Optimization Models for Iraq’s Water Allocation System

by

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ABSTRACT

In the recent past, Iraq was considered relatively rich considering its water resources compared to its surroundings. Currently, the magnitude of water resource shortages in Iraq represents an important factor in the stability of the country and in protecting sustained economic development. The need for a practical, applicable, and sustainable river basin management for the Tigris and Euphrates Rivers in Iraq is essential. Applicable water resources allocation scenarios are important to minimize the potential future water crises in connection with water quality and quantity. The allocation of the available fresh water resources in addition to reclaimed water to different users in a sustainable manner is of the urgent necessities to maintain good water quantity and quality.

In this dissertation, predictive water allocation optimization models were developed which can be used to easily identify good alternatives for water management that can then be discussed, debated, adjusted, and simulated in greater detail. This study provides guidance for decision makers in Iraq for potential future conditions, where water supplies are reduced, and demonstrates how it is feasible to adopt an efficient water allocation strategy with flexibility in providing equitable water resource allocation considering alternative resource. Using reclaimed water will help in reducing the potential negative environmental impacts of treated or/and partially treated wastewater discharges while increasing the potential uses of reclaimed water for agriculture and other applications. Using reclaimed water for irrigation is logical and efficient to enhance the economy of farmers and the environment while providing a diversity of crops, especially since most of Iraq’s built or under construction wastewater treatment plants are located in or adjacent to agricultural lands. Adopting an optimization modelling approach can assist decision makers, ensuring their decisions will benefit the economy by incorporating global experiences to control water allocations in Iraq especially considering diminished water supplies.

DEDICATION

Dedicated to my great parents,

Abdulrazzaq Aljanabi and Faeza Aljanabi,

My beloved wife, Khitam

My beloved kids,

Yousif, Maryam, and Yasir,

My darling siblings

Mohammed, Asraa, Tiba, and Mustafa

And my great uncle,

Abdulwahid Aljanabi

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(In the Name of Allah (God), the Most Beneficent, the Most Merciful)

The journey of my Ph.D. study has not been possible without the support of my family. Nobody has been more important to me in the pursuit of this project than my loving and supportive wife, Khitam, who has shoulder to shoulder supported me, and my wonderful children, Yousif, Maryam, and Yasir, who have provided unending inspiration. Words can not express my love, appreciation and gratitude for my terrific parents, the ultimate role models whose love and guidance are with me in whatever I pursue. Those who planted in my soul the love of prosperity for all others around me. My sincere thanks to my siblings, Mohammed, Asraa, Tiba, and Mustafa, for their prayers, love, and support.

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TABLE OF CONTENTS

Page

CHAPTER

CHAPTER Page

CHAPTER Page

CHAPTER Page

CHAPTER Page

CHAPTER Page

APPENDIX

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

CHAPTER 1 INTRODUCTION

1.1. Introduction

Around the world, there are numerous political, economic, social, and religious conflicts and crises, which are solvable through covert and/or overt agreements and treaties. Another type of problem that forms a permanent concern, can be outlined as the environmental impacts of human activities. Sustaining enough quantity with suitable quality of renewable water resources represents one of the main recent concerns and upcoming challenges. Many of the developed countries, which are in arid and semi-arid regions, have taken significant practical water resources conservation measures to satisfy their people’s recent and future needs. While, other countries, as in the Middle East and North Africa (MENA) region, have followed the same trend of investing in the water sector to satisfy sustainable water resource as in UAE, Kuwait, and Jordan. The importance of public comprehension towards the severity of the upcoming risks threatening renewable water resources is essential to maintain the available resources and to sustain enough for posterity.

Using integrated and sustainable water resources management strategies can mitigate the potential burdens on water resources and protect water users from the impacts on water resources. Factors directly or indirectly have led to the deterioration of water quality and quantity, such as climate change, increasing population, mismanagement, lack of awareness, and pollution. Climate change, for instance, has already sharpened the global hydrological cycle by generating negative impacts on the availability and the continuity of renewable water supplies. On the other hand, high rates of population increase, uncontrolled industries, and mismanagement have their own impacts. The ignorance of these elevated challenges has led to competition among users, which exacerbates the crises. There should be individual and mutual efforts to conserve water quantitively and qualitatively defeating the challenges to sustainably.

Iraq is located in the eastern part of the arid and semi-arid Middle East. The temperature during summer is usually over 48°C during July and August and drops down below freezing in January (Abdul-Kareem et al. 2013). It is surrounded by Saudi Arabia and Kuwait to the south and the Arabian (Persian) Gulf to the southeast, Iran in the east, Turkey to the north, and Syria and Jordan to the west as shown in Figure 1-1. The total area of Iraq is 438,320 km^2 of which 924 km^2 is of inland water.

Iraq is part of Mesopotamia, where the Tigris and the Euphrates Rivers form the main renewable water resources for it. The two rivers flow from Turkey through Syria before crossing the Iraqi border to join later 70 kilometers to the north of Basra forming what is known as Shat Al-Arab, which drains towards the Arabian (Persian) Gulf. Most of the Tigris River water and its tributaries come from Turkey (56%) followed by Iran (12%) and the remainder, which is 32% is from the Iraqi terrain.

In the recent past, Iraq was considered relatively rich considering its water resources compared to its surroundings until the 1970s when Turkey launched the Southeastern Anatolia Project (GAP). The GAP has an ambitious plan to harness the waters of the Tigris and the Euphrates basin for irrigation and hydroelectricity production while providing an economic stimulus to Turkish southeastern provinces (Kolars 1994).

Figure 1-1. Iraq and its surrounding countries (Nord Nord West License, 2016).

1.2. Background

1.2.1. *Shared Water Sources*

Shared freshwater resources frequently form an international tension over many countries. Wherever water scarcity is, a serious concern is founded. Turkey, Iraq and Syria are the main riparian countries in the Euphrates-Tigris basin. Unintegrated development projects as well as natural conditions work together and/or separately in forming water scarcity in the basin. So far, Turkey, Iraq, and Syria have not reached a comprehensive watercourse agreement to ensure sustainable water management in the shared basin (Kaya, 1998; MoWR, 2014).

For many reasons, Iran and Turkey have been reducing and/or eliminating Iraq's water resources to gain the economic benefits associated with increased water resources. Turkey recently completed most of the hydraulic structures for the Southeastern Anatolia Project (GAP) which includes 22 dams and 19 hydropower facilities that impact flows in both the Tigris and Euphrates Rivers. Iran has fully or partially cut or diverted the water from more than 45 small rivers and tributaries that were supplying the eastern part of Iraq's rivers and marshlands with water, forming about 12% of Iraq's transboundary water supplies. The damming along the Tigris and the Euphrates Rivers in Turkey has generated a big concern about Iraq's water resource supplies, especially the Euphrates River which has a great influence on Iraq's water resources where 100% of its water flows from outside the border. Furthermore, it irrigates most of the western and southwest agricultural lands. It is estimated that only 50 percent of the Tigris River water flows from Turkey (Al-Ansari, 2013). Currently, Iraq faces serious periods of water shortages and this is expected to become worse as the supply is predicted to be reduced versus the increases in demand (Rahi and Halihan, 2010).

The large number of the built dams and irrigation projects also have had significant impacts on the environment. Large water surfaces, such as reservoirs, which were created upstream of the dams in hot climate countries such as in the Middle East, has increased the evaporation rate and the concentration of total dissolved solids. The estimated annual evaporation from the Tigris and the Euphrates Rivers Basin has been estimated at 2.0 km^3 in Turkey, 1.0 km^3 in Syria and 5.0 km^3 in Iraq (Hillel, 1994). Iraq has the highest rate of water losses due to evaporation because of the high temperature especially during the summer.

The water quality of the Euphrates River inside Iraq has experienced a significant decline due to irrigation return flows together with the dissolved fertilizer chemicals used in both Turkey and Syria (Frenken 2009). Salinity increases along with water quality decreases in Iraq have increased due to the dams built on the rivers upstream (Rahi and Halihan 2010). Furthermore, the dams and irrigation projects constructed have their own influences on the ecological system of the southern marshes (Alahwar), as well as on freshwater fish habitats in Iraq (Jawad 2003). These marshlands were known as Mesopotamia Marshes which in 2016 were inscribed on UNESCO's World Heritage List.

1.2.2. *Water Supply Facts*

Freshwater scarcity, low quality, complex & aged infrastructure, high population rate of growth, uncontrolled high-water demand, high water losses in the distribution system, low cost recovery & high subsidy, poor management, consumers' carelessness, and institutional framework are some of the common characteristics of urban and suburban water supply systems in developing countries. In Iraq, water is scarce, and supply is limited where it is rationed in almost all provinces. Usually, water supplies are intermittent with a relatively low pressure. It is rare to find a water-saving device because most people are struggling to get enough water for their basic needs. Consequently, it should also be noted that it is very often that water distribution is not uniform. In some wealthy zones, it is possible to get enough water supplies with a high pressure 24h a day while consumers of low-pressure areas or urban poor areas often receive a short period of supply. So, therefore people are not willing to pay for an unreliable, inadequate low level of service.

In Iraq, water scarcity has led to significant competition between different sectors of society (specifically agriculture, industry, and domestic use) (UNICEF/Iraq 2014). Experts predict that resources constraints will witness a significant change in Iraq's water allocation soon due to the confused water availability situation along with the conflicts. With Iraq's current population of about 37.88 million which is expected to be almost 55 million by the year 2030, the proportion of domestic water used may increase by 70% in the same time period, knowing that actual consumption for 2012 is 330 l/capita/day, and is expected to decrease at 170 l/capita/day in 2030 (UNICEF/Iraq 2014).

1.3. Study Objectives

Water shortage has led to significant competition among different types of uses, specifically agricultural, industrial, and municipal uses. The allocation of the available water quantities on different users following an applicable practical and sustainable pattern forms one of the urgent necessities. Furthermore, the deterioration of fresh water qualities due to uncontrolled human activities needs sustainable and practical strategies to minimize pollutant sources protecting the environment. This partially can be implemented by allocating reclaimed water among users following a sustainable manner. This dissertation mainly addresses the following key issues considering optimal water allocation for agricultural and other uses following different scenarios to satisfying the maximum outcomes in terms of benefits.

1.3.1. *Water Issues to be Addressed*

The need for a practical and sustainable river basin management for the Tigris and Euphrates Rivers in Iraq is crucial. This should include applicable water allocation scenarios to minimize the projected future water crises in connection with both quality and quantity. There are many water issues in Iraq that form recent and future concerns, which are:

a. A significant decrease in water supplies of the Tigris and Euphrates Rivers at the Iraqi borders with both Turkey and Syria respectively due to the new developed hydraulic structures in these countries as well as due to the climate change and other factors.

b. A significant increase in water TDS especially in the Euphrates River at the Iraqi border due to the irrigation return flow from both Turkey and Syria.

c. Shortage in water supplies in most of the southern providence due to water overuse in the upstream provinces.

d. A significant deterioration in water quality to the south of Baghdad along the two rivers due to the disposal of treated and/or untreated wastewaters to water bodies as well as due to irrigation return flows.

e. A significant increase in water TDS in the Tharthar Lake to the north of Baghdad which reflects negatively on water quality of the Euphrates River in the middle of Iraq descending to the south.

f. The reflection of water shortage on the aquatic life of southern marshlands which needs to be restored due to its historical and environmental importance.

g. Using old fashion irrigation techniques which waste large quantities of water.
h. No significant interest in treating the generated wastewaters from industry, and some other activities which usually is disposed to water bodies or to the environment.
i. Using the centralized system in the wastewater treatment facilities which might reflect negatively on the quality of the produced treated wastewater.
j. No significant projects, facilities, and activities that employ the reclaimed water as an alternative source of water.

1.3.2. *Overall Goal*

The goal of this dissertation is to construct predictive models which can be used to easily identify good alternatives for water management that can then be discussed, debated, adjusted, and simulated in greater detail. The river basin management model measures the net economic benefits and of the management case study optimizing the system in terms of the most sustainable net economic benefit that is calculated in terms of both use and non-use values. The sustainability can be measured according to the availability of water to the downstream consumers and due to the generated damage from bad quality waters and its reflection on the environment and industry. Environmental, economic, social, and political impacts were discussed. So, the development of sustained water management models maximizing net benefits is the goal of this study.

1.4. Organization of this Dissertation

All the mentioned issues and others form a logical reason to develop a sustainable water resources management model. In this dissertation, eight chapter were considered including five water allocation optimization models, which were developed maximizing the generated net benefit to handle part or all of the already mentioned water issues by following different water allocation scenarios under different availabilities. The developed models herein are expected to promote the understanding of and aid in the development of efficient and sustainable water allocation options for Iraq's water resources considering reclaimed water as an alternative source.

In the following, the organization of the dissertation chapters are listed including the objectives of the developed models:

1. Chapter One: Introduction.

   This chapter includes an introduction about Iraq, water supply issues, and the dissertation objectives.

2. Chapter Two: Water in Iraq.

   This chapter includes a detailed description of Iraq's water resources, facts and issues, water uses, wastewater treatment plants, and reclaimed water as an alternative source.

3. Chapter Three: Literature Summary.

   This chapter includes the literature review considering optimization models for river basin planning and management, water resources allocation optimization models, the Tigris and the Euphrates basins with the related derived optimization models, and sustainability in water resources management.

4. Chapter Four: Application of an Optimization Model for Assessing the Performance of Water Appropriation in Iraq.

Chapter four addresses the ongoing challenge of water governance in Iraq by examining how profitability, at both the farm and basin levels, is affected by various water appropriation systems. Farmland irrigation in Iraq was evaluated using three water appropriation systems; upstream (UPR), downstream (DPR) and proportional (PSR) sharing rule. Their impacts on farm income under normal, dry, and drought water supply scenarios were evaluated using an irrigation water model coupled with a nonlinear programming (NLP) optimization model.

5. Chapter Five: A Reclaimed Wastewater Allocation Optimization Model for Agricultural Irrigation.

   An agricultural irrigation reclaimed wastewater allocation optimization model was developed in chapter five to optimally allocate crops and reclaimed wastewater (RW) on cultivated farmlands to maximize the net benefit. The optimization model was formulated using mixed-integer nonlinear programming (MINLP) solved by the branch and reduce optimization navigator (BARON) in the general algebraic mathematical solver (GAMS). The model maximizes the net farm income to determine the cultivated crop assigned to each farmland using three types of reclaimed wastewater (RW); tertiary treated wastewater; secondary treated wastewater; and primary treated wastewater. Constraints in the optimization model include: (1) reclaimed wastewater availability constraints and (2) irrigated farmlands constraints.

6. Chapter Six: Optimization Model for Agricultural Reclaimed Water Allocation Using Mixed-Integer Nonlinear Programming

A mixed-integer nonlinear programming reclaimed water allocation optimization model was developed in chapter six to maximize the net benefit generated from the cultivation of different types of crops, comparing the use of reclaimed water type A (tertiary treated), and reclaimed water type B (secondary treated). The model was solved using Algorithms for coNTinuous/ Integer Global Optimization of Nonlinear Equations (ANTIGONE) optimizer in the general algebraic mathematical solver (GAMS). A total of 84 agricultural farms located on 5300 hectares to the south of Baghdad, Iraq were available for irrigation with reclaimed water. Analysis considered varying quantities of available reclaimed water and different irrigation efficiencies (45-85%).

7. Chapter Seven: Agricultural Reclaimed Water Allocation Optimization Model Maximizes Individual Farm's Net Benefit

The objective function is to maximize the net benefit, taking into consideration individual farm level, generated from the cultivation of different types of crops using reclaimed water with different quantities and qualities. The optimization model was solved using the mixed integer nonlinear programming (MINLP) using Algorithms for coNTinuous / Integer Global Optimization of Nonlinear Equations (ANTIGONE) optimizer (Misener and Floudas, 2014) in the general algebraic modeling system (GAMS) (GAMS Development Corporation, 2016). In this MINLP water allocation optimization model, reclaimed water was allocated proportionally to all farms. Two reclaimed water qualities were compared, reclaimed water type A (tertiary treated) and reclaimed water type B (secondary treated), considering different RW availabilities with different irrigation efficiencies to validate the sensitivity of the computed results. The objective function of this model is subjected to reclaimed water availability constraints, the cultivated area constraints, the farm-crop connectivity and farm-RW connectivity constraints, and minimum net benefit constraints.

8. Chapter Eight: Regional Water Allocation Optimization Model Using Three Different Water Resources for Five Different Uses

    A linear programming regional water allocation optimization model was developed and solved using GAMS. This optimization model maximizes reclaimed water use through the allocation of surface water (SW), groundwater (GW), and reclaimed water (RW) for five different types of uses; industrial, domestic, agricultural, commercial, and recreational use, considering Baghdad as a case study. The model assures fair allocation of water among all users, as other models have been applied in many other regions around the world. Surface water and groundwater are the main sources of fresh water, while the reclaimed water is the alternative source. All the wastewater generated from the domestic and the commercial demand nodes is diverted to the main wastewater treatment plant (WWTP). While, the wastewater generated from the industrial demand nodes is either diverted to the main WWTP or to the private wastewater treatment plant (PWWTP), depending on the availability of the PWWTP to the industrial demand node. The treated wastewater is assumed either to be reused as reclaimed water, or it will be discharged to the downstream sink. Water availability, water and wastewater treatment plants capacity, allocation percentages, and continuity equations constraints have been used in this model to satisfy the objective function.

9. Chapter Nine: Conclusions and Perspectives

Chapter 9 of this dissertation summarized the entire study and concludes the key finding from the application of the developed water allocation optimization models on Iraq. Recommendations on the future research direction considering Iraq's water management system are included.

It should be mention that chapters 4, 5, and 6 were published in three separate publications earlier in 2018, which are:

Aljanabi, A. A., Mays, L. W., & Fox, P. (2018a). Application of an Optimization Model for Assessing the Performance of Water Appropriation in Iraq. *Environment and Natural Resources Research*, *8*(1), 105. https://doi.org/10.5539/enrr.v8n1p105

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Aljanabi, A. A., Mays, L. W., & Fox, P. (2018c). Optimization Model for Agricultural Reclaimed Water Allocation Using Mixed-Integer Nonlinear Programming. *Water*, *10*(10), 1291. https://doi.org/10.3390/w10101291

CHAPTER 2 WATER IN IRAQ

2.1. Introduction

Iraq is part of Mesopotamia located is in the eastern part of the Middle East in an arid and semi-arid region (Figure 2-1). The temperature during summer is usually over 48°C during July and August and drops below freezing in January (Abdul-Kareem et al. 2013). The country is surrounded by Saudi Arabia and Kuwait to the south and the Arabian (Persian) Gulf to the southeast, Iran in the east, Turkey to the north, and Syria and Jordan to the west. Its total area is 438,320 km^2 of which 924 km^2 is of inland water. Until a few years ago, Iraq was considered as relatively rich for its water resources compared to other surrounding countries. During the 1970s, Turkey launched an ambitious plan to harness the waters of the Tigris and the Euphrates basin for irrigation and hydroelectricity production and to provide an economic stimulus to its southeastern provinces (Kolars 1994), which consequently influenced Iraq's water resources. The Tigris and the Euphrates Rivers form the main surface water resources of Iraq. The two rivers flow from Turkey through Syria before crossing the Iraqi border and join in the south forming what is referred to as the Shat Al-Arab, of about 120 km long, which drains into the Arabian (Persian) Gulf (Figure 2-2). Most of the Tigris River and its tributaries flow from Turkey (56%) followed by Iran (12%) and the remainder, which is about 32% comes from terrain internal to Iraq, as it is listed in Table 2-1.

Figure 2-1 Climate zones of Iraq (Al-Ansari 2013)

Figure 2-2 Iraq’s surface water system (Nord Nord West License, 2016)

Table 2-1 The Tigris River and its tributaries average annual water inflow

Tigris River and its Tributaries	Total Length (km)	Total Area km^2	Annual Water Inflow (Billion m^3)	Annual Inflow (%)	
				Inside Iraq	Outside Iraq
The Tigris River	1900	46700	19.43	-	1
Fiesh Khabour	160	6270	2.1	0.58	0.42
Greater Zab	473	26470	14.32	0.58	0.42
Lesser Zab	456	22250	7.07	0.64	0.36
Adhaim	220	10680	0.7	1.00	-
Diyala	386	3200	5.86	0.41	0.59
Total			49.48	0.32	Turkey 56% Iran 12%

2.2. Water Resources in Iraq

In Iraq, there are two major sources of water; surface water, and groundwater, in addition to three alternative sources; precipitation, desalination, and reclaimed water. The main source of renewable water is the surface water, which comes mainly from the Tigris and the Euphrates Rivers and their tributaries. The groundwater forms the second major source of water which is represented by non-renewable aquifers. In general, groundwater does not satisfy the standards of drinking water except in northern of Iraq and the west desert. Rainwater harvesting, and limited desalination plants are other minor sources of water (UNICEF/Iraq 2014). Precipitation forms the third source of fresh water in the country. The desalinized water, which is mainly focused in Basra, to the south of Iraq, is the fourth source of water. Finally, the reclaimed water, which has not been get the expected interest, forms another alternative source of water that is going to be included in the current study.

1.5. Surface Water

The Tigris and the Euphrates Rivers have played a vital role in the life of human beings in Mesopotamia, which had witnessed the first development of water resources and land that goes back to the beginning of 5500 BC. Fields and cities of the Sumerians and Babylonians were irrigated using the Euphrates River through complicated systems of canals (Altinbilek 1997).

In 1913, the Hindiya Barrage, the first modern water diversion structure, was built in the Tigris–Euphrates river system. It was constructed on the Euphrates River based on plans by the British civil engineer William Willcocks (Kliot 1994). In 1950, the Board of Development, which was created by the Kingdom of Iraq, started the planning for the construction of irrigation and flood control systems. Irrigation projects and many dams were constructed on rivers' streams for irrigation and hydropower generation. Furthermore, another complicated system was established on the Euphrates River for flood control usage. This system includes Ramadi Barrage which regulates the flow of the Euphrates River and to discharge the excess flood water into the Habbaniye Lake. On the other hand, the Tigris River includes regulators, canal systems, the Tharthar Lake project, the Samarra Barrage, and other projects. Later, different other hydraulic structures and irrigation projects were constructed on main rivers and tributaries in Iraq (Figure 2-3). These attractive canals networks facilitate water flow of the Euphrates River with Habbaniyah, Tharthar, and Razaza Lakes to store excess floodwater. Another connection between the Tigris and the Euphrates Rivers was created to the south of Baghdad through Shatt al-Hayy. While, the Main Outfall Drain (MOD), or so-called "Third River," is considered as the largest canal in this network which was constructed in 1953 and developed in 1992. The main objective of the 565km long MOD is to drain the area between the Euphrates and the Tigris Rivers south of Baghdad to prevent soil salinization caused from irrigation (Kolars 1994, Daoudy 2005).

