiring assets, construction lead time, environmental cost of CO_2

emissions and GW utilization, and other technical, economic and environmental criteria involved in the capacity planning of water sector. The results showed that the potable demand in the EAD, currently satisfied by desalination plants, will require a drastic change of technology from thermal processes like MED and MSF to RO; even if moderate consideration is given to the environmental aspects. It was also concluded that treated sewage plants, covering the non-potable demand, would require capacity increase at different stages of the planning period. In all cases, the best opted technology to treat the wastewater is the conventional-ASP process. The GW usage will continue to be the major supply source for irrigational requirement. It was found that when a limit was set for annual GW abstraction, whereby GW reserve would last for another 150 years, the optimal solution showed constant utilization of allowed GW except for few odd years with peak GW use because of dip in DW capacity due to decommission of DW plants at some locations. It was also seen that assigning high environmental cost for the economic value of GW will affect the DW capacity as more DW will be preferred for irrigation in such condition. The model results show that the capacity of DW transmission lines will have to be increased. Especially to Al Ain region, where all potable demand is satisfied by importation since there is no provision to install DW plants. The model solved for optimal diameter of pipelines and also years in which retrofits are required. The model, therefore, has accommodated all possible options of water allocation and supply feasible in the UAE condition. The model developed in this dissertation, to the best of the author's knowledge, is the first of its kind to be developed for an arid or semi-arid region considering multi-period integrated water management and planning. This can be used as a decision making tool for developing long-term water strategies for large geographical land area. Thus, the forth objective was accomplished.

For accomplishing the fifth research objective, a graphical interface that incorporates the ADWBM and ADWCPM to assist water planners and decision makers in water planning is developed (Chapter 7). Thus, a DSS for sustainable water planning is developed for the Emirate of Abu Dhabi (EAD), UAE and is named as "Sustainable Water Budgeter for Abu Dhabi" (SuWaB-AD). With the strong movement toward more sustainable water planning and management, more water decision makers have realized the value of comprehensive models and decision support systems. This is a tool that incorporates economic and environmental criteria into the decision-making process and could help decision makers promote sustainability in water planning.

The final research objective was to demonstrate the use of the developed tool, SuWaB-AD, to: (i) perform scenario-based analysis by building future water scenarios using ADWBM, and (ii) find optimal planning solution for the analyzed scenarios using ADWCPM. SuWaB-AD as an integrated tool for long-term planning of infrastructure (such as water and wastewater treatment plants, and pipeline capacity) was used to simulate a future water scenario for Abu Dhabi and to solve for optimal capacity planning solution. The SuWaB-AD is helpful in sustainable management and planning of natural resources like groundwater. Since it incorporates the cost and environmental aspects into the decision-making process, it can be very useful in promoting sustainability among the decision-makers. Also, the case study showed that SuWaB-AD can be helpful to water decision-makers worldwide. The primary significance of the SuWaB-AD is its usefulness to policy makers in supporting sustainability plans.

8.2 Recommendations

This study presented a review of recommended interventions to achieve a balanced water budget. All of the interventions were tailored to accommodate tangible conservation in water consumption. The main and most important interventions that should have long-term and comprehensive impacts on all types of water use include education and public awareness programs. Other specific technologies and legislation targeting reductions in consumption for different demand sectors were discussed. While both the SC and RES scenarios achieved a BWB throughout the entire period (no shortage), the RES scenario is recommended to be adopted because the interventions are judged to be more achievable and flexible given future uncertainties. The study showed that new resources will be required, e.g., desalinated water, to support the major increase in potable demands in later years if the Business as Usual and Policy First scenarios are followed. The business as usual path is not sustainable and the EAD must make major changes in order to pursue the alternative sustainable pathways modelled. However, efforts need to be maximized at all levels, from household to nationwide, in order to make sustainability a reality.

8.3 Future Improvements

8.3.1 Future Improvements in ADWBM

This can be achieved via the following:

- Furnishing more data on drivers of different demand sectors by installing measuring devices and meters at target locations and sponsoring more and carefully designed field monitoring programs.

- More communications with relevant water entities and stakeholders to provide better representations of the considered scenarios.
- Adding more features to consider new management options as per the feedback of relevant stakeholders as well as potentially quantified impacts of adopted interventions/legislations.

8.3.2 Future Improvements in ADWCPM

The developed ADWCPM in this work can be extended in the future if the researchers follow the suggestions given below:

- The ADWCPM can be reformulated from a MILP model into a MINLP model. Reformulating the model into a MINLP multi-period framework may significantly increase the complexity of the model and inheritably complicate the computational time of the solution.
- The developed model currently does not take into account the selection of new geological location of the new water treatment plants being built. In future work, the model can be modified in order to incorporate the geographical location of the new DW plants. The location of the new stations may directly affect both transmission losses and local distribution strategies.
- Currently the formulated model is designed as a single objective function model which attempts to minimize the cost of water sector while meeting water demand, a specified annual CO_2 limit, annual brine discharge limit and annual GW extraction limit. The model can be reformulated into a multi-objective function that minimizes the total cost of water and other target limits simultaneously.
- The OM costs of various processes and operations considered in this dissertation were assumed to remain constant over time. However, in reality, the OM costs

increase over time due to aging and fluctuations in fuels prices. Therefore, it is suggested that time dependent OM costs be found and used to increase the model's performance.

- The model may be expanded to include the option of planning water infrastructures like DW distribution system, storage facilities of treated water and distribution system for treated sewage.

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