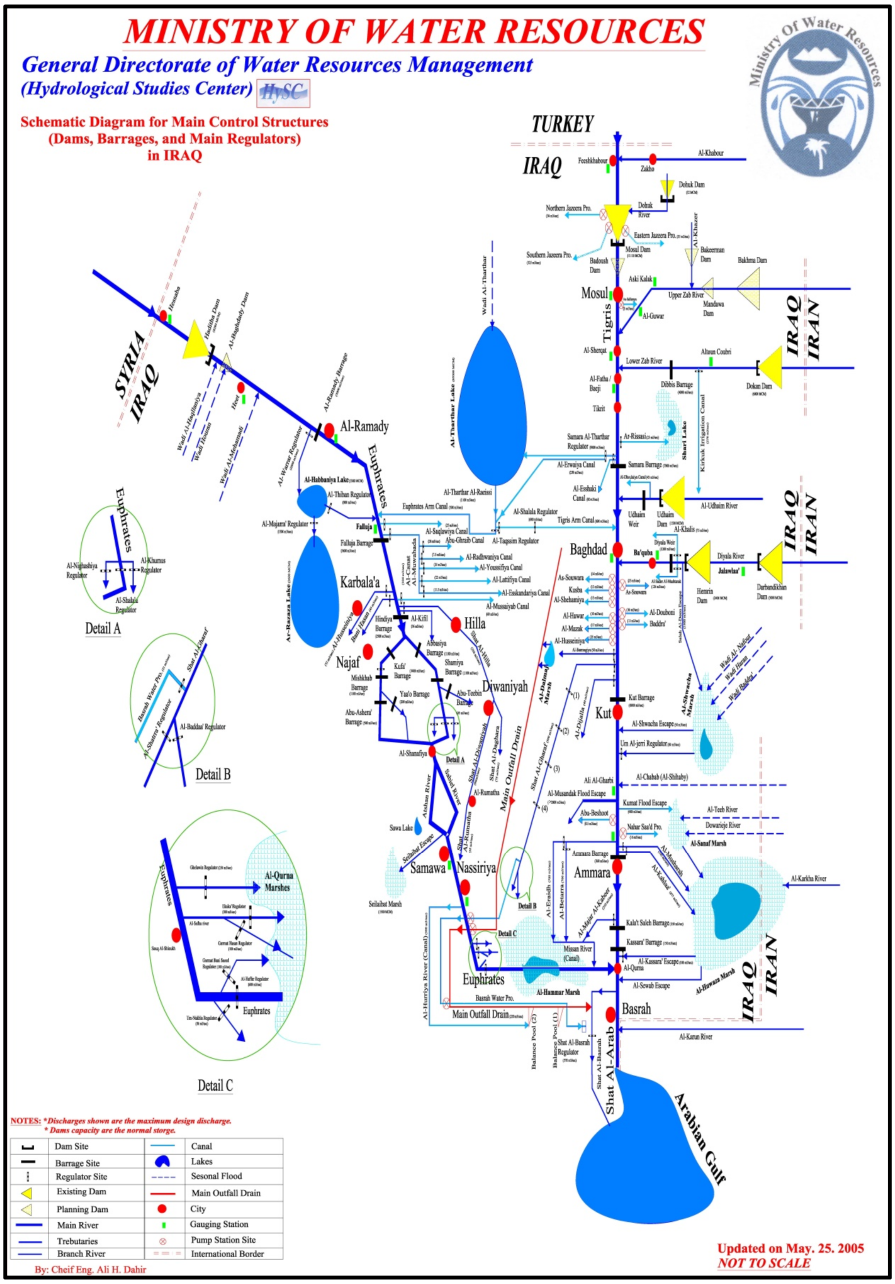


Figure 2-3 Schematic diagram of the main rivers and Tributaries in Iraq (Ministry of Water Resources- Iraq)

2.2.1. *The Tigris River*

The second largest river in Western Asia is the Tigris River of about 1,800 km length. It originates in the Taurus Mountains in Turkey south of the Armenian Highlands and the city of Elazig. The river is formed by the confluence of two headwater tributaries; the Batman and the Botan (ESCWA-BGR 2012). The Tigris River basin extends on Turkey, and Iraq, as shown in Figure 2-4. The total water potential of this basin is shared by Turkey and Iraq with contributions of about 51.9% and 48.1%, respectively. The Tigris River total water inflow, in billion cubic meters (BCM), for the years 1933-2012 shows significant variability with noticeable repetition of water shortages in the last decade (Table 2-2).

Table 2-2 The Tigris River water inflow for the years 1933-2012, (BCM)

Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow
1933	33.81	1947	35.69	1961	32.90	1975	38.06	1989	26.74	2003	57.38
1934	34.94	1948	47.29	1962	39.55	1976	62.28	1990	38.80	2004	44.42
1935	34.78	1949	55.42	1963	75.09	1977	40.76	1991	30.87	2005	37.08
1936	41.52	1950	57.20	1964	53.50	1978	50.71	1992	62.72	2006	41.85
1937	43.57	1951	31.20	1965	41.48	1979	39.60	1993	66.36	2007	37.09
1938	53.30	1952	55.60	1966	44.32	1980	51.99	1994	45.19	2008	18.00
1939	54.38	1953	57.46	1967	55.84	1981	52.93	1995	66.34	2009	22.99
1940	58.94	1954	79.96	1968	67.76	1982	54.40	1996	39.37	2010	37.68
1941	57.02	1955	31.09	1969	96.58	1983	41.27	1997	42.73	2011	32.90
1942	50.75	1956	51.27	1970	39.49	1984	34.00	1998	49.95	2012	28.60
1943	54.09	1957	57.09	1971	39.52	1985	54.96	1999	18.60		
1944	40.28	1958	37.97	1972	62.31	1986	32.46	2000	20.10		
1945	40.48	1959	34.32	1973	35.77	1987	58.54	2001	20.90		
1946	68.32	1960	33.08	1974	53.36	1988	96.09	2002	42.24		

There are several tributaries for the Tigris River basin, most of which are shared by Iraq and Turkey or Iran and Iraq. The Tigris River crosses the Iraqi border at Fiesh Khabur where the Khabur tributary joins the main river shortly to the south. The Tigris River flows south until it reaches Mosul. Its mean discharge at Mosul is about 630m^3/s. Inside Iraq, the Tigris River is supplied by seven tributaries (Figure 2-3), that flow form Turkey, Iran, and/or Iraq, which are:

1- Fiesh Khabour: This tributary is shared between Iraq and Turkey. It arises in Sirnak (Turkey) and flows through Zakho (Iraq) before its confluences with the Tigris at the Iraqi-Turkish border. The mean annual flow of the Khabur is 68 m^3/s with a mean annual flow volume at the confluence with the Tigris of about 2.0 BCM.
2- Greater Zab: It is the largest Tigris River tributary which is originates in Turkey and shared by Iraq and Turkey. It supplies the Tigris River with an average annual flow volume of 12.7 BCM.

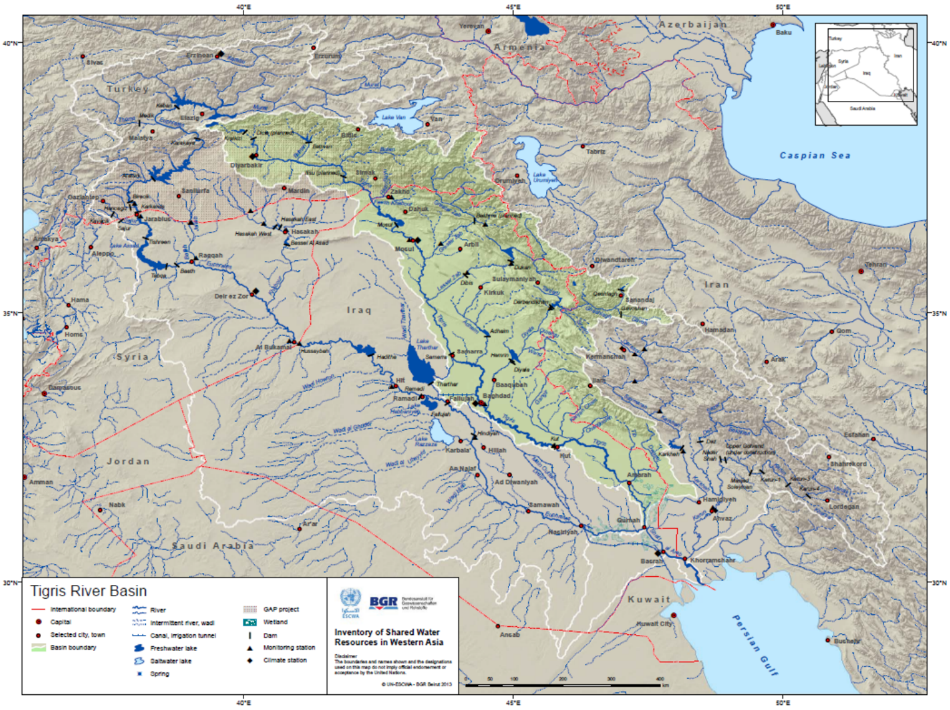


Figure 2-4 The Tigris River Basin (ESCWA-BGR 2012)

3- Lesser Zab: It is originated in Iran not far from the Iraqi border and shared by Iran and Iraq. The average annual flow volume of the Lesser Zab is about 7.8 BCM, contributing in an average flow to the Tigris River of about 249 m^3/s.

4- Adhaim: While it is not a shared tributary, the Adhaim is an intermittent stream that drains an Iraqi area of about 13,000 km^2. The river participates in an annual volume of about 0.79 BCM at its confluence with the Tigris River. The Adhaim River is usually subjected to flash flooding.

5- Diyala: It forms the border between Iraq and Iran for about 30 km and is shared by them. The Diyala River has a mean annual flow volume of 4.6 BCM.

6- Tib: The Tib River is shared by Iran and Iraq with an average annual flow volume of about 1.0 BCM.

7- Dwairej: The Dwairej River originates in Iran and is shared with Iraq. Its average annual flow volume is less than 1 BCM. The Dwairej meets the Tib in the city of Amarah (Iraq).

2.2.2. *The Euphrates River*

The Euphrates River is the longest river in Western Asia with 2781 km long, which arises from the southeastern parts of Turkey. It drains an area of 444,000 km^2 shared by four countries (Iraq 41%, Turkey 28%, Syria 17% and Saudi Arabia 14%). Most of the Euphrates stream-flow originates from precipitation in the Armenian Highlands of Turkey. Other riparian countries participate in a small portion of the Euphrates’s water, such as; the Sajur, Balikh and Khabour which represent the contribution flow in Syria (ESCWA-BGR 2012). Isaev and Mikhailova (2009) estimate the percentages of the drainage basin located within Turkey, Syria and Iraq at about 33, 20 and 47 percent respectively. Figure 2-5 shows the Euphrates's River basin where it extends over Turkey, Syria, and Iraq. Other references estimate that approximately 15 percent of the drainage basin is located within Saudi Arabia, while a small part falls inside the borders of Kuwait (Daoudy 2005, and Frenken 2009). Finally, Jordan was included in the drainage basin of the Euphrates; a small part of the eastern desert (220 km^2) drains toward the east rather than to the west (Isaev and Mikhailova 2009, and Frenken 2009).

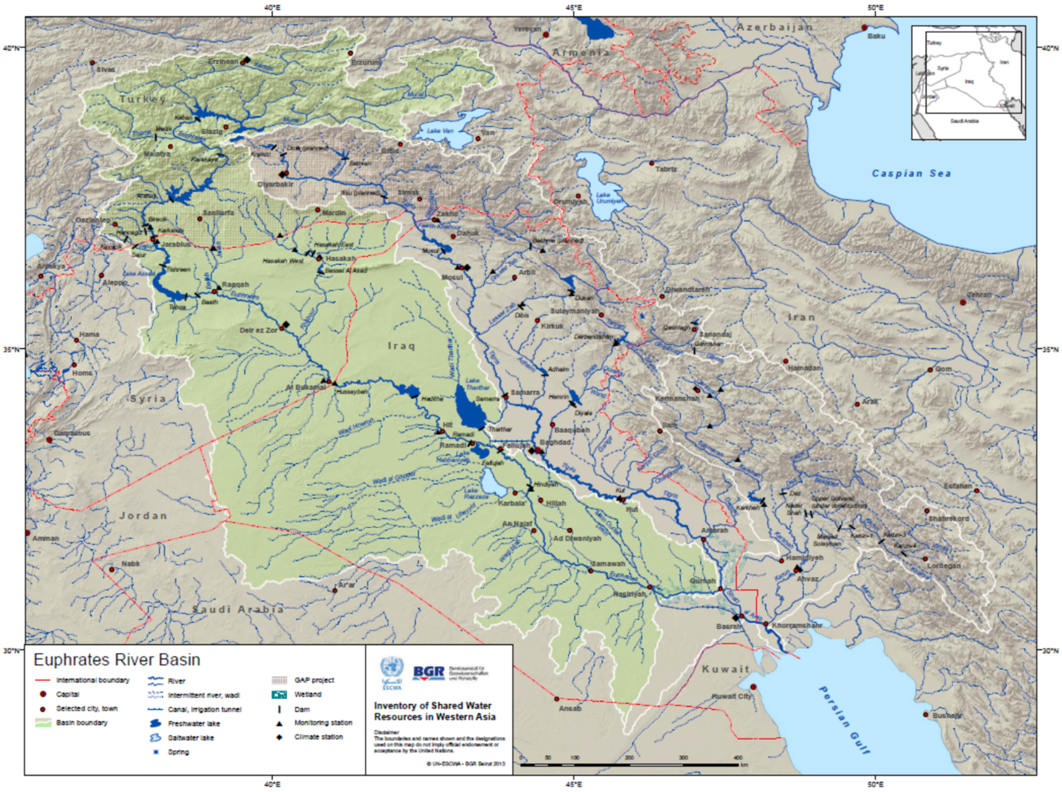


Figure 2-5 The Euphrates River Basin (ESCWA-BGR 2012)

The river crosses the Iraqi border with Syria at Hasaibah to the west. The mean daily discharge of the Euphrates River inside Iraq used to be of about 909m^3/s. The Euphrates River mean discharge at Hit and Haditha cities prior to 1972 was 967m^3/s, which later has dropped to 553m^3/s after 1985 with a reduction in the river's discharge of about 43% (Al-Ansari 2013). The Euphrates River is totally different than the Tigris River inside the Iraqi territory whereas there is no tributary water supply to the river. As the river flows inside the Iraqi terrains, it supplies several small canals in the central and southern parts of Iraq for domestic and irrigation uses of the area between the Tigris and the Euphrates Rivers to the south of Baghdad. In about 135 km south of Faluja, the Hindiya Barrage diverts a maximum discharge of 471.5m^3/s to small parallel tributaries for irrigation purposes (Al-Sahaf 1976). During flood seasons, a small fraction of the Euphrates water is diverted to the Habaniya Lake, which is located about 40 km to south of Ramadi.

The discharge of the Euphrates River has been changed dramatically since Turkey has started the construction of Southern Anatolia Project (GAP) in the 1970s. The collected data about Euphrates discharges after 1990 shows how the construction of the GAP on the Euphrates has influenced the river's water inflows. According to the Ministry of Water Resources (MoWR), data records over the last 80 years, listed in Table 2-3, illustrate a decrease in mean annual flow to about 17.09 billion cubic meters (BCM) for the years 1990-2012 (MoWR, 2012), while average discharges at Hit after 1990 has dropped to 356m^3/s (Isaev and Mikhailova, 2009) in comparison to 967m^3/s prior to 1972.

Table 2-3 The Euphrates River water inflow for the years 1933-2012 (BCM)

Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow
1933	15.60	1947	26.20	1961	15.24	1975	9.42	1989	28.13	2003	15.71
1934	18.30	1948	35.80	1962	23.03	1976	24.76	1990	8.99	2004	20.54
1935	28.00	1949	23.20	1963	40.32	1977	30.47	1991	12.40	2005	17.57
1936	36.20	1950	24.90	1964	25.67	1978	26.9	1992	12.15	2006	20.64
1937	25.80	1951	21.00	1965	26.34	1979	25.37	1993	12.37	2007	19.33
1938	35.70	1952	31.40	1966	35.51	1980	28.87	1994	15.29	2008	14.70
1939	29.60	1953	34.60	1967	42.33	1981	27.92	1995	23.90	2009	9.30
1940	35.50	1954	39.10	1968	51.71	1982	27.92	1996	30.01	2010	12.45
1941	37.50	1955	23.40	1969	63.31	1983	26.47	1997	27.64	2011	14.64
1942	30.60	1956	27.70	1970	26.06	1984	15.82	1998	28.95	2012	20.47
1943	35.30	1957	27.60	1971	28.51	1985	21.08	1999	18.61		
1944	33.20	1958	24.00	1972	23.20	1986	17.21	2000	17.23		
1945	27.60	1959	19.67	1973	15.31	1987	19.60	2001	9.59		
1946	32.00	1960	29.46	1974	9.02	1988	46.73	2002	10.67		

2.3. Groundwater

In the early 1920s, Iraq had started an organized geological investigation which was focused for the purpose of oil resources assessment. Later, geological and geophysical investigation, hydrogeological mapping, groundwater monitoring and management (wells and springs), remote sensing analysis and groundwater quality assessments were conducted in many regions of Iraq, particularly in the northern region during 2000-2003.

Groundwater plays a significant role as a main water source for agricultural and water supply uses in many parts of northern Iraq where it witnesses a fast urbanization and economic expansion. Thousands of wells with depth ranges of 100 to 200 m are used. Safe yield was assessed in some basin through the monitoring and water management schemes to prevent aquifer overexploitation. Over the country, numerous deep wells were drilled to mitigate drought (Stevanovic and Iurkiewicz 2009).

2.3.1. *Groundwater Levels*

After almost one century, groundwater resources in Iraq are still not well explored. However, the development and management of groundwater is a very ancient art in many regions. Stevanovic and Iurkiewicz (2009) have mentioned that no important systematic hydrogeological investigation has taken place in Iraq between 1990 and 2000 and the process of drilling water-wells was practically implemented without adequate feasibility studies or project evaluation.

In 1975, the aquifer layers in the northern region were on an average of 70 m deep, but after drilling, piezometric level stabilized on the depth of 35 m. Recently, there are some differences which have been noticed in the piezometric pressure of the porous aquifer. Therefore, the ground level stabilizes on average at 70 m depth after the drilling and fluctuates throughout the year by 1-2 m. Indications refer that during the last few years, along with fast urbanization and increased water demands in the northern parts of Iraq, there is a significant depletion in groundwater levels by more than 10m (as for Salahaddin governorate) (MoWR, 2014). The groundwater levels in Iraq are illustrated in Figure 2-6.

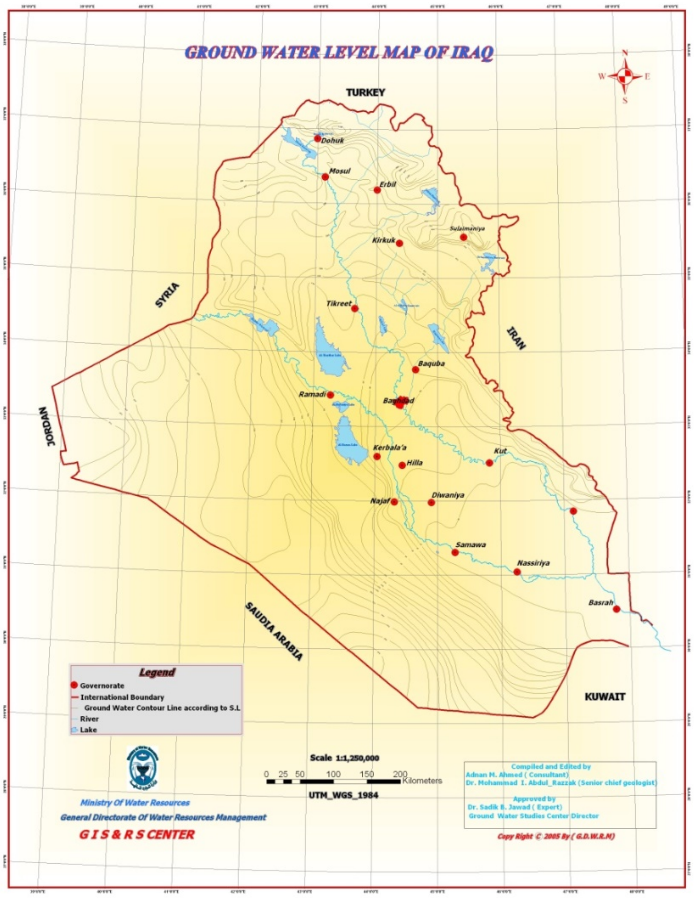


Figure 2-6 Groundwater level in Iraq (MoWR)

2.3.2. *Groundwater Quality*

The quality of the available groundwater varies due to the aquifer’s type of soil. For instance, the predominance of carbonate sedimentary rocks in the mountains of the north leads to pH values from 6.5 to 8.0 and a generally low mineral content (Stevanovic and Iurkiewicz 2009). The Bakhtiari aquifer, which is located in the northwestern mountain foothills, has a thickness of up to 6000m and its water is generally of good quality. There are some exceptions related to the shallow groundwater wells which are close to cities and villages that might be polluted by the infiltrated wastewater due to the use of septic tanks in these areas. The presence of evaporitic gypsum or anhydrite layers affect the quality of groundwater drained through complex aquifer systems or Fars formations. Where they are present, the total salinity and content of Na, Cl, NO_3, SO_4 and Fe ions increase accordingly (Stevanovic and Iurkiewicz 2009). The availability of good quality groundwater in the southern parts of Iraq is rare (Figure 2-7) due to the high levels of salinity. For instance, in Basra, the salinity levels are way above 7000 ppm. While, World Health Organization (WHO) water standard for human consumption is 500 ppm or less (IZDIHAR, 2007). Recently, the effect of pollution, such as nitrate from fertilizers and acid rain, influences the groundwater chemistry. Due to the long residence time of groundwater in the invisible subsurface environment, the effects of pollution may first become apparent tens to hundreds of years afterwards.

Al–Basrawi, et al. (2015) concluded that the salinity of the groundwater in Baghdad generally ranges from fresh water to brine water. The researcher observed that the predominant groundwater type is Chloride water with the presence of Sulphate water in some other places. Furthermore, they found the main direction of groundwater flow is from the west towards the east, with the presence of local movements in other directions. The transmissivity coefficient generally ranges between (50-350) m^2 /day, but these values decrease toward the east, especially east of the Tigris River. The groundwater depth in Baghdad ranges between (2-50) m depending on the distance between the groundwater's well and the main river stream or irrigation channels, which form the main sources of the natural groundwater recharge in the area (Al–Basrawi et al. 2015). Groundwater levels range between (>25 – <36) m above sea level and it is noticed that there is an increase in the value of the hydraulic slope to the north as a result of the rocks' low permeability of the area (Al–Hitti 1985, Al–Basrawi et al. 2015).

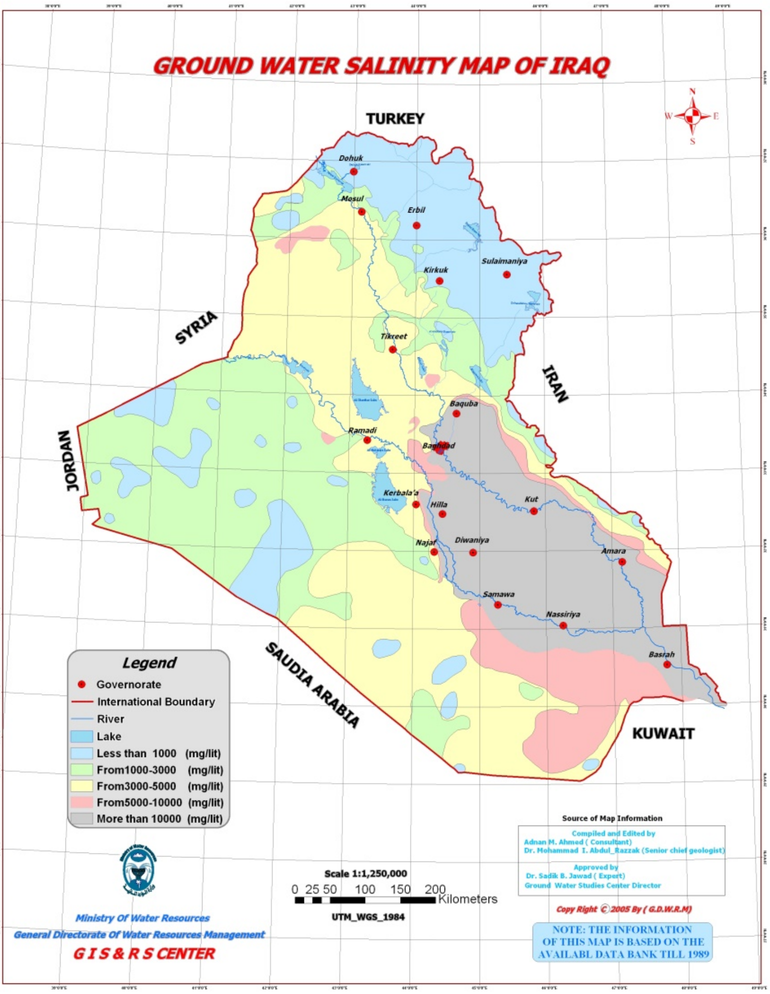


Figure 2-7 Groundwater salinity map of Iraq (MoWR).

In fact, urbanization has a significant negative impact on groundwater quality due to the nitrate and phosphate which make the groundwater unsuitable for drinking but relatively good for irrigation. On the other hand, low groundwater quality may cause waterborne diseases and crop damage. The World Health Organization (2006) stated that about 80% of waterborne diseases in the world and over one-third of the total deaths in the developing countries were caused by the consumption of polluted water. The interest of society in groundwater geochemistry is mainly to ensure good drinking water quality. Although drinking water can be processed through desalination units, it is a very costly alternative of treatment due to the high energy requirement.

2.3.3. *Groundwater Use*

Groundwater management must be planned, organized, and thoroughly synchronized with decision makers and authorized personnel while there should be designated programs that control of well drilling to avoid groundwater over-exploitation. A randomly determined minimal distance between wells is still the main principle while drilling in Iraq. It should be substituted by consistent geological and hydrogeological studies on both regional and local scales to decide the location and the feasible pumping rates of the proposed wells (Stevanovic and Iurkiewicz 2009).

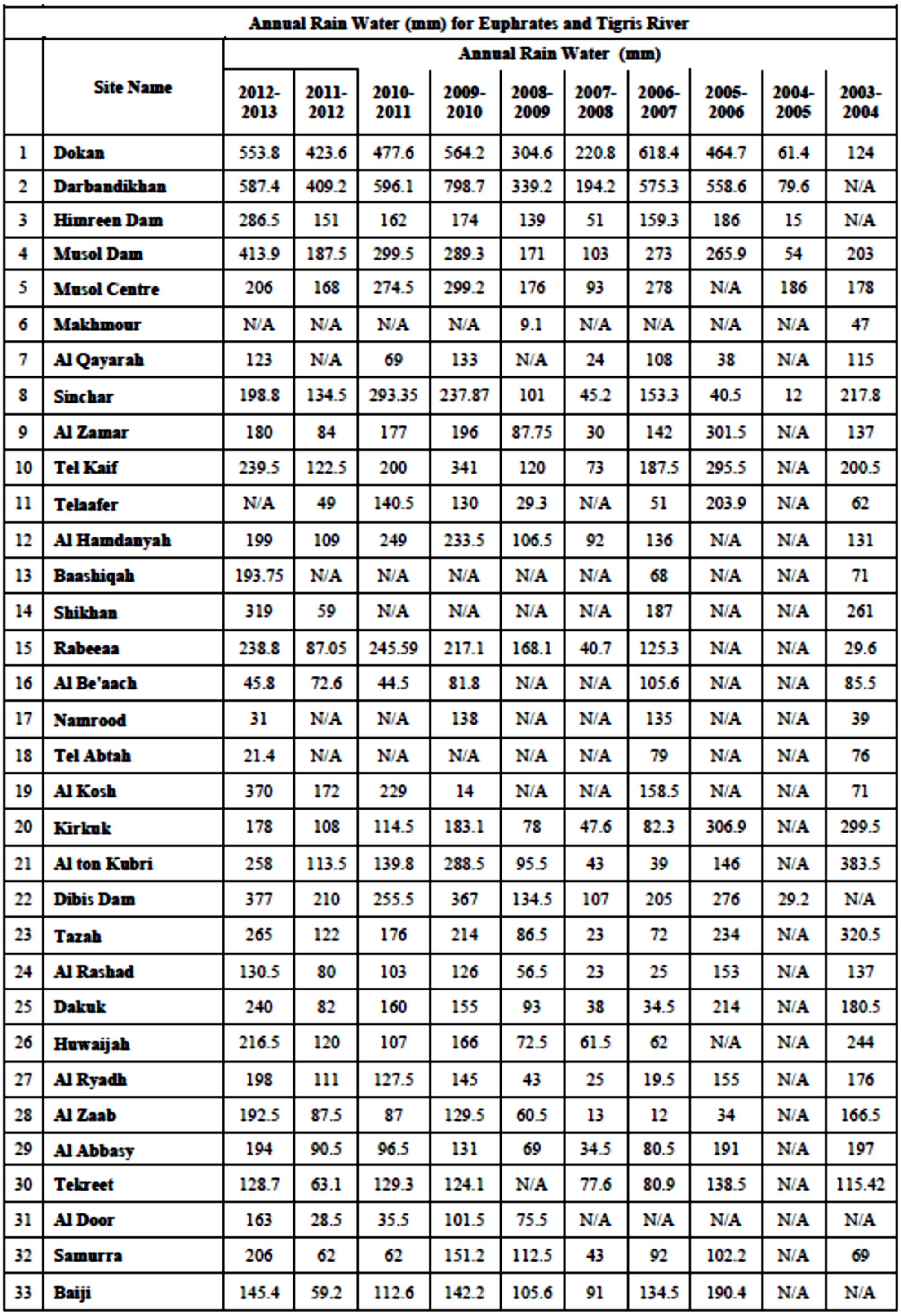
Using groundwater protection measures is necessary to prevent overexploitation, contamination, and to improve the water availability in the region. Annez and Buckley (2009) mentioned that the most endangering factors causing groundwater pollution and depletion are the accelerated urbanization of the main cities, and the disposal of the industrial and/or municipal untreated wastewater to the environment. Therefore, groundwater quality must be carefully monitored while suitable measures to treat the existing pollution sources should be considered and enforced by responsible authorities (Annez and Buckley 2009).

The effect of rapid population increase on the quality of groundwater needs to be investigated. Groundwaters mainly are controlled by chemical weathering of rock-forming minerals. Al-Manmi (2007) compared the quality standards of Iraq's groundwater for potable uses. The study proved that most of the groundwater samples were unsuitable for drinking indicating that the majority were good for irrigation, breeding and livestock in addition to its suitability for some industries.

2.4. Rainfall

Since Iraq has a variety of terrains that vary from mountainous lands in the north to flat lands in the middle heading to the south. Therefore, rainfall intensity varies from location to another taking into account sea surface elevation, temperature, humidity, and the atmospheric pressure. The wettest season in Iraq is winter which receives about 42-56 % of the total annual rainfall. Spring and autumn contribute about 27-32 % and 15-27 % of the total annual rainfall in the country, respectively. Finally, the driest season is summer which contributes less than 0.5% of the total annual rainfall that can be neglected (Al-Rijabo and Salih 2013). The mean annual rainfall intensities for different locations in Iraq, for the period 2003-2013, are listed in Table 2-4. The majority of Iraq experiences either dry or semi-dry climate, except for the mountainous regions of the north and northeast. The average annual rainfall is 154 mm (Al-Ansari 2013), but it ranges from less than 100 mm over 60% of the country in the south up to 1200 mm in the northeast. The rainy season is restricted between October to April (Al-Ansari and Knutsson 2011). Figure 2-8 shows the rainfall intensity distribution over the entire country. The high evapotranspiration rates due to relatively high temperatures diminish the value of the precipitated water that is available. So, getting the economic benefit from precipitation is mainly limited to the northern regions of Iraq.

Table 2-4 Average rainfall intensities for different locations in Iraq for the period 2003-2013 (MoWR, 2014).



	Annual Rain Water (mm) for Euphrates and Tigris River										
	Site Name	**Annual Rain Water (mm)**									
		2012-2013	**2011-2012**	**2010-2011**	**2009-2010**	**2008-2009**	**2007-2008**	**2006-2007**	**2005-2006**	**2004-2005**	**2003-2004**
1	**Dokan**	553.8	423.6	477.6	564.2	304.6	220.8	618.4	464.7	61.4	124
2	**Darbandikhan**	587.4	409.2	596.1	798.7	339.2	194.2	575.3	558.6	79.6	N/A
3	**Himreen Dam**	286.5	151	162	174	139	51	159.3	186	15	N/A
4	**Musol Dam**	413.9	187.5	299.5	289.3	171	103	273	265.9	54	203
5	**Musol Centre**	206	168	274.5	299.2	176	93	278	N/A	186	178
6	**Makhmour**	N/A	N/A	N/A	N/A	9.1	N/A	N/A	N/A	N/A	47
7	**Al Qayarah**	123	N/A	69	133	N/A	24	108	38	N/A	115
8	**Sinchar**	198.8	134.5	293.35	237.87	101	45.2	153.3	40.5	12	217.8
9	**Al Zamar**	180	84	177	196	87.75	30	142	301.5	N/A	137
10	**Tel Kaif**	239.5	122.5	200	341	120	73	187.5	295.5	N/A	200.5
11	**Telaafer**	N/A	49	140.5	130	29.3	N/A	51	203.9	N/A	62
12	**Al Hamdanyah**	199	109	249	233.5	106.5	92	136	N/A	N/A	131
13	**Baashiqah**	193.75	N/A	N/A	N/A	N/A	N/A	68	N/A	N/A	71
14	**Shikhan**	319	59	N/A	N/A	N/A	N/A	187	N/A	N/A	261
15	**Rabeeaa**	238.8	87.05	245.59	217.1	168.1	40.7	125.3	N/A	N/A	29.6
16	**Al Be'aach**	45.8	72.6	44.5	81.8	N/A	N/A	105.6	N/A	N/A	85.5
17	**Namrood**	31	N/A	N/A	138	N/A	N/A	135	N/A	N/A	39
18	**Tel Abtah**	21.4	N/A	N/A	N/A	N/A	N/A	79	N/A	N/A	76
19	**Al Kosh**	370	172	229	14	N/A	N/A	158.5	N/A	N/A	71
20	**Kirkuk**	178	108	114.5	183.1	78	47.6	82.3	306.9	N/A	299.5
21	**Al ton Kubri**	258	113.5	139.8	288.5	95.5	43	39	146	N/A	383.5
22	**Dibis Dam**	377	210	255.5	367	134.5	107	205	276	29.2	N/A
23	**Tazah**	265	122	176	214	86.5	23	72	234	N/A	320.5
24	**Al Rashad**	130.5	80	103	126	56.5	23	25	153	N/A	137
25	**Dakuk**	240	82	160	155	93	38	34.5	214	N/A	180.5
26	**Huwaijah**	216.5	120	107	166	72.5	61.5	62	N/A	N/A	244
27	**Al Ryadh**	198	111	127.5	145	43	25	19.5	155	N/A	176
28	**Al Zaab**	192.5	87.5	87	129.5	60.5	13	12	34	N/A	166.5
29	**Al Abbasy**	194	90.5	96.5	131	69	34.5	80.5	191	N/A	197
30	**Tekreet**	128.7	63.1	129.3	124.1	N/A	77.6	80.9	138.5	N/A	115.42
31	**Al Door**	163	28.5	35.5	101.5	75.5	N/A	N/A	N/A	N/A	N/A
32	**Samurra**	206	62	62	151.2	112.5	43	92	102.2	N/A	69
33	**Baiji**	145.4	59.2	112.6	142.2	105.6	91	134.5	190.4	N/A	N/A

Annual Rain Water (mm) for Euphrates and Tigris River

	Site Name	Annual Rain Water (mm)									
		2012-2013	2011-2012	2010-2011	2009-2010	2008-2009	2007-2008	2006-2007	2005-2006	2004-2005	2003-2004
34	**Baakuba**	166	65.5	38.5	35.3	28	N/A	N/A	122.5	N/A	N/A
35	**Al Adheem**	205.5	65.5	79.5	178	84	53	147.5	150.8	N/A	N/A
36	**Galawlaa**	217	100	54	55.5	N/A	N/A	N/A	123.5	17.5	N/A
37	**Khanekeen**	221.6	120.3	54.5	67.3	27	N/A	N/A	205.3	34.6	N/A
38	**Dyala Dam**	214	105	47.8	41.6	29.2	N/A	157.1	87	11.2	N/A
39	**Mandeli**	222	104	49	44.1	N/A	N/A	N/A	85	N/A	N/A
40	**Al Khalis**	134.2	30	N/A	31.7	N/A	N/A	N/A	101	N/A	N/A
41	**Baghdad**	290	26.2	125.85	120.8	141.5	47.1	51.9	143.6	N/A	N/A
42	**Al Kut**	191.4	N/A	124.2	93	65.1	43.3	126.3	141.9	10.5	N/A
43	**Al Suwairah**	72	N/A	34	52	N/A	N/A	N/A	N/A	N/A	N/A
44	**Al Hay**	160	N/A	89.5	82.5	N/A	N/A	N/A	N/A	N/A	N/A
45	**Al Azizzyah**	82.8	N/A	50.5	51.5	43	66	59	115.85	N/A	N/A
46	**Badrah**	128.2	N/A	69.4	86.3	87.8	30.5	85.1	121.9	36.6	N/A
47	**Al Numanyah**	90	N/A	75	88	47	33	72.5	131.07	N/A	N/A
48	**Al Umarah**	337.75	N/A	51.5	263.1	N/A	N/A	N/A	N/A	N/A	N/A
49	**Ali Al Gharbi**	223.2	33.5	89.7	113.4	71.1	N/A	N/A	N/A	7	N/A
50	**Babil Centre**	158.2	N/A	82.5	64.5	N/A	N/A	N/A	N/A	N/A	N/A
51	**Al Musayab**	112	N/A	61.5	78.5	N/A	N/A	N/A	N/A	N/A	N/A
52	**Sadat Al Hindyah**	166.5	N/A	94.5	69.5	37.9	29.4	78	76.7	N/A	N/A
53	**Al Rumadi**	125.65	44.5	109.25	51.35	21.3	20.4	N/A	52.3	N/A	N/A
54	**Heet**	90.25	32.3	67.35	83.6	87.3	N/A	25.5	N/A	N/A	N/A
55	**Hadeetha**	104.9	33.3	92.9	89.2	76.6	49.5	42	86.6	N/A	N/A
56	**Husaibah**	85.5	30.2	102.2	108.6	49.4	23.5	101.7	130.9	N/A	N/A
57	**Al Muthana Centre**	90.9	N/A	22.3	N/A	33	N/A	N/A	43.5	N/A	N/A
58	**Thi Qar Centre**	118	N/A	62.12	52.1	58.7	N/A	N/A	48	N/A	N/A
59	**Al Najaf Centre**	29.3	N/A	N/A	5.42	N/A	N/A	N/A	N/A	N/A	N/A
60	**Al Basrah Centra**	54.5	49.45	56.8	56	N/A	N/A	N/A	N/A	N/A	N/A
61	**Al Qadesyah Centre**	93.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
62	**Karbala Centre**	N/A	N/A	20.5	60.7	N/A	N/A	N/A	37.6	N/A	N/A
63	**Sherkatt**	134	72.5	123	140.5	109	86.5	120	195.5	N/A	140.33
64	**Arbil**	498.7	123.5	254.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A
65	**Sulaimanyah**	522.7	348.3	326.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
66	**Al Qaem**	N/A	N/A	N/A	18.8	N/A	N/A	26.5	54	N/A	N/A
67	**Al Kuwair**	N/A	N/A	N/A	9	N/A	N/A	N/A	N/A	N/A	37
68	**Misan Centre**	N/A	N/A	N/A	43.89	N/A	18.7	95.1	106.5	N/A	N/A
69	**Hamam Al Aleel**	N/A	N/A	N/A	N/A	N/A	N/A	65	N/A	N/A	32
70	**Al Hameedat**	N/A	N/A	N/A	N/A	N/A	N/A	155	N/A	N/A	123.5
71	**Al Shimal**	N/A	N/A	N/A	N/A	N/A	N/A	84	N/A	N/A	75

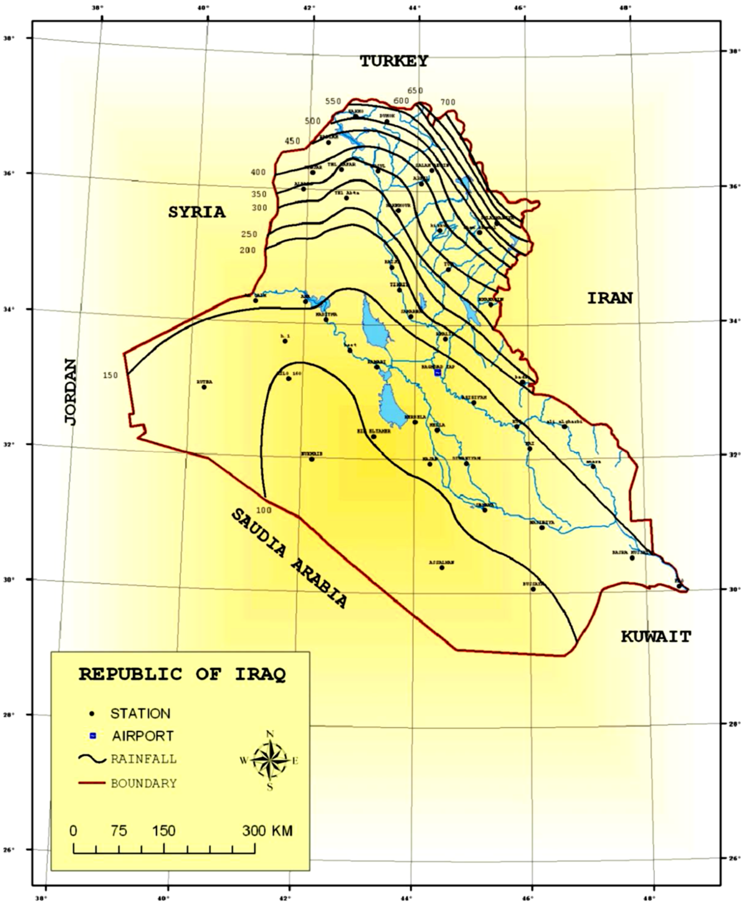


Figure 2-8 Average seasonal rainfalls in mm (MoWR).

There has been a significant variability in Iraq’s climate which led to a noticeable challenge in how to adapt that change especially in water availability season. For example, between 2007-2009 Iraq had experienced severe droughts that were followed by a sudden change in the climate. Unexpected heavy rainfalls and storms during short periods acted severely on some parts of the central and southern regions. During these extreme events, Iraq experienced rainfall amounts of about 200% of the normal. For instance, in 2013, up normal flooding rainfall of more than 225% of the average annually rainfall caused severe flooding in Salahaddin, Baghdad, Wasit, Maysan, and other areas that severely damaged many residential and agricultural sectors.

2.5. Desalination

One of the alternative water sources, which should be taken care of due to the recent water crises in Iraq, is desalinized sea water. Desalination technology already has been used in many Middle Eastern countries, especially in the Gulf region. As the efficiency of desalination plants been improved, desalination would successfully improve the quantity and the quality of the existing water supplies in many cities in the south of Iraq. Therefore, due to the recent water challenges in both quantity and quality in Basra, the largest city in the south of Iraq with a population of more than 2.85 million people, adopting water desalination represents an urgent sustainable measure to provide an alternative source of water satisfying drinking water requirements. The main principle of a desalination process is to convert sea and/or brackish water, which is exists abundantly, into fresh water suitable for drinking or irrigation uses. The main issue with the desalination process is that it needs electric power and high investment.

Recently, the only way to satisfy drinking water demand for Basra is through buying desalinized drinking water in gallons provided by reverse osmosis (RO). Furthermore, it is often that people use potable reverse osmosis units in their houses to desalinize the tap water due to its relatively high salt concentration. Recently, there is under construction a desalination project in Basra with a daily treatment capacity of 0.199 MCM which is expected to satisfy a good portion of the city’s water demand. The project is going to be a positive action in providing a good quality drinking water. Therefore, the construction of water desalination units in the southern part of Iraq may attract investments from industries because it is considered a popular area in terms of marketing and economic growth in the region. So, using desalination would be an effective solution to provide potable water for this growing area for a better future.

The cost of desalination is consequently very high taking into account the prices of oil and technology used. Large-scale desalination projects require significant amounts of energy and expensive infrastructure. Like Arab Gulf countries, Iraq is a relatively rich due to the internal energy reserves which can be partially invested to desalinize water. On the other hand, because this technology is not practiced professionally in Iraq, the cost per liter of desalinized water is also an issue. The projected costs of desalinized water in the region range from \$0.50 to \$1.00 per cubic meter (Ghaffour et al. 2013). Using sustainable energy sources like solar and wind energy may make the process of desalination as feasible alternative to provide the required water quantities.

2.6. Reclaimed Water

Reclaimed water is the treated wastewater effluent which usually is discharged from wastewater treatment plants either to the river streams or to the environment. Recently, reclaimed water use is receiving increased attention as an alternative and reliable source of water in many developing countries while it is already used in a wide range in many developed countries. The best water reuse projects, in terms of economic viability and public acceptance, are those which saves part of the available freshwater by substituting it with the produced reclaimed water to be used at least in irrigation, industry, and/or recreation. Furthermore, reclaimed water use is friendly to the environment and helps in the reduction of water pollution.

In some countries, reclaimed water is known as reused wastewater while other countries call it as used water. In Singapore, the reclaimed water is known as the new water (NEWater) to give it more acceptance among people. The majority of the Middle Eastern countries have followed new experience in the field of treated wastewater reuse. On the other hand, Iraq has nothing to do in the field of reclaimed water use and it been detected that only in Baghdad there is an average daily disposal of more than 1.0 MCM of secondary treated wastewater to the Tigris River.

It is possible to use the tertiary and the secondary treated wastewater to irrigate different types of crops, as it is usually followed in many developed countries such as in the United States especially in California and Florida. Furthermore, reclaimed water is possible to be used as an alternative source in many other applications such as; industrial, domestic, commercial, groundwater recharge, and recreational uses.

Recently, in Iraq there is a growing awareness of the impact of the improper dealing with the generated wastewater due to the resulted contamination of river streams, groundwater, and the environment, which already receives great attention all over the world.

2.6.1. *Reclaimed Water as an Alternative Source of Water*

Due to the increase in urbanization along with the rapid increase in population, reclaimed water deserves greater attention to be converted into an alternative and reliable source of water with limited uses in Iraq. The inclusion of reclaimed water as an alternative source is necessary in the implementation of future water resource projects and to mitigate the pressure on built ones. Using reclaimed water in irrigation is one of the most practiced applications around the world. Other uses, as in environmental restoration, cleaning, toilet flushing, car washing, power plants cooling systems, air conditioning, groundwater recharge, and industrial uses are potential methods to utilize reclaimed water. Most of the previously mentioned reclaimed water uses are practiced today in many arid and semi-arid regions all over the world which are facing drought and water shortage challenges. Furthermore, agricultural reclaimed water use is a common practice in several Mediterranean countries, and there is a considerable interest in the long- term effects of treated wastewater on cultivated crops for human consumption and other related uses (Angelakis et al. 1999).

2.6.2. *Reclaimed Water Produced in Iraq*

Iraq has nineteen provinces. Each Iraqi province contains several administrative units, which either directly dispose their treated and/or untreated wastewater to water bodies. The quality of the disposed treated wastewater influences the quality of freshwater and groundwater resources when it is discharged in large quantities. Very little investment has been made in wastewater treatment facilities due to the lack of finance. Potable water treatment and supply often receive more priority than wastewater collection and treatment. In addition, physical and commercial losses in water supply networks are high. Potable water is often supplied for a few hours per day or even per week. Tariffs are low so that the operation and maintenance costs of the utilities are often not recovered. Wastewater, in most cases, is not appropriately treated, leading to environmental and health hazards.

Due to the increased trends of urbanization along with rapid population increase, wastewater treatment deserves greater emphasis and investment.

2.7. Bottled Water

Bottled water is a relatively new product which is extensively used in Iraq. Many Iraqi households are considering bottled water as a healthier alternative in comparison to the low-quality tap water in many regions. This product forms an everyday item in the shopping basket of the typical Iraqi urban family. However, bottled water consumption is largely limited to key urban areas where consumers' monthly incomes are higher and where such products benefit from better availability, visibility and accessibility.

Bottled water is still an immature market in Iraq despite the impressive growth with an annual average per capita consumption estimated to be no more than 45 liters based on the whole population in 2013 (UNICEF/Iraq 2014). It is worth to mention that in Iraq, people prefer to use either bottled water and/or small filtration units connected to tap water rather than using tap water because of the common belief that the tap water quality does not meet quality standards. The limitations of safe water sources and/or unqualified treatment or other factors have pushed the people to consume bottled water (Figure 2-9) (Izdihar Project, 2007).

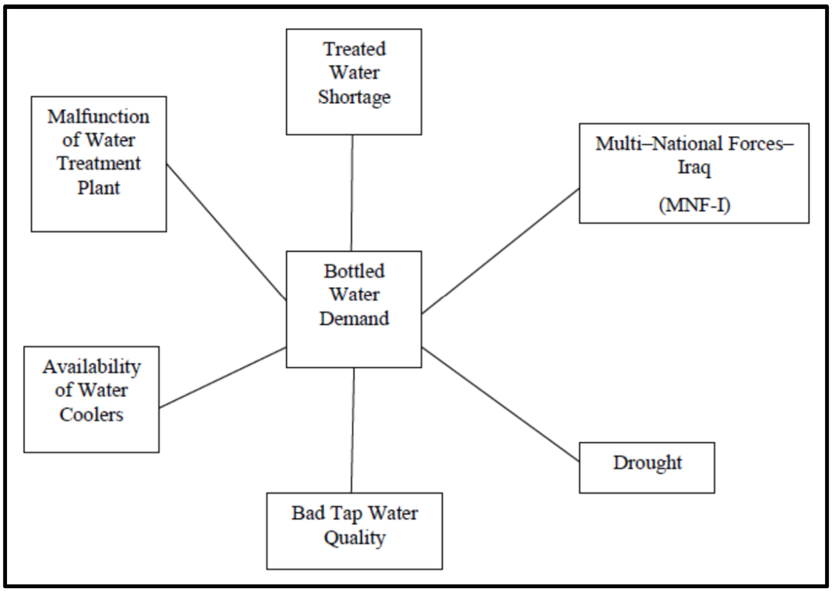


Figure 2-9 Factors affecting increasing demand for bottled water in Iraq (IZDIHAR, 2007)

According to the Iraqi Ministry of Planning, in 2006, the total consumption of bottled water in Iraq was 1340 million liters, and it was estimated as 1500 million liters as for 2013 considering the population growth.

2.8. Surface Water Quality in Iraq

In Iraq, the water quality of the Tigris River near the border of Turkey is assumed to be good, including water originating in both Turkey and Iraq. As the Euphrates and Tigris Rivers flow downstream, water quality declines due to the inflow of major pollutants the disposal of treated wastewater in urban areas in addition to the irrigation return flows. The water quality of the Euphrates River, where it crosses the Iraqi border, is much worse than the Tigris River because it has been influenced by the return flow from irrigation projects in Turkey and Syria (Erdem 2003). The recent water quality condition of the

Euphrates River is expected to get worse with the increase of the irrigated lands in Turkey, Syria and Iraq and due to the decline in transboundary water supplies.

Furthermore, water quality deterioration of the two rivers also is caused by flood flows which are diverted into off-stream storage in Tharthar Lake, that is released later to the Tigris and the Euphrates Rivers. The return flows from irrigation inside Iraq along with the low-quality treated wastewater discharges has deteriorated water quality in both the Euphrates and the Tigris Rivers, especially downstream the big cities. Furthermore, both quantity and quality of transboundary water flows from Iran into the southern region of Iraq are unknown, which mainly have been impacted by irrigation return flow and other activities formed in Iran. As a consequence, the environment of the Iraqi southern cities and marshlands have be influenced accordingly (FAO, 2016).

In Iraq, quality deterioration of the available water resources is forming a significant issue because the available water monitoring and controlling measures are inefficient. One of the main problems related to the weakness of water quality monitoring system is the lack to an active quality control of the treated wastewater discharges to the environment. The water quality tests might be taken in a continuous manner, while there must be an active monitoring system that controls the quality (UNICEF/Iraq 2014). One of the quality parameters measured is the total dissolved solids concentration in ppm (TDS). It is significant that the concentration of TDS increases with the increase of human activities along the rivers as illustrated in Figures 2-10 and 2-11 for the Tigris and the Euphrates Rivers respectively.

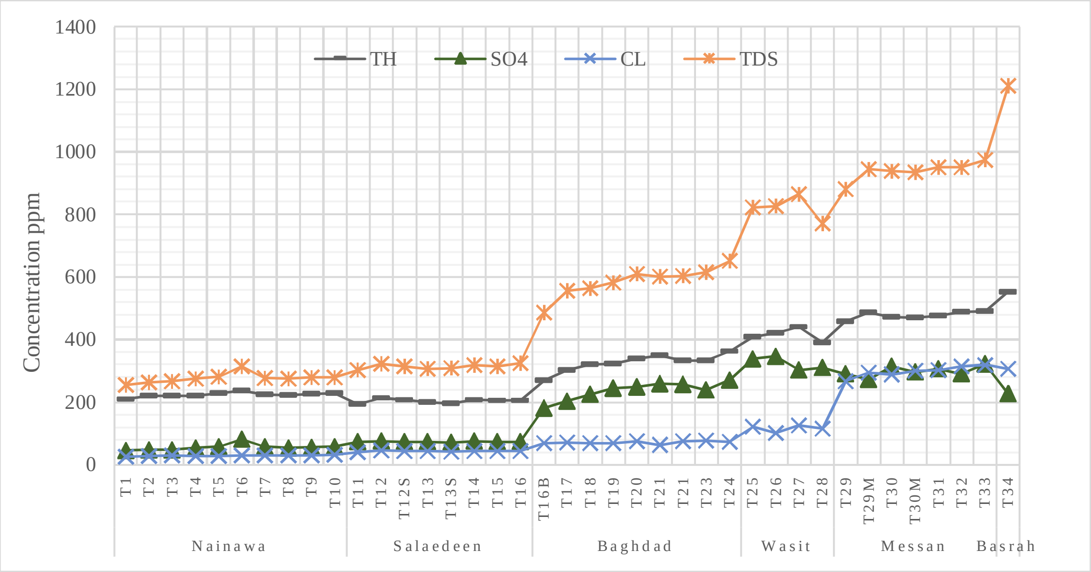


Figure 2-10 Measured water quality parameters along the Tigris River, 2011 (Ministry of Environment)

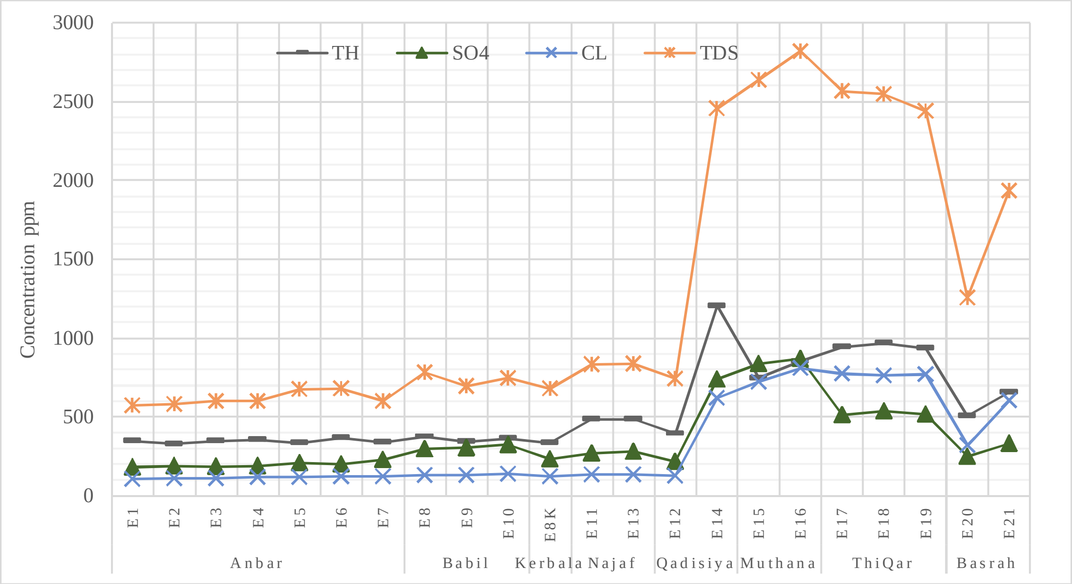


Figure 2-11 Measured water quality parameters along the Euphrates River, 2011 (Ministry of Environment)

About 60% of the populations of Baghdad’s population is connected to a sewer system. It is a common practice to discharge untreated sewage directly into water bodies which causes significant health and economic risks. This is true for all the other cities in the country. The measured quality parameters show a significant deterioration in water quality as the rivers flow downstream to the south. Table 2-5 lists part of these measured quality parameters along the Euphrates River.

2.9.Transboundary Water Quality

There are many disputes between Iraq, Turkey and Syria related to the quantities and qualities of received water by the downstream countries. Water usage by Turkey has been limited mainly to hydropower generation and irrigation especially after the construction of the GAP project in comparison to the previous usage which generally was a non-consumptive usage. In general, the irrigation return flow mainly causes water pollution, which consequently affects potential downstream uses. The agricultural lands in Turkey have been increased to several times larger than before the construction of the GAP project. Al-Bahrani (2014) studied water quality parameters between 1998 and 2010 using irrigation, drinking, and industrial indices for his study. The author concluded that water quality for irrigation use has declined from excellent in 1998 to good in 2010. The classification of the river for drinking purposes was reduced from good to the polluted level from 1998 to 2010, respectively. For industrial use, the quality declined from acceptable in 1998 to severely polluted in 2010. Therefore, the authors concluded that the Euphrates River has been polluted in Turkey and Syria before entering the Iraqi border (Al-Bahrani, 2014). Figures 2-13 and 2-14 illustrate the monthly concentrations of several quality

Table 2-5 Measured water quality parameters along the Euphrates River inside Iraq, 2011 (MoE)

Province	Anbar							Babil			Kerbala	Najaf		Qadisiya		Muthana		ThiQar			Basra	
Station	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E8K	E11	E13	E12	E14	E15	E16	E17	E18	E19	E20	E21
PH	7.4	7.45	7.55	7.61	7.79	7.89	8.13	7.22	7.48	7.58	8.14	7.69	7.79	8	8	7.81	7.83	8.01	8.23	8.16	8.24	7.96
Temp. (^{o}C)	21.4	21.6	22	21.8	21.7	21.7	22.4	26.2	26.2	26.2	27.6	24.6	24.5	24	24.2	22.4	22	25.3	24.6	25.1	15	15.6
DO2 (mg/L)	7.71	7.64	7.61	7.51	7.36	7.2	7.31	7.82	8.32	8.1	6.76	8.09	7.86	6.9	6.62	8.33	8.59	7.48	7.18	6.73	6.32	5.09
BOD$_5$ (mg/L)								1.87	1.66	1.98		1.89	1.94									
PO$_4$ (ppm)	ND	ND	ND	ND	0.05	0.03	0.02	0.2	0.21	0.2	0.35	0.13	0.06	0.12	0.13	0.35	0.34	0.23	0.16	0.11	0.32	0.32
NO$_3$ (mg/L)	3.39	3.21	3.13	3.2	3.53	3.56	3.46	3.63	3.7	3.55	2.38	4.49	4.33	5.41	6.41	3.98	3.86	1.53	1.67	1.66	10.4	10.9
Ca (mg/L)	68.5	71.8	73.3	75.5	73.2	75.4	81.7	87.4	83.3	86.5	75.2	122	115	85.2	197	188	211	194	192	197	121	140
Mg (mg/L)	35.8	39.1	39.7	39.4	37.4	41.6	37.8	37.6	32	37.6	36.3	46.2	48.4	55.6	212	67.6	78.7	114	122	113	65	90.4
TH (mg/L)	349	330	346	354	337	367	340	376	343	364	334	487	484	393	1204	744	851	943	966	936	507	655
K (mg/L)	3.14	3.25	3.29	3.42	3.6	3.78	3.97	5.04	4.45	4.64	3.95	6.14	6.27	5.34	12.5	15.2	15.7	10.5	10.2	10.4	5.39	10
Na (mg/L)	78.6	77	77.2	77.3	84.7	98.6	88.3	95	86.2	96.2	79.6	108	115	86.8	358	428	464	561	544	540	292	529
SO$_4$ (mg/L)	182	191	184	191	209	201	230	297	305	324	234	268	281	218	737	837	870	513	538	518	250	330
CL (mg/L)	106	110	111	118	119	123	123	129	130	140	121	133	134	128	620	722	808	775	764	769	321	606
TDS (mg/L)	573	579	599	602	676	678	598	782	696	745	678	834	835	744	2457	2638	2820	2567	2545	2439	1257	1935
EC	1170	1184	1221	1218	1366	1492	1174	1222	1064	1157	1031	1347	1356	1187	3498	3786	4063	4092	4079	3959	1932	3047
Alk. (mg/L)	135	134	136	140	140	145	144	149	140	141	133	118	120	121	159	175	176	214	213	216	164	175

parameters for the Euphrates River in the city of Al-Qaim at the Iraqi border with Syria for the years 1998 and 2010.

On the other hand, there are natural causes and other parameters which have direct and/or indirect influence on water quality deterioration in the Tigris and the Euphrates Rivers. Some of those natural causes are; climate change, the high rate of evaporation which accumulates salts, the accumulation of sediments due to erosion, poor drainage, and low soil quality in the south of Iraq.

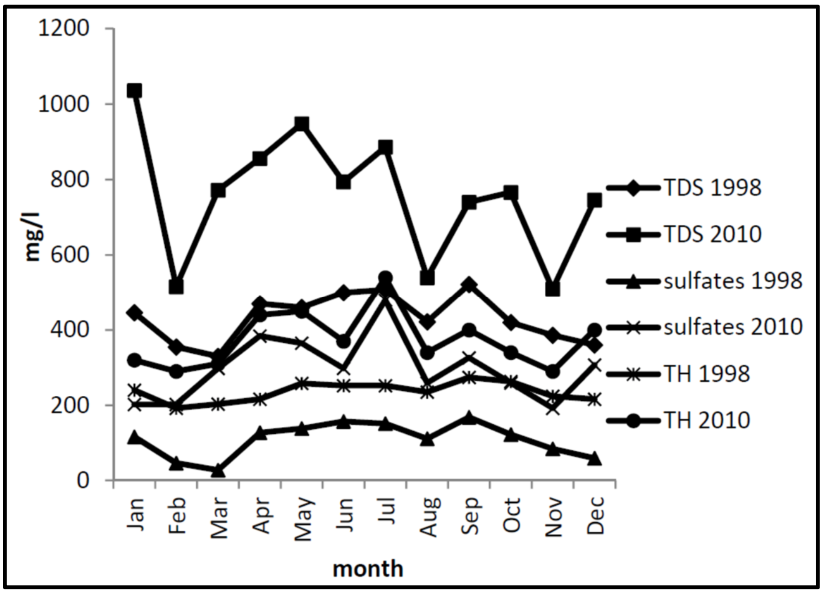


Figure 2-12 Monthly concentrations of total dissolved solids, sulfates, and total hardness for the Euphrates River in Qaim Station for 1998 and 2010 (Al-Bahrani, 2014)

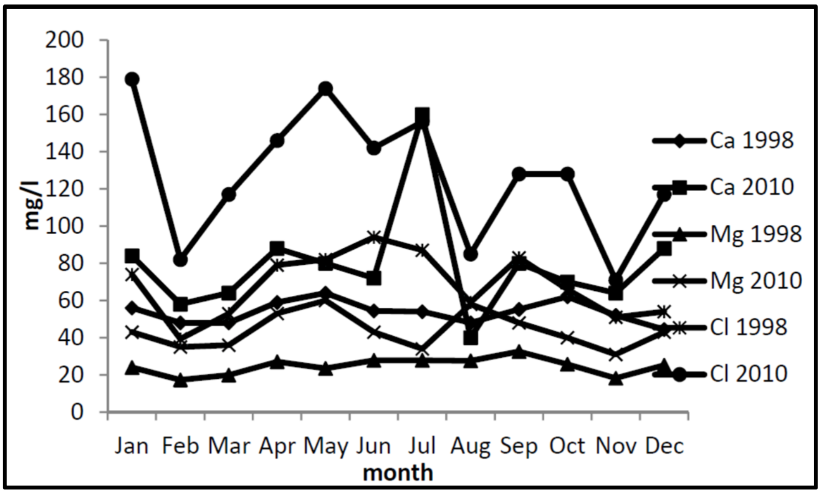


Figure 2-13 Monthly concentrations of calcium, magnesium, and chlorides for Euphrates River in Qaim station for 1998 and 2010 (Al-Bahrani, 2014)

2.10. Population

Iraq's population is approximately 37.88 million (2016) with a growth rate of 2.9% (Iraqi Central Statistical Organization, 2016). Its annual average water demand per capita is about 180 m^3 as domestic and 1430 m^3 as a total for 2013 (Al-Ansari 2013). There has been a significant annual increase in water demand in the Tigris-Euphrates river basin of about 0.527 km^3 in the Tigris river and approximately 0.475 km^3 in the Euphrates river due to the increase of population and related life activities. The expected average water demand in 2020 will increase to 42.8 km^3/yr for the Tigris River basin and 29.2 km^3/yr for the Euphrates river basin inside Iraq. So, the projected shortage of water will be about 8.6 km^3 if the water inflow is limited to 63.5 km^3/yr for both of the rivers (Issa et al. 2013).

2.11. Drought Sequences in Iraq

Iraq represents the downstream country of the Tigris and the Euphrates Rivers and other boundary valleys. Therefore, when Turkey started the construction of its Southeastern

Anatolia Project (GAP) in the 1970s, water resources in Iraq started facing a direct threat from the upstream dams. In 2007-2009 Iraq experienced severe water shortage events due to the low values of precipitation which resulted in serious economic impacts due to the decline in agricultural productivity of the highly populated areas in the Euphrates and the Tigris Rivers basins (Shean 2008). In 2009, Iraq experienced the second year of a severe drought, the second one in 10 years, and the fourth consecutive dry year while precipitation dropped to 25-65% of normal levels. Other factors have prolonged the drought conditions as the transboundary water inflows from Turkey and Iran have decreased. Theses water shortages inflicted significant harm on Iraq's economy and environment. Therefore, the Iraqi Ministry of Water Resources declared to the public that it may not be able to meet the water requirements for the summer season of 2010. Figure 2-15 reflects the condition of plants growing throughout Iraq as observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite between April 7 and April 22, 2009. The brown area shows where plants were growing less than what they used to in between 2000 and 2008. Green areas show better than average growth, and tan areas reflect average conditions (NASA, 2009) Iraq's crop production has declined to half of its usual production rates. For instance, in 2009 wheat production was estimated as 45% less than the normal harvest. By then, food imports had increased at high cost as a consequence of the decrease in crop production (United Nations Development Programme, 2009). Recently, Iraq imports the majority of the daily domestic vegetables and fruits because farmlands were abandoned due to water shortages.

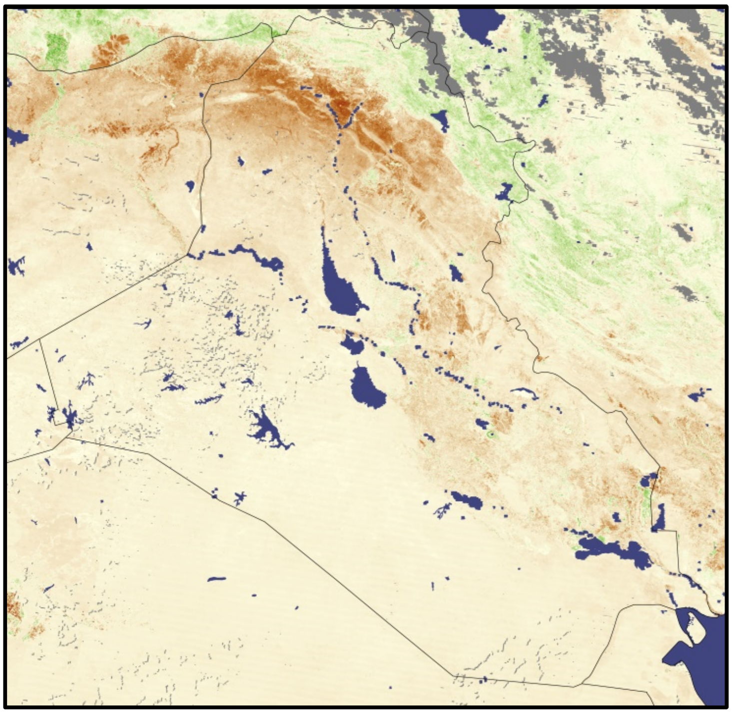


Figure 2-14 The condition of plants growing throughout the region as observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite between April 7 and April 22, 2009 (http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=38914)

2.12. Water State and Uses in Iraq

Iraq is still considered as one of the highest ranked countries regarding water demand per capita (Figure 2-16). Statistics indicate that Iraq is the third highest annual water per capita in the Arab world of about 180 m^3 as domestic and 1430 m^3 as a total for 2013, while others put it in the first level of demand per capita. FAO (2010) estimated the total annual water per capita for the year 2010 is 2400 m^3 (IAU, 2010).

Due to the high population growth rate, the available renewable annual water resources per capita have dropped drastically from 14285 m^3 in 1946 to 1430 m^3 in recent years which is about 10 times less (UNICEF/Iraq 2014). Other factors have triggered the stress on the available water resources such as the climate changes, pollution, mismanagement, and water conflicts.

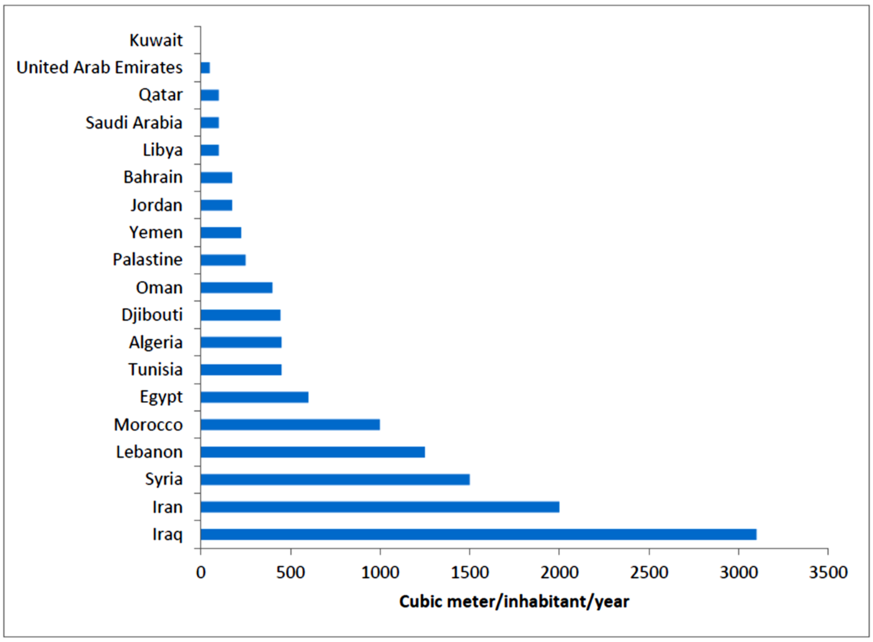


Figure 2-15 Total renewable water resources per capita for several Arab countries and Iran (Water Resources Data, World Bank, 2010)

In urban cities of developing countries, it is common to find many wasteful habits and practices related to the water sector. Therefore, common characteristics have aggravated problems with water supply, such as; resource scarcity, poor quality, complex and aging infrastructure, high population and high-water demand, high water losses in the distribution system, low cost recovery and high subsidy, all leading to mismanagement.

Due to the scarcity of water and the limited supply, it is not unusual to find a discontinuous supply and a relatively low pressure in the water supply system regardless the type of use. Water-saving devices may not be attractive to people who are struggling to get enough water for basic needs. Furthermore, it should also be noticed that it is very often the water distribution is not uniform nor equitable. Some wealthy areas in high-pressure zones receive enough water 24h a day while residents of low-pressure areas or urban poor areas often receive a short supply. Therefore, people do not have the motive to pay for an unreliable, inadequate, and low level of water service.

1.5.1. *Municipal Water Demand*

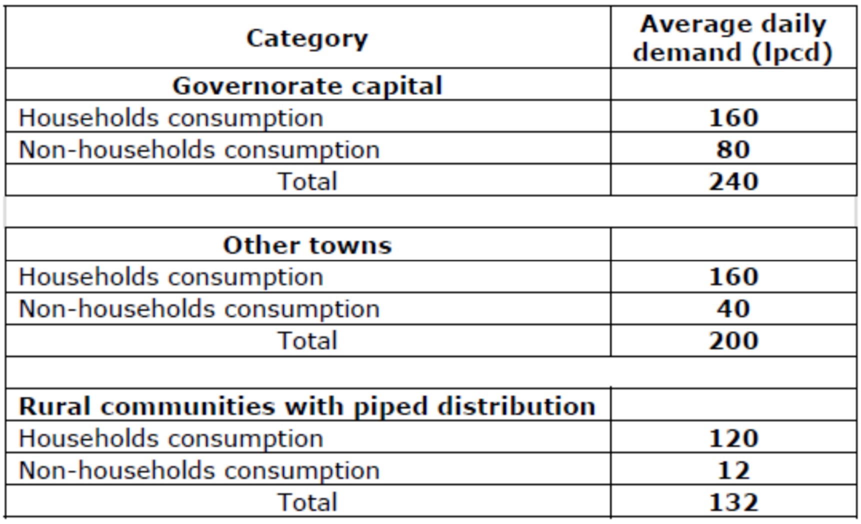
The continuous increase in Iraq's population has been reflected directly on water demand. Accordingly, the agricultural water demand has been increased because Iraq is an agricultural country. The access to safe drinking water is poor, and this is the same in how much is required for irrigation and other uses. In many regions, it is common that the drinking water networks have been polluted by wastewater from leaking sewage pipes and septic tanks. In 2010, the Inter-Agency Information and Analysis Unit has announced that 20% of households in Iraq rely on an unsafe source of drinking water and a further 16% report that they have daily problems with water supply (IAU, 2010). The situation is much worse in rural areas, where only 43% have access to safe drinking water. The World Health Organization (WHO) has supported Iraq in conducting sanitary inspection for about 1600 drinking water resources at Sulaymaniya, Thi-Qar and Anbar provinces. The WHO provided technical and logistical support to implement environmental awareness and education campaigns where it implemented hygiene awareness campaigns in six Iraqi provinces.

In Iraq, the municipal water is usually treated either at the full-scale water treatment plants (WTPs) and/or at compact water treatment plants (CWTPs). The full-scale WTPs were usually located in the main cities and large towns depending on the size of their population. While, the CWTPs usually serve small towns and villages with low populations. In general, municipal water demand has been defined by the Ministry of Water Resources (MoWR, 2014) as:

1. Domestic consumption
2. Non-domestic consumption which consists of human consumption considering the employment in institutional, commercial, and industrial sectors.
3. Non-revenue water, which considers water losses due to leakage and metering errors.

The per capita water demands for municipal uses are listed in Table 2-6, which was estimated by the MoWR (2014).

Table 2-6 Per capita water demand for municipal uses (MoWR, 2014)



Category	Average daily demand (lpcd)
Governorate capital	
Households consumption	**160**
Non-households consumption	**80**
Total	**240**
Other towns	
Households consumption	**160**
Non-households consumption	**40**
Total	**200**
Rural communities with piped distribution	
Households consumption	**120**
Non-households consumption	**12**
Total	**132**

2.12.1.1. Water treatment plants and compact units

The actual daily production of treated water was estimated by the MoWR (2014), considering the design capacity of each WTP and CWTP, by multiplying the design capacity in m³/s times 22 hours operation time and 80% production efficiency. The available data about the treatment capacities of each WTP and CWTP was secured from the previously mentioned study which covered a very wide range of water availabilities and demand in Iraq. In general, the WTPs belong to main cities while the CWTP are associated with districts and subdistricts. Their treatment capacities vary according to the population served. The data provided by the MoWR (2014) covers the design capacity in m³/s as shown in Table 2-7 for all the Iraqi governorates. In Baghdad, there are 10 WTPs and 137 CWTPs with an estimated daily treatment capacity of about 3.532 and 0.252 MCM, respectively with a total of 3.874 MCM.

Table 2-7 Actual capacity of WTPs and CWTPs aggregated at governorate scale (MoWR, 2014)

ACTUAL CAPACITY (m^3/d)				
ID Gov.	**Governorate**	**WTP**	**CU**	**Total**
1	DOHUK	200,160	0	200,160
2	NINAWA	727,591	91,316	818,907
3	ERBIL	333,952	0	333,952
4	SULAYMANIYAH	212,566	0	212,566
5	KIRKUK	393,876	265,937	659,813
6	SALAH AD DIN	336,200	282,410	618,610
7	ANBAR	394,418	177,003	571,421
8	DIYALA	237,043	215,180	452,223
9	BAGHDAD	3,531,898	252,067	3,783,965
10	WASIT	185,500	247,351	432,851
11	BABIL	245,920	502,408	748,328
12	KARBALA	242,620	215,283	457,903
13	MISSAN	68,600	383,223	451,823
14	DIWANIYAH	198,773	188,531	387,304
15	NAJAF	248,960	233,270	482,230
16	THI-QAR	209,140	277,182	486,322
17	MUTHANNA	157,017	114,945	271,962
18	BASRAH	237,000	654,720	891,720
Total		**8,161,234**	**4,100,824**	**12,262,058**

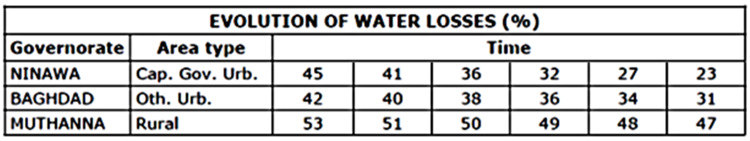
To complete the inputs of the regional water allocation optimization model considering Baghdad as a case study, data form the Iraqi Ministry of Water Resources (2014) related to water demand and availability, has been used. Thus, the correspondence between surface water and groundwater sources considering WTP and CWTPs connectivity to the related water source supplying consumers has been defined taking into account the location in the system and the available resources.

2.12.1.2. Potable water supply and sewage management

According to the MoWR (2014), the potable water supply system in urban and rural areas was estimated to be about 86% and 62%, respectively. In some districts, water losses reach 50%, where there is mostly an old water supply network. To enhance the potable water supply, the MoWR (2014) has recommended to reduce water losses through the renewal and rehabilitating of the existing water distribution systems and to adopt practical water management policies. The enhancement of potable water supply system may participate in a yearly reduction of water losses of about 2%, 1%, and 4% considering the capital, urban, and, rural cities, respectively (MoWR, 2014).

The availability of financial sources added to the stability of security conditions and increasing of the public perception should participated in the improvement of potable water supplies. The MoWR (2014) has estimated that the projected reduction of water losses for the period 2010-2035 of about 50% for the capital of provinces, 75% for the urban cities, and 90% for rural towns, as illustrated in Table 2-8 for Ninawa, Baghdad, and Muthanna provinces.

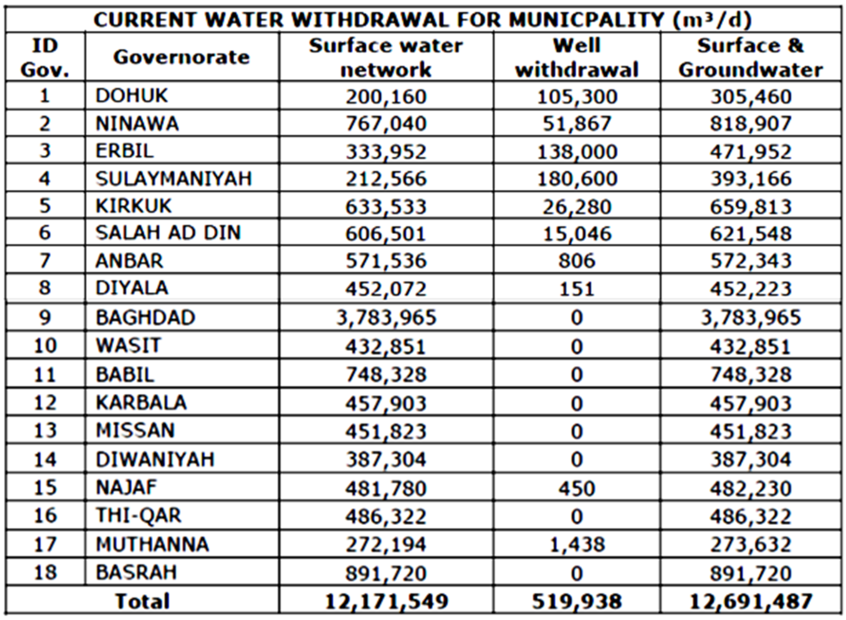
Table 2-8 Example of the projected potable water losses with time for some provinces (MoWR, 2014)



EVOLUTION OF WATER LOSSES (%)							
Governorate	**Area type**	**Time**					
NINAWA	Cap. Gov. Urb.	45	41	36	32	27	23
BAGHDAD	Oth. Urb.	42	40	38	36	34	31
MUTHANNA	Rural	53	51	50	49	48	47

The amount of potable water has been calculated including both surface water and groundwater withdrawal (Table 2-9). The estimated potable water amounts were based on the actual capacity of existing water treatment plants considering the WTPs and CWTPs (MoWR, 2014).

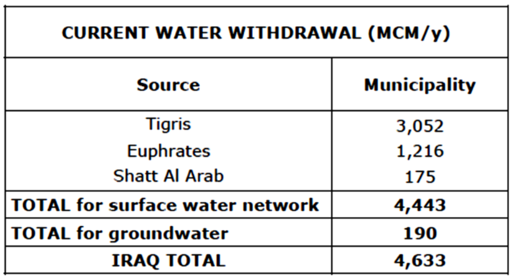
Table 2-9 Surface water and groundwater withdrawal for municipal uses (MoWR, 2014)



CURRENT WATER WITHDRAWAL FOR MUNICPALITY (m^3/d)				
ID Gov.	**Governorate**	**Surface water network**	**Well withdrawal**	**Surface & Groundwater**
1	DOHUK	200,160	105,300	305,460
2	NINAWA	767,040	51,867	818,907
3	ERBIL	333,952	138,000	471,952
4	SULAYMANIYAH	212,566	180,600	393,166
5	KIRKUK	633,533	26,280	659,813
6	SALAH AD DIN	606,501	15,046	621,548
7	ANBAR	571,536	806	572,343
8	DIYALA	452,072	151	452,223
9	BAGHDAD	3,783,965	0	3,783,965
10	WASIT	432,851	0	432,851
11	BABIL	748,328	0	748,328
12	KARBALA	457,903	0	457,903
13	MISSAN	451,823	0	451,823
14	DIWANIYAH	387,304	0	387,304
15	NAJAF	481,780	450	482,230
16	THI-QAR	486,322	0	486,322
17	MUTHANNA	272,194	1,438	273,632
18	BASRAH	891,720	0	891,720
Total		**12,171,549**	**519,938**	**12,691,487**

The total annual amount of the of potable water is the sum of water diverted from the surface water network and groundwater, which are estimated at 4,443 and 190 MCM/y, respectively (Table 2-10).

Table 2-10 Estimated total annual water withdrawal (MCM/y) from surface water and groundwater resources



CURRENT WATER WITHDRAWAL (MCM/y)	
Source	**Municipality**
Tigris	3,052
Euphrates	1,216
Shatt Al Arab	175
TOTAL for surface water network	**4,443**
TOTAL for groundwater	**190**
IRAQ TOTAL	**4,633**

2.12.1.3. Municipal future water demand

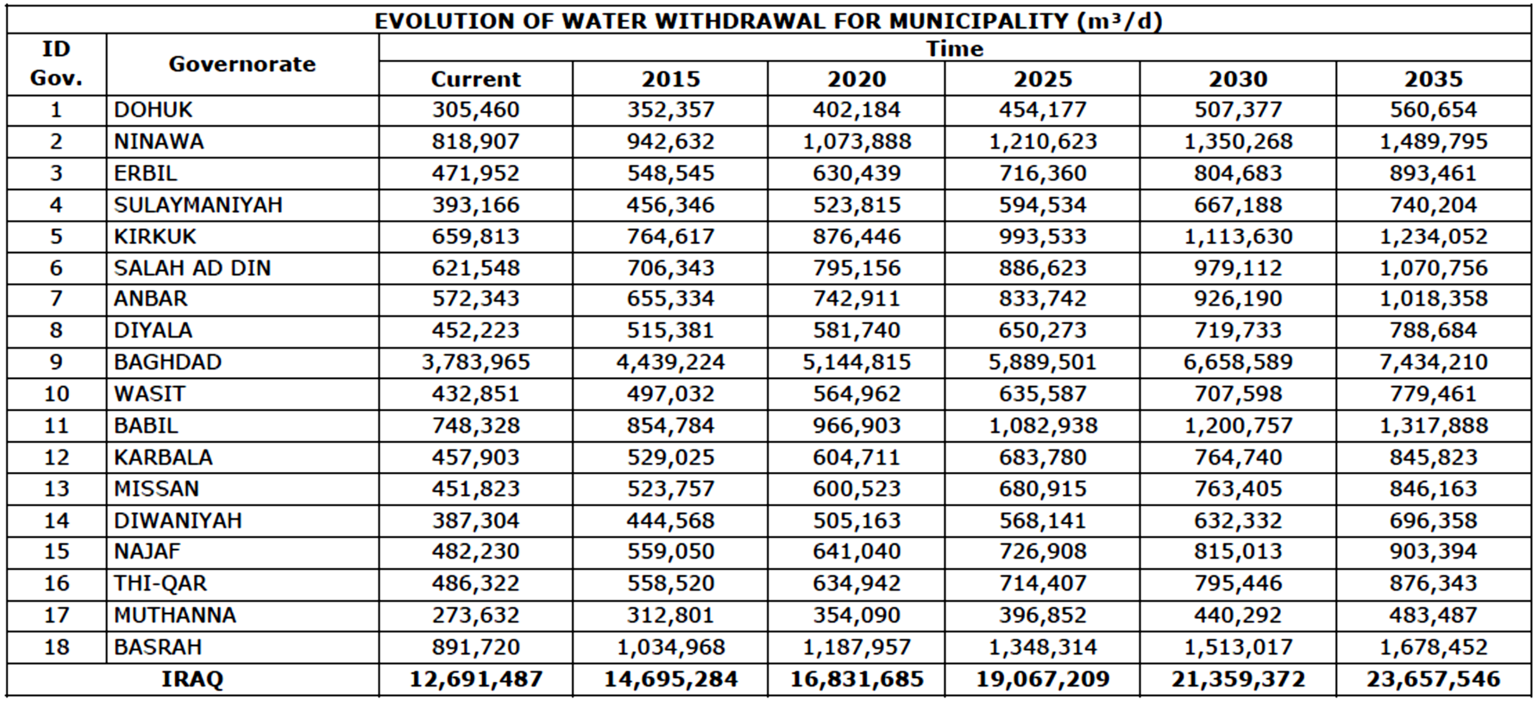
The projected values of future water withdrawal were built on the number of the estimated population times the expected per capita water demand. The potential daily and annual water withdrawals covering the period 2014-2035 for all the Iraqi provinces are listed in Tables 2-11 and 2-12 (MoWR, 2014).

1.5.2. *Agricultural Water Demand*

In Iraq, the agricultural area is estimated at 8 million hectares, which forms 70% of the total cultivated area. About 40% - 50% of this area is irrigable and is located along river plains. While, the remainder is rain fed and is located in the northeastern plains and mountain valleys (Al-Ansari 2013). Agriculture is the largest user of water which has a potential demand of about 72% of the total water demand while it only generates 3.6 % of Iraqi gross domestic product (GDP) (MoWR, 2014).

In general, the irrigated farmlands are mainly supplied by the surface water from the main rivers while only 7% of the area uses groundwater (World Bank, 2006). Due to fallow practices and the unstable political situation, annually there are about 3 to 5 million hectares of cultivated area. In 1993, the cultivated farmlands were estimated at 3.73 million

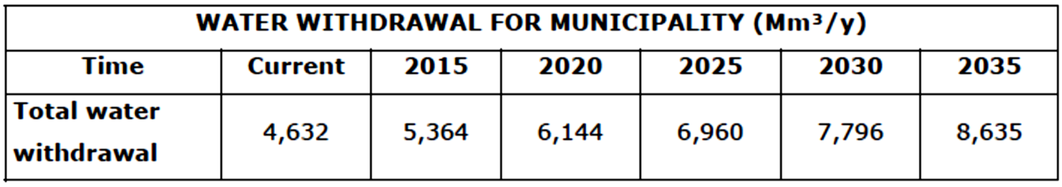
Table 2-11 Overall estimated daily water withdrawal (m^3/d) by Iraqi provinces for the years 2014-2035 (MoWR, 2014)



EVOLUTION OF WATER WITHDRAWAL FOR MUNICIPALITY (m^3/d)

ID Gov.	Governorate	Time					
		Current	2015	2020	2025	2030	2035
1	DOHUK	305,460	352,357	402,184	454,177	507,377	560,654
2	NINAWA	818,907	942,632	1,073,888	1,210,623	1,350,268	1,489,795
3	ERBIL	471,952	548,545	630,439	716,360	804,683	893,461
4	SULAYMANIYAH	393,166	456,346	523,815	594,534	667,188	740,204
5	KIRKUK	659,813	764,617	876,446	993,533	1,113,630	1,234,052
6	SALAH AD DIN	621,548	706,343	795,156	886,623	979,112	1,070,756
7	ANBAR	572,343	655,334	742,911	833,742	926,190	1,018,358
8	DIYALA	452,223	515,381	581,740	650,273	719,733	788,684
9	BAGHDAD	3,783,965	4,439,224	5,144,815	5,889,501	6,658,589	7,434,210
10	WASIT	432,851	497,032	564,962	635,587	707,598	779,461
11	BABIL	748,328	854,784	966,903	1,082,938	1,200,757	1,317,888
12	KARBALA	457,903	529,025	604,711	683,780	764,740	845,823
13	MISSAN	451,823	523,757	600,523	680,915	763,405	846,163
14	DIWANIYAH	387,304	444,568	505,163	568,141	632,332	696,358
15	NAJAF	482,230	559,050	641,040	726,908	815,013	903,394
16	THI-QAR	486,322	558,520	634,942	714,407	795,446	876,343
17	MUTHANNA	273,632	312,801	354,090	396,852	440,292	483,487
18	BASRAH	891,720	1,034,968	1,187,957	1,348,314	1,513,017	1,678,452
IRAQ		**12,691,487**	**14,695,284**	**16,831,685**	**19,067,209**	**21,359,372**	**23,657,546**

Table 2-12 Overall estimated annual water withdrawal (MCM/y) by Iraqi provinces for the years 2014-2035 (MoWR, 2014)



WATER WITHDRAWAL FOR MUNICIPALITY (Mm³/y)						
Time	**Current**	**2015**	**2020**	**2025**	**2030**	**2035**
Total water withdrawal	4,632	5,364	6,144	6,960	7,796	8,635

hectares, of which a total of 3.46 million hectares consisted of annual crops, and 0.27 million hectares farmed permanent crops (Al-Ansari and Knutson, 2011). According to the Iraqi Ministry of Water Resources (2014), the total cultivated area in 2011 was estimated at 3.73 million hectares.

Agricultural demand of water is predicted to drop to about 55 percent of the average annual by 2030 due to the potential use of modern irrigation methods (Evans and Sadler 2008). Even though, agriculture will still be the largest user. Meanwhile, the demands for municipal, industrial, and other uses are predicted to increase, leading to an increase of the total water demand in Iraq.

The variation of the Iraqi climate between the continental and sub-tropical has created a cold winter and an extremely hot and dry summer which influences the types of crops cultivated and the cultivation season. Therefore, the MoWR (2014) defined eight agro-ecological zones (Figure 2-17) taking into account the climate (Figure 2-18 and Table 2-13), cultivated crops, and the irrigation type.

The variation in Iraq’s climate and geography have created a distinguished attribute in the cultivated crops along with their productivity. In general, Iraq is suitable for almost all field crops and vegetable in addition to fruit trees to be cultivated on its land. In general, most of the farmers prefers to cultivate only one crop in regions where they rely on rain, which are located to the north of Iraq. While, farmers who rely on surface water and/or groundwater irrigation usually cultivate two type of crops over the year depending on the continuity of water flow and on the economic outcomes. Wheat and barley are the most dominant crops which are preferred to be cultivated in Iraq while in 2011-2012 they occupied about 74% of the total cultivated area in Iraq’s central and southern regions.

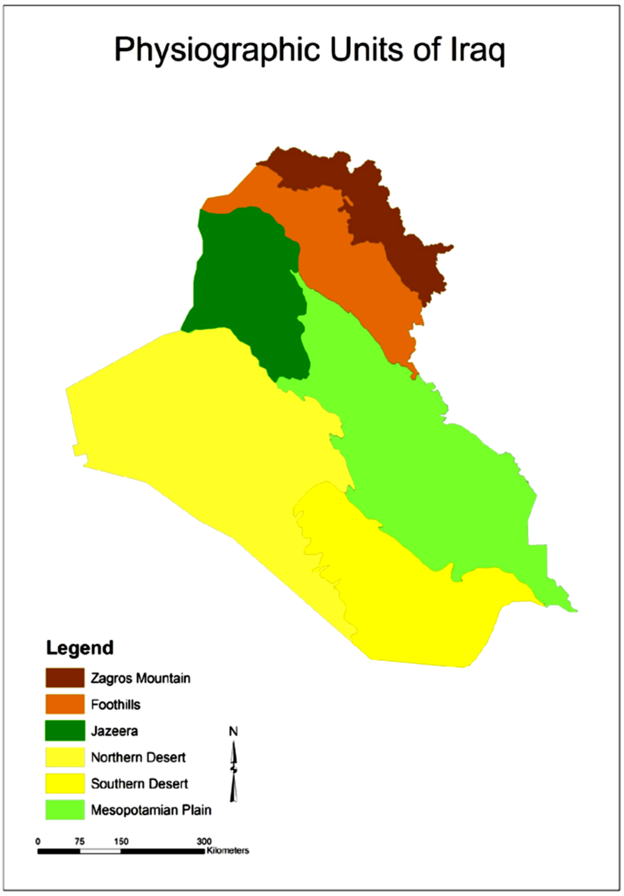


Figure 2-16 Physiographic units of Iraq (MoWR, 2014)

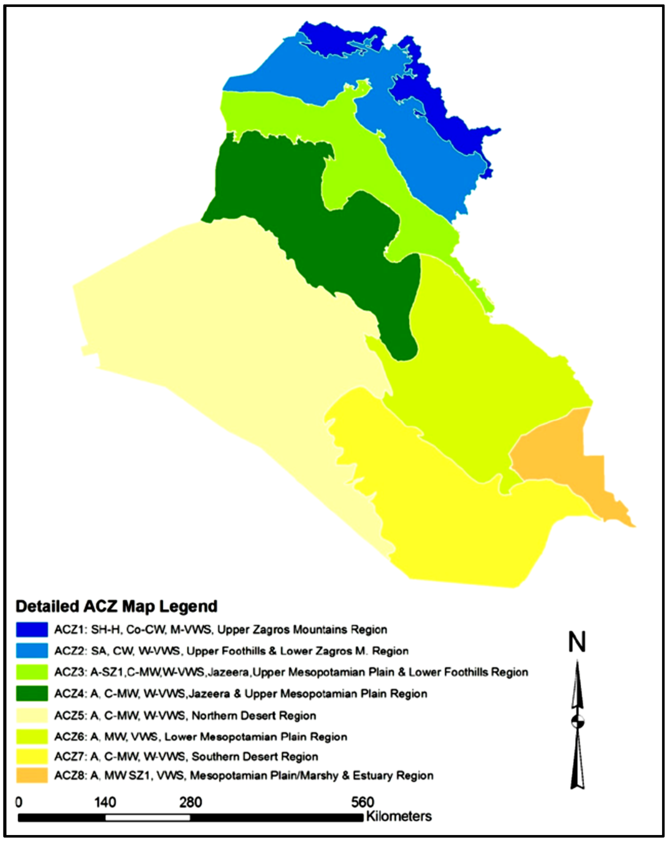


Figure 2-17 The location of agro-climate zones as it is defined by the MoWR (2014)

Table 2-13 The description of each agro-climate zone in Iraq (MoWR, 2014)

ACZ	Description	Area (%)
ACZ 1	**Sub-humid to humid, cold to cool winter, mild to very warm summer, Upper Zagros Mountains Region**	**3,5**
ACZ 2	**Semi-arid, cool winter, warm to very warm summer, Upper Foothills and Lower Zagros Mountains Region**	**9,2**
ACZ 3	**Arid, Subzone 1, cool to mild winter, warm to very warm summer, Jazeera, Upper Mesopotamian Plain and Lower Foothills Region**	**8,6**
ACZ 4	**Arid, cool to mild winter, warm to very warm summer, Jazeera & Upper Mesopotamian Plain**	**13,3**
ACZ 5	**Arid, cool to mild winter, warm to very warm summer, Northern Desert Region**	**31,1**
ACZ 6	**Arid, mild winter, very warm summer, Lower Mesopotamian Plain Region**	**15,2**
ACZ 7	**Arid, cool to mild winter, warm to very warm summer, Southern Desert Region**	**15,4**
ACZ 8	**Arid, mild winter Subzone 1, very warm summer, Marshy and Estuary of the Mesopotamian Plain Region**	**3,8**

1.5.3. *Industrial Water Demand*

In general, water quality and quantity for industrial consumption varies with the type of industry. In Iraq, the industrial water demand can be divided into oil fields, refineries, which are relevant to the Ministry of Oil, thermo-power plants, which are controlled by the Ministry of Electricity, and other industries that are mainly under the supervision of the Ministry of Industry. The industries which are controlled by the Ministry of Industry includes all types of main industries and production sites that are mainly connected to the public water and wastewater network which distinguishes them from oil fields, refineries, thermo-power plants. Due to instability in the water supply, major industries have been relying primarily on their own water supply units, especially if they are located close to surface water or groundwater resources, while secondary industries are considered as part of the municipal water demand.

The industrial water consumption data were retrieved from the study entitled “Strategy for Water and Land Resources in Iraq” which was prepared for the Iraqi Ministry of Water Resources (MoWR, 2014). The industrial water consumption was estimated in the previously mentioned study based on computing the ratio between water losses and withdrawal to find the ration of total losses by each industry, which was about 20% of the total water withdrawal.

Most of the small private industries are completely under private control and it was hard to secure data related to their water requirements. However, it was concluded that most of the private industries are small and often rely on the municipal water network. Therefore, the private industrial water demand has been considered as part of the municipal water demand.

There are two different types of thermo-power plants: gas and steam power plants. Water consumption of the two-mentioned types was estimated by summing the evaporation and losses as a consequence of the electricity production. The resulted net water consumption was estimated to be 25% higher than the norm taking into account water losses along the supply system in order to estimate the related water withdrawal (MoWR, 2014). A conversion factor of 45 m^3/h for each MW of generated electricity was used to estimate water demand. While, the evaporation and losses from generating electricity was estimated at 2.7 and 0.1 m^3/h, respectively for each MW of electricity.

In Iraq, the estimated industrial total water consumption was about 155 MCM/y, which was calculated considering the percentage of water losses of about 20% of water withdrawal including 15 MCM/y withdrawals from groundwater. Water consumption for oil fields and refineries was estimated at 709 MCM/y and 45 MCM/y, respectively. While, thermal power plants water withdrawal was estimated at 155 MCM/y (MoWR, 2014). The estimated amount of water withdrawal for other industries was around 190 MCM/y (Table 2-14).

Table 2-14 Industrial water withdrawal (MCM/y) from surface water and groundwater sources (MoWR, 2014)

Source of water	Thermal power plants	Oil fields	Refineries	Industries	Total
Surface water	119	709	45	154	1027
Groundwater	36	0	0	36	72
Total	155	709	45	190	1099

The industries which withdrawal their water directly from water sources are described previously. Other industries which depend on the public water supply were included within the domestic (municipal) water consumption. Therefore, future industrial water demands are hard to estimate due to the lack of information provided by the authorized agencies. It may not follow a simple growing function according to population growth, but it might be subject to significant discontinuity in space and in time.

According to a strategic study for water and land resources, 2014, which was the most recent study done by the Ministry of Water Resources, Baghdad's current daily water consumption for industrial uses was estimated at 10,990 m^3. Also, it was predicted to be 80,000 m^3 in 2035 considering the expected national industrial growth. Furthermore, industrial water consumptions for all Iraq's provinces were also estimated in the study for the years 2010, 2015, 2020, 2025, 2030, and 2035 (Table 2-15). The final industrial water withdrawals projected for all its sectors are presented in Table (2-16).

2.12.2. *Environmental Water Demand*

The satisfaction of clean and sustained surface water flow enhances the environment and maintains healthy livelihoods and improves the economy. Environmental surface water need is defined as the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Dyson et al. 2003, and Arthington et al. 2010). The environmental flow needs help in the enhancement of the ecosystem and provides a sustainable water source to satisfy an acceptable level of wellbeing.

Iraq has a robust and developed hydraulic system which consists of the two rivers and their tributaries, dams, lakes, wetlands, regulators, and irrigation hydraulic structures, and environmental surface water also needs to be satisfied accordingly. The construction of extensive hydraulic structures in Iraq after the 1950s led to the modification of the

Table 2-15 Projected industrial water consumption (m^3/d) for Iraq’s provinces (MoWR, 2014).

n°	Governorate	2010	2015	2020	2025	2030	2035
1	DOHUK	10,433	15,650	20,867	26,083	31,300	36,517
2	NINAWA	24,306	36,459	48,613	60,766	72,919	85,072
3	ERBIL	43,083	64,625	86,167	107,708	129,250	150,792
4	SULAYMANIYAH	45,883	68,825	91,767	114,708	137,650	160,592
5	KIRKUK	1,208	1,812	2,416	3,020	3,624	4,228
6	SALAH AD DIN	5,060	7,590	10,120	12,651	15,181	17,711
7	ANBAR	6,125	9,188	12,251	15,313	18,376	21,439
8	DIYALA	463	694	925	1,156	1,388	1,619
9	BAGHDAD	10,665	15,998	21,331	26,663	31,996	37,329
10	WASIT	4,444	6,666	8,888	11,110	13,332	15,553
11	BABIL	19,781	29,672	39,563	49,453	59,344	69,235
12	KARBALA	2,025	3,037	4,050	5,062	6,075	7,087
13	MISSAN	2,643	3,964	5,285	6,606	7,928	9,249
14	DIWANIYAH	1,713	2,569	3,425	4,282	5,138	5,994
15	NAJAF	951	1,427	1,903	2,379	2,854	3,330
16	THI-QAR	6,100	9,150	12,200	15,250	18,300	21,350
17	MUTHANNA	5,469	8,203	10,938	13,672	16,406	19,141
18	BASRAH	327,473	491,210	654,946	818,683	982,419	1,146,156
TOTAL (m^3/d)		**517,826**	**776,740**	**1,035,653**	**1,294,566**	**1,553,479**	**1,812,392**
TOTAL (Mm^3/y)		**155**	**233**	**311**	**388**	**466**	**544**

Table 2-16 Projected industrial annual water withdrawal (MCM/y) (MoWR, 2014)

TIME	**Current**	**2015**	**2020**	**2025**	**2030**	**2035**
Oil Field	190	280	365	446	524	598
Refinery	709	1,030	1,478	1,617	1,709	1,836
TPP	45	78	140	170	197	199
Other Industry	155	216	280	327	371	363
Overall Industry	1,099	1,603	2,263	2,560	2,800	2,995

ecoregion (Evans, 1994). Water structures in Iraq are mainly regulated and controlled by the Ministry of Water Resources. Water resources allocation is controlled by considering the priorities of each sector of water demand including irrigation, municipal, energy production, industrial, environmental, and recreational water uses. Due to climate change, population increase, decline of transboundary water supplies, pollution and other factors, the natural flow of the Tigris and the Euphrates rivers and their tributaries has been negatively affected (Evans, 1994, and Stattersfield et al. 2005). Therefore, the ecosystems inside Iraq have been significantly deteriorated, especially the southern provinces.

The Iraqi Ministry of Water Resources (2014) has listed the parameters to be considered in the allocation of Iraq’s water resources, which are:

- Minimum operational surface water flow requirements for the Tigris and the Euphrates Rivers.
- Minimum environmental surface water flow requirements for the Tigris and the Euphrates Rivers.
- Minimum allowed water flow for the Shat al Arab

The minimum surface water flow requirements are necessary to maintain aquatic life and to provide sustainable environmental protection for the water system.

According to MoWR (2014), no legal framework has been considered in Iraq for the evaluation of environmental water needs to optimize the minimum environmental surface flows for inland or coastal water bodies. Therefore, the UN Convention on Biological Diversity and the Ramsar Convention on Wetlands of International Importance have established a policy and legislative framework in this regard based on a commonly adopted international standard. To satisfy the equity in water sharing among consumers while adopting sustainable in water resources to provide environmental water flows was a major concern of the World Bank which consider this as an essential part of any integrated water resources management (IWRM) system (Hirji and Davis 2009).

The significant interest of international donors in Iraq's heritages, which are descending from Mesopotamia, have led to several achievements taking into consideration of the marshlands, such as; the declaration of Mesopotamia Marshlands as UNESCO World Heritage site (July 2017), establishing a National Park in the Central Marshes and Abu Zirig marshes (July 2013), the New Eden Master Plan for integrated water resources management (October 2015), and declaring Hawizeh Marshes as a Ramsar site (2008).

The MoWR (2014) has suggested the minimum environmental flow to be maintained in the Tigris and Euphrates rivers considering the present water conditions (Tables 2-17 and 2-18). It was suggested that the 75% exceedance flow duration provides the highest minimum flow to satisfy water demands and the environmental needs. Therefore, to provide a safe and sustained water flow, the higher minimum flow values are recommended, while lower values are references for short term minimum environmental flows.

Table 2-17 Minimum environmental flow requirements along the Tigris River (MoWR, 2014)

Key points and main diversions	**Flow duration -. 75 % exceedance (m^3/s)**	**Flow duration - 90% exceedance (m^3/s)**	**Flow duration - 95% exceedance (m^3/s)**	**Flow duration - 99% exceedance (m^3/s)**	**7Q10 (m^3/s)**	**Tennant “Good” conditions**		**Range of minimum flow (m^3/s)**
						November-May **20%**	June-October **40%**	
Mosul city	300	200	180	130	124	112	210	124-300
Sherqat	524	379	288	144	154	200	285	144-524
Baiji	587	487	393	345	242	260	347	242-587
D/S Samarra barrage	460	381	350	328	286	123	260	286-460
Baghdad	470	400	375	345	154	144	290	154-470
D/S Kut Barrage	175	145	135	110	100	84	137	100-175
Amara	50	38	32	23	24	23	35	23-50
Qalat Salih	28	11	10	9	24	8	14	9-28

Table 2-18 Minimum environmental flow requirements along the Euphrates River (MoWR, 2014)

Key points and main diversions	**Flow duration -. 75 % exceedance (m^3/s)**	**Flow duration - 90% exceedance (m^3/s)**	**Flow duration - 95% exceedance (m^3/s)**	**Flow duration - 99% exceedance (m^3/s)**	**7Q10 (m^3/s)**	**Tennant “Good” conditions**		**Range of minimum flow (m^3/s)**
						November-May **20%**	June-October **40%**	
D/S Haditha dam	301	231	200	125	151	95	207	125-301
Hit	561	267	227	128	133	95	207	128-561
D/S Hindiya barrage	140	90	70	40	43	40	133	40-140
Samawa barrage					28	9	30	9-30

2.12.3. *Factors Affecting Water Use*

Many factors either work separately or together can influence water usage. Mostly, the human factor plays a significant role in water availability and whether it is safe for human consumption. A high percentage of people have are not aware about the importance of water and how it is difficult and complicated to get suitable drinking water. Regardless of the severe water shortages and expected droughts, there are many bad habits which are widely practiced in many Iraqi communities that have negatively impacted drinking water quantity and quality, such as:

a) The uncontrolled water consumption of domestic daily activities, such as; cleaning the house, cooking, dish washing, car washing, etc. All these activities have no any kind of water saving devices. For instance, people usually wash their cars at home where they use the tap water without using any automatic shutoff nozzle to control water flow, that results in wasting large amounts of water.

b) Garden irrigation mostly rely on flood irrigation, which consumes much more water in comparison to the use of drip irrigation or sprinklers.

c) The uncontrolled and unplanned expansion in each individual housing unit has experienced a dramatic increase which consequently increase the pressure on the built infrastructure, especially on drinking water demand, generated wastewater, and electrical power demand. Most of the old and modern constructed cities based the design of their infrastructure on a certain human capacity, but later on, these capacities have exploded due to the lack of control on the expanded units and due to the absence of new built cities and residential complexes. For instance, in 1980-

1990s', a housing unit of an area of 800m^2 used to include one family with an average of 5 people while there was no shortage in water supplies and no low water pressure in the supply network. Recently, it is common to find the same 800 m^2 housing unit divided into more than 4 housing units (sometimes more than ten) with the same average number of residents. This unexpected and unplanned expansion has led to overloading the entire potable water supply system as well as the sewerage system.

d) Using flooding for agricultural irrigation wastes great amounts of water while using technology in irrigation does not find public acceptance due to its complexity, cost, and the lack of electrical power supply.

e) Farmlands which are located upstream of the water supply canals usually get their water first with no responsibility about the farms that come next even if they get a full share of water or some or nothing. Their priority is to irrigate their farms, satisfy the daily water requirements of their farms and animals ignoring any downstream consequences. This is mainly because there is no controlling devices on their water intakes that assures the equity or proportionality in water allocation among farmers. Such misuse of water resources reflects negatively on the available of water shares to the downstream farms.

Other factors play a negative role in wasting water such as the lack of technology in water allocation. For instance, automated drip irrigation and sprinklers generally saves more than 50 percent of the consumed water in comparison to the use of conventional irrigation methods. In addition, the use of water conserving faucets helps to reduce daily domestic water consumption. Unlined canals might be another factor which influence water conservation due to the high rate of water seepage where most of the irrigation canals are either unlined or the liner was installed imperfectly.

2.12.4. *Reclaimed Water Use in Iraq*

Recently, in Iraq there is a growing awareness of the impact of improper dealing with wastewater that has resulted in the contamination of rivers, streams, groundwater, and the environment (SECB, 2014). The increases in urban development along with the high population growth increases interest in the use of reclaimed wastewater which is an alternative reliable source of water with limited uses depending on its quality. Therefore, it is important to include this water source in the future planning and implementation of water resources projects especially due to its huge size.

Reclaimed water effluent is receiving an increasing interest as an alternative and reliable source of water in many developing countries, while it is already used in many developed countries such as in the United States and Singapore. Research indicates that the majority of the Middle East countries have a relatively new experience in the field of treated wastewater reuse (Bahri, 2003). However, Iraq has nothing to do in the field of reclaimed water use at the time it has been detected that in Baghdad there is a daily flow of more than 1.0×10^6 m^3 of secondary treated wastewater that is disposed to the Tigris River. After getting secondary or tertiary treatment, it is possible to use the treated wastewater to irrigate thousands of hectares cultivating different types of crops as done in the United States especially in California and Florida.

Wastewater reuse in agricultural irrigation is one of the most well-known and common applications in several Mediterranean countries, and there is considerable interest in the long- term effects of treated wastewater on cultivated crops for human consumption and other related uses (Angelakis et al. 1999). Furthermore, other uses such as in environmental restoration, cleaning, toilet flushing, car washing, power plant cooling systems, air conditioning, and industrial uses. All these uses are practiced today in most arid and semi-arid regions all over the world especially in the Mediterranean countries, which are facing significant challenges due to the increase in water shortages.

2.12.5. *Baghdad as a Case Study*

The municipal wastewater discharges of Baghdad are treated by two main wastewater treatment plant complexes. Wastewater discharges from the east side of the city are treated in the Rustmia (old) wastewater treatment plant complex which contains the original wastewater treatment plant and three extensions which later dispose the treated wastewater to the Diyala River that later confluences with the Tigris River. While, municipal wastewater discharges from the west side of the city are secondary treated in the Karkh wastewater treatment plant and disposed directly to the Tigris River. Effluent discharges from the the Rustamia WWTP into Diyala River were not in complete agreement with the Iraqi standard number 25 on effluent discharges into receiving water for the year 1967.

2.12.6. *Evaluation of WWTPs in Baghdad*

Because Iraq has experienced wars, conflicts, and political instability since 1980, it has been noted that the operation, maintenances, rehabilitation, and construction of Baghdad’s sewerage systems have not been properly undertaken. Moreover, most of the built projects were looted during the 2003 war causing significant wastewater overflow and contamination of the rivers and the environment (SECB, 2014).

2.12.7. *The Karkh WWTP*

Municipal wastewater discharges from the west side of Baghdad are treated in the Karkh wastewater treatment plant which later is disposed to the Tigris River. For the period 2003-2014, a daily of about 5×10^5 m^3 of untreated wastewater from the Karkh side were by-passed directly to the Tigris River without treatment because the WWTP was totally out of order due to looting and vandalism. New twin wastewater treatment units with a total daily treatment capacity of 2.0×10^5 m^3/day WWTP were completed at the end of 2014. The old Karkh WWTP is under rehabilitation which started in 2004 by the USAID, but the program has not been completed due to security reasons. The Mayoralty of Baghdad has taken the advantages of a Japanese Government donation to construct a 3.5×10^5 m^3/day WWTP in the same Karkh site which has not been started yet (Baghdad Mayoralty (BM), 2013). Therefore, the total daily treatment capacity of the Karkh site is expected to reach 7.5×10^5 m^3 serving the west side (Al-Karkh) of Baghdad.

2.12.8. *The Rustumia WWTP*

The Rustamia wastewater treatment complex is located in the eastern part of Baghdad, on the Diyala River which treats the wastewater discharges from the east side of Baghdad. The Rustumia wastewater treatment site consists of the original wastewater treatment plant and three extensions along with the addition of five compact units. The treated wastewater at the WWTP complex is discharged to the Diyala River before its confluences with the Tigris River south of Baghdad. The Rustumia 3rd extension of the

WWTP shows acceptable treatment as compared to the old Rustumia WWTP where about 50% of the inflowing raw sewage is disposed to the Diyala River without treatment (SECB, 2014). In addition, there are five individual WWTP units with a daily treatment capacity of 1.5×10^4 m^3 each were installed in the old Rustamia WWTP complex. The total daily treatment capacity for this site is 4.0×10^5 m^3 (treated) + 1.75×10^5 m^3 (directly by-passed to the river). The conventional activated sludge method is used as the wastewater treatment process for the old existing facilities. Thickening, digestion and drying beds are the technique used for sludge treatment processes.

2.12.9. *Evaluation of the Treated Wastewater*

In Baghdad, approximately 60% of its population are connected to sewerage system. It is a common practice to discharge untreated wastewater directly to water bodies which causes negative health impacts and economic risks (BM, 2013). In addition, there is a high level of physical losses in the water supply networks due to the poor habits of many of water users. In some regions, water is often supplied for few hours per day or even per week. Meanwhile, tariffs are relatively low, so the operation and maintenance costs of the utilities are often not recovered. Therefore, wastewater treatment processes are not well implemented which results to environmental and health issues (BM, 2011).

Related to wastewater treatment facilities, there is very little investment that has been done in the past three decades, while water supply and treatment often received more priority than wastewater collection and treatment (UNICEF/Iraq 2014). Currently there is a significant growing awareness of the impact of wastewater contamination on water bodies and the environment which supports the opportunity for wastewater treatment of receiving greater interest. It is projected that in 2020 the amount of the daily generated wastewater in Baghdad will reach 4.25×10^6 m^3 considering the expected population and the expansion of the constructed sewerage networks (BM, 2013). The predicted increase of treated wastewater provides an opportunity to use it as an alternative source of water for different uses.

2.13. Wastewater Generated in Baghdad

The Baghdad Mayoralty (BM) estimates that 60% of the consumed water results in wastewater that is collected by the municipal sewer system. In Baghdad, the estimated wastewater generated taking into account the type of water use is listed in Table 2-19 (BM, 2013).

Table 2-19 Daily per capita wastewater generation, Liter/capita/day (Lpcd) (BM, 2013)

Category of Users	Baghdad	Municipality	Municipalities	Rural
Domestic users	200	180	150	110
Industrial/ Commercial	25	20	15	0
Institutional	35	30	20	10
Infiltration	40	40	35	30
Total	300	270	220	150

Wastewater production increases as the population and per capita water consumption increase. The future wastewater productions in the BM area are usually estimated every five years based on the estimated water consumption rates and population. Therefore, the reuse of treated municipal wastewater can be applied for different uses that reduces the amount of consumed fresh water extraction from natural resources as well as reduces the discharges of contamination to the environment. Herein, the priority should be given to agricultural irrigation uses using modern irrigation techniques due to the availability of agricultural lands and the locations of the Baghdad's two WWTPs which are close to agricultural farmland and orchards.

The estimated wastewater production rates for the period 2004-2017 and the required treatment capacities for the WWTPs to scope all the inflowing wastewaters are listed in Table 2-20. After the Baghdad Mayoralty, as soon as the presently on-going or planned improvement programs for the Rustumia and Karkh WWTPs are completed, it is expected that the daily wastewater treatment capacity could reach the level of 9×10^5 m^3.

Table 2-20 Estimated wastewater flow rates 2004-2017 (Baghdad Mayoralty, 2013)

Items	2004	2007	2012	2017
Served population (1,000 people)	4,769	5,400	6,050	6,700
Av. per capita wastewater flow (Lpcd)	216	222	228	240
Av. wastewater flow (1,000 m^3/d)	1,040	1,200	1,380	1,610
Total WWTP capacity (1,000 m^3/d)	565	565	770	770
Deficit of WWTP capacity (1,000 m^3/d)	475	635	610	840

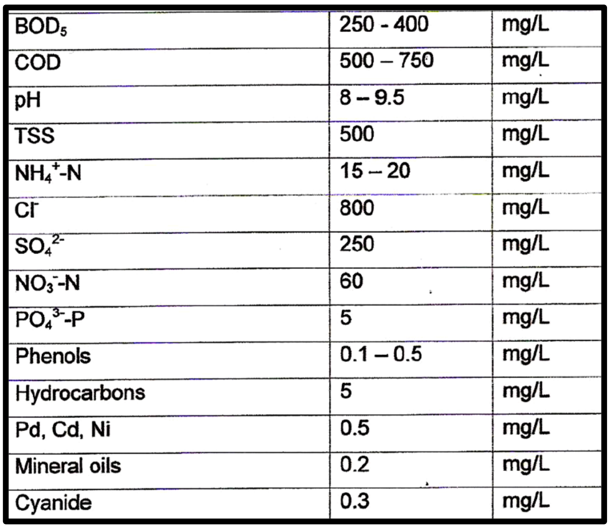
In Baghdad, as it is expected in 2017, there is a daily flow of 1.6×10^6 m^3 of wastewater and 8.5×10^5 m^3 of this amount is expected to be disposed directly to the river without receiving the simplest type of treatment if the WWTPs capacities remain under current conditions.

2.13.1. *Quality of the Treated Wastewater at the Karkh WWTP*

The environmental situation has become far more serious in the Karkh district where it is estimated that a daily flow of 7×10^5 m^3 of wastewater is generated in the

Karkh district, of which 2×10^5 m^3 of wastewater is treated through the twin WWTP while about 2.05×10^5 m^3 was supposed to be treated by the existing Karkh WWTP, which has been out of service since 2005. The situation before 2014 was so miserable that a daily flow of 7×10^5 m^3 of untreated wastewater was directly discharged to the Tigris River. Therefore, negative impacts and diseases were caused due to the severe pollution. The presence of the recently built WWTPs mitigate the negative impacts of the untreated wastewater on the Tigris River by treating about 2×10^5 m^3/day which is the full capacity of the plants. If the proposed new daily treatment capacity of 3.15×10^5 m^3 will be constructed, then the total capacity of the Karkh WWTP complex will reach 7.5×10^5 m^3. After the Mayoralty of Baghdad, the supposed influent concentrations which enter the WWTP are listed in Table 2-21.

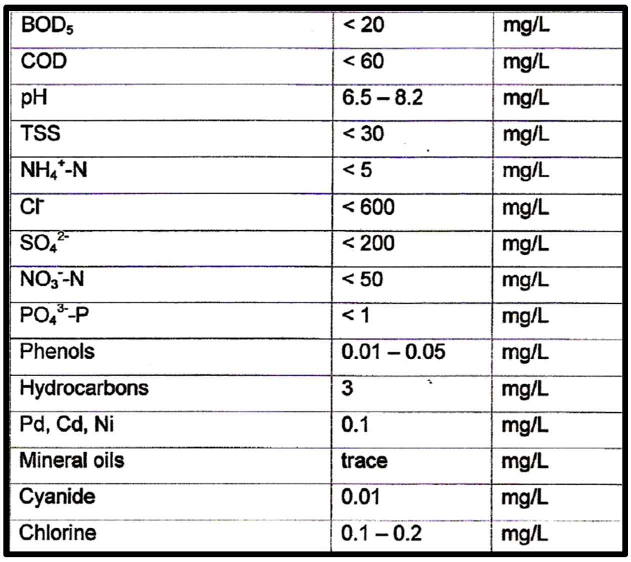
Table 2-21 The Karkh WWTP influent parameters concentrations



BOD_5	250 - 400	mg/L
COD	500 – 750	mg/L
pH	8 – 9.5	mg/L
TSS	500	mg/L
NH_4^+-N	15 – 20	mg/L
Cl^-	800	mg/L
SO_4^{2-}	250	mg/L
NO_3^--N	60	mg/L
PO_4^{3-}-P	5	mg/L
Phenols	0.1 – 0.5	mg/L
Hydrocarbons	5	mg/L
Pd, Cd, Ni	0.5	mg/L
Mineral oils	0.2	mg/L
Cyanide	0.3	mg/L

The treated wastewater along with the potential treatment capacity of the Karkh WWTP are part of this study as reclaimed water which is proposed to be used in different types of uses in different application specifically for irrigation. Considering the secondary and/or the tertiary wastewater treatment, the reclaimed water becomes appropriate to be used in irrigation. In addition to the economic benefits of agricultural reclaimed water uses, it probably could help in reducing the effect of dust storms. The proposed effluent concentration parameters after a complete treatment through the Karkh new WWTPs are listed in Table 2-22 (Baghdad Mayoralty, 2013).

Table 2-22 The Karkh new WWTP effluent quality after a complete treatment



BOD_5	< 20	mg/L
COD	< 60	mg/L
pH	6.5 – 8.2	mg/L
TSS	< 30	mg/L
NH_4^+-N	< 5	mg/L
Cl^-	< 600	mg/L
SO_4^{2-}	< 200	mg/L
NO_3^--N	< 50	mg/L
PO_4^{3-}-P	< 1	mg/L
Phenols	0.01 – 0.05	mg/L
Hydrocarbons	3	mg/L
Pd, Cd, Ni	0.1	mg/L
Mineral oils	trace	mg/L
Cyanide	0.01	mg/L
Chlorine	0.1 – 0.2	mg/L

2.13.2. *Quality of the Treated Wastewater at the Rustumia WWTPs*

The final effluent which is discharged from the Rustamia WWTP consists of two effluent discharge lines; F1 and F2 that dispose the effluent into the Diyala River. The current average BOD_5 of the effluent stream lines F1 which is about 12 mg/L while that of F2 is about 14 mg/l (Table 2-23) (AbdulRazzak, A. M., 2013). Those listed results are for the treated wastewater but do not include the by-passed untreated wastewater which is discharged directly to the Diyala River at daily rate of about 2 ×10^5 m^3 (AbdulRazzak, A. M., 2013).

The suspended solids (SS) concentrations of the effluents disposed from lines F1 and F2 are listed in Table 2-24. It is obvious that the average values of SS of the effluent of both stream lines are meeting the standard limits as set by Iraqi Regulation 25 in 1967.

Table 2-23 Statistical analysis of wastewater parameters (AbdulRazzak, A. M., 2013)

Mg/l	No. of Obs. (N)	Min	Max	Mean	Std. Dev.	Variance
BOD	117	73.0	850.0	192	139.8	19554
Flow (F1)	104	0.56	1.9	1.012	0.22	0.054
Flow (F2)	104	0.45	1.5	0.926	0.22	0.048
BOD (F1)	116	1.0	43.0	12.16	7.99	63.8
BOD (F2)	113	2.0	57.0	14.12	9.56	91.1
(F1 + F2)	104	1.22	3.40	1.95	0.40	0.16
COD (Inlet)	136	133.0	2038	513.52	20.35	237.2
COD (F1)	140	3.0	111	29.7	1.53	18.1
COD (F2)	137	3.0	89.0	27.28	1.50	17.6

Table 2-24 Suspended solids (mg/L) in stream lines F1 and F2 (Baghdad Mayoralty, 2013)

	Valid N	Mean	Minimum	Maximum	Standard Deviation	Standard
SS-1	21	49.71	5.0	98.0	19.6	4.20
SS-2	20	39.1	9.0	79.0	19.8	4.43

The average monthly water flows of the Diyala River have experienced high fluctuations in its monthly and yearly averages (Table 2-25). A minimum water flow as low as 5 m^3/s results in a critical dilution where a mixing ratio of discharge to river flow of (1.95:5) or (1:2.56) is achieved (Mohammed, 1999), which is a very low dilution ratio. Meanwhile, the lowest dilution ratio specified by Haist and Partners in 1981 was set at a value of 1:8 which was computed taking into consideration the entire flow from the Rustamia WWTP. Therefore, employing the secondary and/ or tertiary wastewater treatment techniques will mitigate this potential source of pollution. Furthermore, including the tertiary wastewater treatment is necessary for both the environmental and economic consideration to ensure the protection of public health and to restore reclaimed water to be used later for more applications.

Table 2-25 Monthly and annual average flow for the Diyala River (m^3/s) (SECB, 2014)

Watery year	October	November	December	January	February	March	April	May	June	July	August	September	Annual average flow (m^3/s)
1990-1991	16	15	24	71	123	167	393	462	134	71	30	29	128
1991-1992	19	20	24	22	20	103	76	17	16	16	16	16	30
1992-1993	34	39	40	94	148	45	23	29	28	23	6	6	42
1993-1994	10	26	27	161	152	111	182	81	33	33	40	40	74
1994-1995	48	127	246	285	159	82	57	124	28	31	38	53	107
1995-1996	46	43	42	22	10	30	24	22	34	20	23	12	27
1996-1997	12	18	6	6	5	10	15	24	17	5	5.5	9	12

2.14. Regulations and Permits for Reclaimed Water Use in Iraq

The Iraqi Government has issued act No.3 of 2012 on the National Determinants for the use of treated wastewater in agricultural irrigation, which consists of 7 articles and 2 annexes. Every effort should be made to construct and maintain sewage treatment works to comply with these standards. Both the secondary and the tertiary treated wastewater specification were listed in the previously mentioned act to be considered for agricultural irrigation reclaimed water use, as in Table 2-26. Furthermore, the standards of the treated wastewater to be disposed into water bodies are listed in Iraqi Law No. 25 of 1967, which was upgraded with Regulation No. 2 of 2001, (Table 2-27). The standards have been set to safeguard the requirements of downstream users for drinking, irrigation, fishing and amenities. The limits that concern the operation of a sewage treatment works are the suspended solids, biological oxygen demand and nitrate standards. Furthermore, the regulations have the maximum permissible water quality standards, which are the maximum allowed that must not be exceeded for receiving bodies.

Table 2-26 Iraqi Government Act No.3 of 2012 on the National Determinants for the use of treated wastewater in agricultural irrigation

Component	Secondary treated wastewater Upper limit (mg/L)	Secondary treated wastewater Upper limit (mg/L)
Total Suspended Solid (TSS)	40 mg/L	10 mg/L
Total Dissolved Solids (TDS)	2500 mg/L	2500 mg/L
pH	4-6, 8	4-6, 8
BOD5	40 mg/L	10 mg/L
COD	100 mg/L	40 mg/L
Oil and Grease	-	-
PHENOL	0.002 mg/L	0.002 mg/L
Nitrate (NO3-N)	50 mg/L	50 mg/L
Ammonium (NH4)	5 mg/L	5 mg/L
Aluminum (Al)	5 mg/L	5 mg/L
Arsenic (AS)	0.1 mg/L	0.1 mg/L
Barium (BE)	0.1 mg/L	0.1 mg/L
Boron (B)	0.75 mg/L	0.75 mg/L
Cadmium (Cd)	0.01 mg/L	0.01 mg/L
Chlorine (Cl2)	0.5 mg/L	0.5 mg/L
Chromium (Cr)	0.1 mg/L	0.1 mg/L
Cobalt (Co)	0.05 mg/L	0.05 mg/L
Copper (Cu)	0.2 mg/L	0.2 mg/L
Fluoride (F)	1 mg/L	1 mg/L
Iron (Fe)	5 mg/L	5 mg/L
Lead (Pb)	0.1 mg/L	0.1 mg/L

Component	Secondary treated wastewater Upper limit (mg/L)	Secondary treated wastewater Upper limit (mg/L)
Lithium (Li)	2.5 mg/L	2.5 mg/L
Manganese (Mn)	0.2 mg/L	0.2 mg/L
Mercury (Hg)	0.001 mg/L	0.001 mg/L
Molybdenum (Mo)	0.01 mg/L	0.01 mg/L
Nickel (Ni)	0.2 mg/L	0.2 mg/L
Selenium (Se)	0.02 mg/L	0.02 mg/L
Vanadium (V)	0.1 mg/L	0.1 mg/L
Zinc (Zn)	2 mg/L	2 mg/L
Phosphate (PO4)	25 mg/L	12 mg/L
Sodium (Na)	250 mg/L	230 mg/L
Calcium (Ca)	450 mg/L	400 mg/L
Magnesium (Mg)	80 mg/L	60 mg/L
Potassium (K)	100 mg/L	20 mg/L
SAR	6.0-9.0	< 6.0
Fecal coliform	1000 cells/100ml	2.2 cells/100ml

Table 2-27 Iraqi Sewage Regulation No. 25, treated wastewater pollutant concentration which can be discharged to rivers (MB, 2005)

Item	Component	Upper limit (mg/L)
1	Color	-
2	Temperature	Lower than 35℃
3	Suspended Solid	60 mg/L
4	pH	6 to 9.5
5	Dissolved Oxygen	-
6	BOD5	Lower than 40 mg/L
7	COD	Lower than 100mg/L
8	Cyanide (CN)	0.05mg/L
9	Fluoride(F)	5mg/L
10	Free Chlorine	Trace
11	Chlorine (Cl)	When the ration of the amount of the discharged water to the amount of water of the source is 1:1000 or less, it is allowable to increase the concentration in the source by 1% before discharging. When the ration of the amount of the discharged water to the amount of water of the source is more than 1:1000, the chloride concentration in the discharged water should not exceed 600 mg/L
12	Phenol	0.01 to 0.05 mg/L
13	Sulphate (SO_4)	As “chloride” a. As “chloride” b, but limit is 400mg/L
14	Nitrate	50 mg/L
15	Phosphate	3 mg/L
16	Ammonium	-
17	DDT	Nil
18	Lead	0.1mg/L
19	Arsenic	0.05 mg/L
20	Copper	0.2 mg/L
21	Nickel	0.2 mg/L
22	Selenium	0.05 mg/L

Item	Component	Upper limit (mg/L)
23	Mercury	0.005 mg/L
24	Cadmium	0.01 mg/L
25	Zinc	2.0 mg/L
26	Chromium	0.1 mg/L
27	Aluminum	5.0 mg/L
28	Barium	4.0 mg/L
29	Boron	1.0 mg/L
30	Cobalt	0.2 mg/L
31	Iron	0.2 mg/L
32	Magnesium	0.2 mg/L
33	Silver	0.2 mg/L
34	Total Hydrocarbons and its Compounds	Only allowable to rivers and streams in a state of continuous flow. The following limits shall not be exceeded: 10 mg/L when the ratio of the amount of the discharged water to the amount of water of the source is 1:1000 or less. 5 mg/L when the ratio of the amount of the discharged water to the amount of water of the source is 1:500 or less. 3 mg/L when the ratio of the amount of the discharged water to the amount of water of the source is 1:300 or less.
35	Sulphide S	-
36	Ammonia (N as NH_3)	-
37	Ammonia gas (N as free NH_3)	-
38	Sulphur dioxide (SO_2)	-
39	Petroleum Alcohol	-
40	Calcium Carbide (CaC)	-
41	Organic Solvents	-
42	Benzene	-
43	Chlorobenzene	-
44	T.N.T	-
45	Bromine	-

CHAPTER 3 LITERATURE SUMMARY

3.1. Optimization Models for River Basin Planning and Management

3.1.1. *Introduction*

Due to the lack of water resources and the expected shortage of water supplies in many regions, water might be used as leverage in many conflicts in the world. The development of river basin modeling has been one of the recent necessities to control water flow and to conserve the available resources. Researchers all over the world have found and developed suitable and applicable ways to manage water resources by modeling river basins to avoid floods and to satisfy increasing water demands. Water resource optimization models can be one of the techniques used to control water shortages and to minimize the related crises. Water resource optimization models have been applied in arid and semiarid regions all over the world using different approaches such as; dynamic programming (Rao et al. 1988; Paudyal and Manguerra, 1990; Naadimuthu, et al. 1999; Ghahraman and Sepaskhah, 2004), genetic algorithms (Wardlaw and Bhaktikul, 2001; Raju & Kumar, 2004; Haq et al. 2008; Haq & Anwar, 2010), and game theory approaches (Wang et al. 2003; Sadegh et al. 2010). Accordingly, Dinar, et al. (2007) reviewed the literature on optimization models combined with techniques from cooperative game theory, while Brouwer, (Brouwer and Hofkes, 2008) reviewed hydro-economic modeling. Singh (2014) reviewed irrigation management optimization models for agricultural irrigation water allocation under different programming assumptions.

Burton (1994) mentioned that the development of some optimization models was to explore the multi-objective analysis of water allocation. Some software packages were used in times of water shortage by analyzing the outcome from a variety of water allocation policies. Water allocation optimization models were developed for regions which have experienced water resource recent and potential water shortages, such as in Arizona and other arid regions (Maddaus and McGill, 1976; Oxley et al. 2016), Southern California (Lejano and Davos, 1995), Africa (Gakpo et al. 2001), and Asia (Fischhendler, 2008).

3.1.2. *Water Resources Allocation Optimization Models*

Rivers form the main source of renewable water resources which have experienced significant disruption in their water supplies due to many factors. The development of integrated water resources management became mandatory for many of those rivers to overcome the projected disruptions in supply. Water resources management modeling of rivers has been practiced on all over the world. The Nile River in Egypt has its share of these models that calculate the generated benefits from water use for cooperative and non-cooperative strategies using a water allocation optimization modelling developed by Wu and Whittington (2006). The computed results proved that countries sharing water resources will benefit in a scheme in which all members cooperate in a grand coalition. Gohar and Ward (2010) introduced an optimization model to maximize the total agricultural irrigation net benefit along the Nile River in Egypt subject to hydrologic, environmental, and institutional constraints. The economic performance could be elevated by the expanded intra-regional water trading among Egyptians and other users of the Nile River. Dinar and Wolf (1994) presented the potential of water trading among Middle East regions, including Egypt, the Gaza Strip, the West Bank, and Israel. A linear programming optimization model which trades both water (from Egypt to the other parties) and technology (from Israel to the other parties) to reduce water use in agriculture and system losses. Using a multiple-objective approach, McKinney, et al. (1997) developed a water allocation optimization model for the Amudarya and the Kashkadarya Rivers. They concluded that putting more weight on salt management using less water in the upstream increases the flow to the Aral Sea. This model was recommended by the authors to be used as a tool for the decision makers in order to perform a trade-off analysis. An inter-regional price equilibrium model using linear demand and cost functions with quadratic programming was developed by Flinn and Guise (1970). The model was applied to a hypothetical river system incorporating seasonal variations in demand by subjecting the model to the maximum reservoir supply and conveyance capacity constraints. Vaux Jr and Howitt (1984) developed a similar model which was applied to California by using nonlinear demand and price-sensitive linear supply functions. Due to the market-based water transfers, the model resulted in a reduction in the need for water supply increase and a noticeable of the generated benefit.

Five decades ago, water system optimization and game theory modelling concepts were pioneered by Rogers (1969) using linear programming to maximize the benefits from hydropower production and irrigation. An optimal multipurpose development model for the Ganges-Brahmaputra basin, which straddles India and Bangladesh, was adopted by considering the interactions between hydropower, irrigation, flood control, and salinity control. Rogers (1993) developed another Ganges-Brahmaputra basin water allocation model by incorporating Nepal into the analysis. The optimization model considered the applicability of game theory and its interaction with water allocation by taking into account individual country and two-country coalitions. The model concluded that the core of non-dominated benefits imputations is small, but not empty. Coalitions over extended time periods was proposed by Dufournaud and Harrington (1990) by expanding the traditional core constraints including the spatial and temporal patterns of costs and benefits from river development. Wang, et al. (2015) proposed a multi-objective water resources allocation optimization model in a typical river basin applied in the water deficient of Heihe River Basin. Their results demonstrate that the optimal program can predicate the actual situation of water allocation in the future.

An intrastate and interstate water transformation model within the Colorado River basin was developed by (Booker and Young, 1994). The model accounts both water quantity and quality (salinity) using an explicit representation of the river as a twenty-node network with tributary inflows, diversion points, reservoirs, and hydropower plants. Siehlow, et al. (2012) developed an optimization model examining different cooperation scenarios using a consecutive interest maximization approach. The model optimizes an inter-temporal optimal water allocation in the Orange-Senqu River basin in South Africa using different techniques of cooperative game theory. The Colorado River Institutional Model (CRIM) is a nonlinear water allocation optimization model which maximizes the total net benefits as developed by McKinney et al. (1999). The model is subjected to linear water balance and nonlinear salinity balance constraints considering the river as a closed system which has a constant water supply, while water withdrawals, exports, and salt discharges were considered as indicators for flows and salinity concentrations.

You, et al. (2011) developed a water allocation optimization model based on evapotranspiration (ET) considering water scarce conditions in the Haihe River Basin to achieve the requirement of water inflow into the Bohai Sea. The developed model simulates the scenario of water cycle and water allocation adopting multi-objective decision criteria. Lu, et al. (2011) presented an inexact rough-interval fuzzy linear programming (IRFLP) model to test the differences between the IRFLP model and an interval-valued linear programming model for water allocation. It was concluded that the IRFLP was capable of handling the interaction between dual intervals of highly uncertain parameters, as well as their joint impact on the system. A nonlinear water allocation optimization model maximizing the net benefit from allocating water on domestic, irrigation, industrial, and hydropower demand nodes was developed and applied to Southern Alberta, Canada (Mahan et al. 2002) based on Booker and Young (1994).

The potential impact of irrigation-water-rights trading on the Yellow River Basin was tested by Shao, et al. (2009), and Yang, et al. (2009) by developing a water allocation optimization model using a multi-agent system (MAS) modeling framework. The authors defined nine water-use agents for those provinces which share the Yellow River. Three water-use agents to reflect downstream ecological needs, five water-use agents to represent key reservoirs, and thirty-five water-use agents to represent key tributaries and inflows.

Using the integrated water resource management (IWRM) faces a variety of challenges that several of them were described by Biswas (2004). The integrated water resources and environmental management model (IWEM) solves the rational allocation of water resources in Haihe River Basin by promoting the efficiency and benefits of water resources utilization, ecology and environment restoration, water shortage mitigation, pollution to the Bohai Sea, and improving the water environmental quality of the Haihe River Basin. Shao, et al. (2009) developed water allocation model which is applied on the Yellow River Basin to provide efficient solutions to the decision makers under water shortage conditions.

An integrated modeling approach linked the soil and water assessment tool (SWAT) to the generic river basin management decision support system (MODSIM) for water allocation in the Karkheh river basin was developed by Vaghefi, et al. (2015). Their analyses indicate that it is possible to use changes in cropping patterns considering the hydro-energy production as an effective measure to adapt to the negative impacts of climate change.

Fang, et al. (2013) applied a comprehensive water resources allocation model in the Wuwei Basin. Four different scenarios were solved and evaluated using a Bi-Level Multi-objective Linear Programming (BLMOLP). The upper level is solved and used as the tolerance for the lower level in order to evaluate the weights of each objective function in the lower level. Its authors proved that it can effectively balance the benefits among all regions and sections of the basin.

Three water management scenarios were developed by Schmidt, et al. (2008) which describe how are the hydrologic and economic water conservation measures influence the water management in the Boise Valley. An interaction between the surface water and groundwater in order to maximize the economic utility of water use by satisfying the equilibrium of the economic outcome. Variety of water management alternatives, such as the construction of new water storage, new water conservation measures, and/or market-based water management, were tested.

Water allocation optimization models have been used to handle different irrigation issues around the world. Different water allocation rules were tested by the development of a Computer Aided and Management Simulation of Irrigation Systems model (CAMSIS) (Burton, 1994). The model simulates farm income by using different water allocation rules and polices under water shortage or drought conditions in East Africa. Paul, et al. (2000) developed a multi-level approach considering the competition between crops for irrigation water and farmed areas taking into account the seasonal and intra-seasonal agricultural irrigation water allocation in a semiarid region of Punjab, India. Salman, et al. (2001) developed an agricultural water allocation model to be used as a decision-making tool for planners of agricultural production on both local and regional levels adopting an inter-seasonal irrigation water allocation. Shangguan, et al. (2002) presented an agricultural irrigation water allocation optimization model adopting the principle of maximum capacity and harmony. The model shows that the obstacles in using dynamic programming with multiple dimensions could be overcome. Brown, et al. (2002) used an AQUARIUS model to evaluate the temporal and spatial allocation of flows among competing water uses in a river basin. Babel, et al. (2005) introduced an Integrated Water Allocation Model (IWAM) which determined the optimal decisions regarding water consumed through different sectors by considering socio-economic, environmental and technical factors. The model was solved using three computational modules; for reservoir operation, economic analysis and water allocation.

An agricultural irrigation water allocation optimization model using stochastic dynamic programming was developed by Ghahraman and Sepaskhah (2004). The model optimizes agricultural water allocation with a predetermined multiple cropping pattern in Iran. The irrigation water management model MOPECO was applied by Alvarez, et al. (2004) for a semi-arid area of Spain. The authors concluded that the irrigation depth for maximum benefits is lower than that necessary to obtain maximum production. A non-linear programming optimization model to maximize the total farm income using an integrated soil water balance was developed to determine the optimal reservoir releases, the water allocation for irrigation purposes, and the optimal cropping pattern for irrigated farmlands with the Havrias River in Northern Greece (Georgiou and Papamichail, 2008).

Using a Genetic Algorithm (GA), an irrigation scheduling problem was evaluated by Haq, et al. (2008). The authors demonstrated the powerful role of using a GA in comparison to the use of integer programing. A methodology based on Shapely games was proposed by Sadegh, et al. (2010) to be used in the allocation of water resources among different users sharing the Karoon River basin in Iran. The result of the developed model is the satisfaction of the equity standard to increase the total net benefit of the system. Haq & Anwar (2010) evaluated simultaneous irrigation scheduling using a GA comparing the stream tube model with the time block model.

Fotakis and Sidiropoulos (2012) developed a multi-objective evolutionary algorithm to simultaneously solve the problem of land use planning and resource allocation which performs optimization on a cellular automaton domain, applying suitable transition rules on the individual neighborhoods. Xuan, et al. (2012) developed an optimal water allocation model based on water resources security assessment. Ward, et al. (2013) provided a framework for identifying, designing, and implementing water allocation rules for food security in Afghanistan's irrigated area as a case study.

The Shuffled Complex Evolution Method was used by Kang and Park (2014) to develop a combined simulation-optimization model for simulating reservoir operations. They concluded that the model is useful for assessing reservoirs' irrigation water supply capacities when establishing operation plans and providing feasible alternatives for new operational rules (Wang et al. 2015). An integrated land-use and water allocation optimization model was developed which maximizes the economic benefit, while minimizing water extraction and transportation costs under ecological constraints (Fotakis and Sidiropoulos, 2014).

A multi-objective water allocation optimization model to maximizes crop yields was developed by Lalehzari, et al. (2015). An improved agricultural crop and water allocation model using ant colony optimization (ACO)was developed by Nguyen, et al. (2016) by enabling the dynamic decision variable option (DDVO). The model maximizes the net benefit from the allocation of water cultivating certain types of crops. A water allocation optimization model using the particle swarm optimization (PSO) algorithm was developed by Davijani, et al. (2016). The model maximizes the number of the generated jobs in both agricultural and industrial sectors in the central desert region of Iran. It provides an indication about the optimal solution in case of certain policies to be used by water policy makers.

A general optimization framework optimizes crop and water allocation using ant colony optimization and dynamic decision variable options (ACO -DDVO) was introduced (Nguyen et al. 2016B). The model reduced search space size and increasing the computational efficiency of evolutionary algorithm application. Abdulbaki, et al. (2017) developed an integer linear programming decision support model has the flexibility to consider seawater, surface water, groundwater and reclaimed water to be optimally allocated. The model minimizes the water treatment, allocation, and environmental costs by allocating the water to different consumers (irrigation, potable, and industrial) considering different quality requirements. A genetic simulation-optimization framework for optimal irrigation and fertilizer scheduling was developed using ant colony optimization (ACO) to evaluate the objective function, and dynamic decision variable option (DDVO) to reduce the search space size of the optimal solution (Nguyen et al. 2017).

A genetic algorithm (GA) optimization model was presented by (Anwar and Haq, 2013) which solves sequential irrigation scheduling problems. Four different irrigation scenarios were considered separately allocating irrigation water to 94 farms. Raju & Kumar (2004) developed an agricultural irrigation water allocation optimization model using a GA to be applied on the Sri Ram Sagar project in India. Kumar, et al. (2006) presented a water allocation optimization model for agricultural irrigation using GA to maximize the net benefit from the use of certain types of crops adopting a certain cropping pattern in Karnataka, India. A nonlinear programming optimization model using a GA was developed (Sadati et al. 2014). The model maximizes farm income by determining optimal reservoirs release and optimal cropping pattern.

3.2. The Tigris Euphrates River Basin

3.2.1. *Introduction*

Turkey, Syria, and Iraq share the Tigris and the Euphrates Rivers Basin. In the past, before 1940s, there were no significant conflicts considering water sharing among these three neighbor countries while water management was well controlled as the countries were under the control of the Ottoman Empire (Allan and Allan 2002). The ineffective and inefficient management did not have substantial negative impacts on both the quantity and quality of the two transboundary rivers (Kibaroglu and Ünver, 2000). After 1960, the three countries have started to construct hydraulic structures on the Tigris and the Euphrates rivers and their tributaries to use their water in irrigation and hydropower generation and this has been reflected negatively on the international relations among those neighbors. The behavior of Turkey by starting the GAP project has developed a permanent concern for the downstream users of the shared water including Syria and Iraq. The GAP project is diverting and preventing huge quantities of water from being discharged to Iraq and Syria, which has negative social, economic, quality, and environmental impacts.

Hasan Aljanabi, the minister of Iraqi water resources, has mentioned that because Iraq is the farthest downstream of the Tigris-Euphrates River Basin, it is extremely difficult, if not impossible, to plan, manage and allocate its water resources due to the uncertainty of the incoming flows from Turkey and Syria. Furthermore, there is no cooperation between the three riparian countries in discussing their proposed projects and considering others water demands as well as the absence of any obligation of a water sharing agreement. In 1946, Iraq and Turkey have signed a Treaty of Friendship and Neighborly Relation which states that Turkey should consult with Iraq before the construction of any upstream projects and make adjustments to meet the requirements of both countries (Elhance, 1999). Theoretically, the application of this treaty still enforce, but in reality, there was a lot of fluctuation in the application of this agreement because Syria was excluded and it was not clearly specified how the term "consultation", which was listed in the treaty, will be defined and adjudicated (Elhance, 1999, and Dinar, 2012). Furthermore, Turkey confirms that there is sufficient water in the basin and accuses Syria and Iraq for mismanaging the water resources in their territories. Turkey debates that because the Tigris and the Euphrates Rivers are formed and flow on its lands, therefore, it has the full right to invest the water in its territory until it reaches Syria (Zawahri, 2006 and Williams, 2011). So, Turkey initiated the Southeastern Anatolia Development Project (GAP) to develop land and water resources which includes the construction of 22 dams and 19 hydro-power plants to irrigate an additional 1.7 million ha and to produce 27 billion kWh of electricity per year through a total capacity of 7460 MW. When the project is finished, it will employ additional 3.8 million people and increase the per capita income by 209 percent in the Turkish upstream area of the Tigris and Euphrates. The total GAP area is bigger than Benelux, Denmark, and Ireland altogether (Projesi, 2006). So, by considering the economic and the social positive impacts of the GAP project on Turkey, it will be obvious why it insists to invest in the GAP project regardless of the negative consequences on the downstream countries.

Falkenmark, (1989) and Postel, (1996) included in their research a resources evaluation for the Tigris-Euphrates basin. Kolars, (1994), Waterbury, (1994), and Scheumann, (1998) presented the history of water conflicts between Turkey, Syria, and Iraq in particular after the start of the Southeast Anatolia Development Project (GAP) by Turkey in 1976. Naff and Matson, (1984), Kolars and Mitchell, (1991), Kolars, (1992), Kolars, (1994), Kliot, (1994), and Altinbilek, (1997) have described the Tigris-Euphrates River Basin hydrology.

3.2.2. *Optimization Models Derived for the Tigris-Euphrates Rivers Basin*

The Tigris- Euphrates basin literatures in water resources, hydrology, history, economics, and politics have been considered in many publications. The Tigris and Euphrates River Basin has been investigated using an optimal water allocation optimization model by introducing the WATER-Model (Oei and Siehlow, 2014) (Oei and Siehlow, 2016). Different scenarios were taken into consideration to examine the effects of different levels of cooperation for an optimal water allocation considering the effects of filling new Turkish reservoirs on Turkey, Syria, and Iraq. Modeling results show that Turkey is most efficient in its water usage. The authors concluded that the total outcome is a net decrease in benefits as a result of giving the priority to Turkey to use the water for irrigation purposes instead of the Iraqi or Syrian domestic and industrial sector. A loss of up to 33% was estimated in the Euphrates River basin as a result of such attitude.

The Euphrates and the Tigris River Basin Model (ETRBM) was modelled by Kucukmehmetoglu and Guldmann, (2004) which maximizes the net benefits generated from water uses by considering water-conveyance costs. The model is a combination of game theory and a fuzzy modeling approach to deal with linguistic data in the basin. The water-conservation balances, and the maximum and minimum water consumption were the constraints of the model. The model evaluates the economic outcomes resulting from different cooperation and noncooperation strategies which were proposed to be followed by Turkey, Syria, and Iraq. The ETRBM was transferred into Inter-Temporal Euphrates and Tigris River Basin Model (ITETRBM) (Kucukmehmetoglu and Guldmann, 2010). The potential political and economic impacts of reservoirs from an inter-temporal perspective are the constraints of ITETRBM. The authors concluded it is more efficient to enhance the basin wide coalitions rather than the construction of further costly reservoirs on the Tigris-Euphrates Rivers basin. Kucukmehmetoglu, (2009) developed another approach which integrates both game theory and Pareto frontier concepts that searches for an acceptable solution set over the Pareto frontier surface via cooperative game theory-based constraints.

Davis and Fauwaz, (2004) developed a Tigris-Euphrates River Basin hydrologic model. The model includes the socioeconomic and environmental aspects considering Iraq as the case study. They confirm that in order to build a tool for future studies, re-flooding and restoration of the Iraqi marshland must be included considering the ecosystem health of the marsh.

Tilmant and Kelman, (2007) presented a stochastic dual dynamic programming approach which analyzes trade-offs under hydrological uncertainty applied to the GAP project in Turkey. Simulation results show a significant reduction in the total energy output and an increase in the risk of not satisfying Syrian and Iraqi water demand after the completion of GAP’s irrigation proposed projects. Tilmant, et al. (2009) presented a stochastic programming approach to evaluate the allocation of marginal water values in cascade considering the hydroelectric-irrigation reservoirs in the Euphrates River in both Turkey and Syria.

Güner, (1999) used a non-cooperative game modeling approach to model the interaction between Turkey and Syria taking into account terrorism and water. It mentions that Iraq benefits from Turkish-Syrian concessions, but its downstream location prevents it from getting benefit from these concessions. A unique equilibrium stipulates the conditions for cooperation between both upstream countries that resulted in the formation of Turkish-Iraqi and Syrian-Iraqi alliances to handle the potential threats in the basin.

Despite the significant achievements described above, many of these articles recognized the need to develop more flexible rules for the allocation of irrigation water. Allocation rules that allow for flexibility in drought seasons are needed to allow for adaptation to climate change and to sustain food security and rural livelihoods in the Tigris and Euphrates Rivers basin downstream countries.

An assessment of water appropriations in Iraq was previously modeled by developing a non-linear water allocation optimization programming model which maximizes the agricultural net benefit (Salman et al. 2014). The optimization model allocates water using an appropriation system for adapting to water shortage to cultivates different types of crops in the Tigris and Euphrates Rivers basin. Four water appropriation systems are compared for impacts on farm income under each of the three water supply scenarios.

3.3. Sustainability

The tremendous increase in population with the limited availability of natural resources, such as the fresh water, water stresses are a significant concern for many regions all over the world (Alcamo et al. 2007; Vörösmarty et al. 2000; Rijsberman, 2006; Rosegrant et al. 2002). Furthermore, as a finite resource, the world's fresh water supply does not increase according to the National Science Foundation (2011), "One of the most urgent challenges facing the world today is ensuring an adequate supply and quality of water in light of both burgeoning human needs and climate variability and change" (NSF, 2011). Therefore, it is of significant interest for people who deal with water issues as they started looking for a practical and applicable measure to conserve this valuable source of life by considering sustainability. The definition of water resources sustainability varies according to the assumptions, understanding, and the interpretation of scientists and authors to its implicit meanings. A long-term, stable and flexible water supply capacity to meet demands and to maintain a healthy environment taking into account irrigation practices are the main obligations to satisfy a sustainable water resource management (Cai et al. 2003).

The sustainable water resources management goals is to satisfy real improvements in water use efficiency, protect the environment, preserve available water resources and any other action related to water use improvement. Structural solutions are often necessary; however, the traditional emphasis on structural solutions is more expensive and often can result in greater environmental damage than nonstructural solutions. Increased consideration of non-structural measures may lead to reduced financial pressures and environmental damages (Zilberman, 1998).

After the World Commission on Environment and Development (1987) report (Brundtland, 1987), Oxley and Mays (2016) mentioned that the concept of sustainability gained significant traction especially after the discussion on its definition and application. Generally, environmental concerns, long term availability and use patterns are usually linked with sustainability. Consequently, researchers on water resources management began considering sustainability principles which might be suitable for answering key water management issues. However, translating the current definitions and principals of water resources sustainability into practical application remains problematic (Gleick, 2000; Kuhlman and Farrington, 2010; Lant, 2006; Loucks, 1997; Solow, 1991; Unver, 2007).

Several indices related to the standards of sustainability were considered, which are; reliability, resilience, and vulnerability of the water supply system, environmental system integrity through consideration of water quantity and quality, spatial and temporal equity, and ‘socio-economic acceptability’ (Oxley et al. 2016). So, Loucks, (1997); Sandoval-Solis and McKinney, (2009); Rothman and Mays, (2013), have used the concept of a sustainability index (SI) to measure the sustainability of water resources. Water supply management, water distribution system, and groundwater management are connected to sustainability in many previous applications.

Mays, (2007) presented the following definition of water resources sustainability: “*Water resources sustainability is the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for* *the present and the future to sustain life and to protect humans from the dangers brought about by natural and human-caused disasters that affect sustaining life*".

The World Commission on Environment and Development (1987) defined sustainable development as "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." (Brundtland, 1987).

Herman E. Daly, the former Chief Economist for the World Bank, suggests three operational rules defining the condition of ecological sustainability: (1) Renewable resources such as fish, soil, and groundwater must be used no faster than the rate at which they regenerate. (2) Nonrenewable resources such as minerals and fossil fuels must be used no faster than renewable substitutes for them can be developed. (3) Pollution and wastes must be emitted no faster than natural systems can absorb them, recycle them, or render them harmless (Daly, 2007).

Rothman, (2007) developed an optimization model that incorporates water resources sustainability from the regional water supply viewpoint. Rothman and Mays (2013) developed a multi-objective genetic algorithm (MOGA) optimization model considering water resource sustainability. The model was applied to the Prescott Active Management Area (AMA) in Arizona.

The sustainability in water resources planning and management was presented by Cai and McKinney, (1999) by proposing a holistic basin management model that was applied to the Syr Darya River basin in Central Asia (Cai and McKinney, 1999; Cai et al. 2001; Cai et al. 2003). The concept of the management approach has combined the structural solutions and the non-structural measures to achieve sustainability in real world practices. The model considers an integral river basin system under arid or semi-arid climates and an irrigation dominated water supply. Salinity control, as a major water quality and environmental concern, also was considered in the model.

Oxley and Mays, (2016) developed a model to evaluate four scenarios to test the validity of the developed model and to provide examples of its potential applications. The model defines the net economic benefits calculated in terms of both use and non-use values and sustainability in terms of the risks to water supplies and riverine ecological, environmental and hydrological integrity. A new methodology for the sustainable and optimal allocation of water for a river basin management area was presented by Oxley, et al. (2016). The model defines the net economic benefits calculated in terms of both use and non-use values and sustainability in terms of the risks to water supplies and riverine ecological, environmental and hydrological integrity.

CHAPTER 4 APPLICATION OF AN OPTIMIZATION MODEL FOR ASSESSING THE PERFORMANCE OF WATER APPROPRIATION IN IRAQ

1.6. Introduction

The magnitude of water resources shortages in the Middle East represents an important factor in the stability of the region and it is a vital element in protecting sustained economic development in the region. This investigation addresses the ongoing challenge of water governance in Iraq by examining how profitability, at both the farm and basin levels, is affected by various water appropriation systems. Farmland irrigation in Iraq was evaluated using three water appropriation systems; upstream (UPR), downstream (DPR) and proportional (PSR) sharing rule. Their impacts on farm income under normal, dry, and drought water supply scenarios were evaluated using an irrigation water model coupled with a nonlinear programming (NLP) optimization model. As compared to UPR, PSR provided a 32% and 75% increase in total farm income for the Tigris River under dry and drought supply conditions, respectively. As compared to DPR, PSR provided a 47% and 83.5% increase in total farm income for the Euphrates River under dry and drought supply conditions, respectively.

Iraq is located in the eastern part of the arid and semi-arid Middle East. The country's climate tends to have temperatures of 43°C during the months of July and August and drop-down to an average of 16-20°C during the winter (Al-Ansari 2013; Al-Ansari et al. 2012). In addition, the Tigris and Euphrates Rivers form the primary sources of fresh water for Iraq (Figure 4-1). The average annual flow for the Tigris River from 2003 to 2014 has been estimated as 36.4 billion m^3/yr. Most of the Tigris River water and its tributaries originate in Turkey (56%) followed by Iran (12%) and the remaining 32% from sources inside Iraq (Table 4-1). During the period of 1933-2012, the Tigris's River experienced significant fluctuations in its annual water income and a noticeable repetition of water shortage since 1999. Furthermore, the Euphrates River sources originate in Turkey (88%) followed by Syria (9%) and Iraq (3%). The Euphrates River experienced significant water shortages from 2009 to 2014. These two rivers also experience significant water demands upstream of Iraq. Combining the recent situation of water supply decreases and increasing demands in Turkey and Iraq, more severe shortages in surface water resources are to be expected in the future, particularly if the effects of climate change are considered (Voss et al. 2013).

In Iraq, the planning and construction of new irrigation and flood control systems by the Board of Development began in 1950. As a result, numerous dams, canal systems, irrigation projects and flood control structures were constructed on the river systems inside Iraq (Partow 2001; Iraqi Ministry of Water Resources, 2013). These structures had positive impacts on the receiving agricultural lands and the installation of tile drainage systems helped develop and improve agricultural lands providing an important impact on the country's economy.

The Southeastern Anatolia Project (GAP) in Turkey began in 1970 and will consist of 22 dams on both the Tigris and Euphrates Rivers. This project has reduced the flow of water to Iraq by approximately 50% and also increased the salinity of the water entering Iraq. The combination of reduced water flows, reduced rainfall, and population growth in Iraq resulted in periods of severe water shortages in 2007- 2009. There was a steep decline in agricultural productivity in the highly populated areas along the Euphrates and Tigris river basins (Shean 2008). Iraq's crop production was reduced to one half of its usual rate of production and many farmers abandoned their agricultural lands. Consequently, food imports had to increase while the majority of food is currently imported into Iraq resulting in elevated costs to consumers (UNDP, 2009).

Figure 4-1 Iraq provinces and surface water system (Nord Nord West License, 2016).

Table 4-1 The Tigris River and its tributaries average annual water flows.

Tigris River and its Tributaries	Total Length (km)	Total Area km^2	Annual Water Flows (Billion m^3)	Annual Water Flow (%)	
				Inside Iraq	Outside Iraq
Tigris River	1900	46700	19.43	-	1
Fiesh Khabour	160	6270	2.1	0.58	0.42
Greater Zab	473	26470	14.32	0.58	0.42

Lesser Zab	456	22250	7.07	0.64	0.36
Adhaim	220	10680	0.7	1.00	-
Diyala	386	3200	5.86	0.41	0.59
Total			49.48	0.32	Turkey 56% Iran 12%

Currently, there remains a serious threat to the Mosul Dam due to a potential foundation failure. This threat has been known for an extended period of time. Iraqi authorities have attempted to stabilize the foundation of the dam using grout. A lack of funding and the dangerous security conditions around the Mosul Dam have made it difficult to completely stabilize the dam. A dam breach would cause flooding and increase downstream water shortages. In late 2016, efforts to solve the problem at the Mosul Dam were resumed by the Iraqi government which created hope in recovering the dam to its full functionality.

4.1. Objective

Combining the reduction in water supply, the recent political conflicts, in addition to future predictions based on global warming, increased severe water shortages are to be expected in Iraq’s surface water resources. Serious and time responsive measures should be adopted in order to overcome this potential problem. Regional cooperation and coordination should be taken by the decision makers to implement practical and applicable water management strategies. So, the agricultural water allocation optimization model implemented in this study, through maximizing the net farm benefit, was modified and applied to provide guidance for the future water authorities and to sustain water in Iraq’s future.

4.2. Optimization for Water Allocation Modeling

Water allocation models have been developed for regions with climates similar to Iraq using a variety of methodologies. Burton (1994) developed a Computer Aided and Management Simulation of Irrigation Systems model (CAMSIS) to simulate farm income by using different water allocation rules and polices which were adopted under water shortage or drought scenarios in East Africa. Paul, et al. (2000) used a multi-level approach to solve problems related to seasonal and intra-seasonal irrigation water resources allocation in a semiarid region of Indian Punjab considering the competition of the crops in a season, both for irrigation water and area of cultivation. An agricultural water allocation system model using linear programming was developed by Salman, et al. (2001) for analysis of inter-seasonal irrigation water allocation and their effects on the net farm income. The function of the model is to serve as a decision-making tool for planners of agricultural production on both local and regional levels. Shangguan, et al. (2002) presented an irrigation water allocation optimization model using multiple water resources allocation and their results demonstrated that obstacles in dynamic programming with multiple dimensions could be overcome. Brown, et al. (2002) used an AQUARIUS model developed to evaluate temporal and spatial allocation of flows among competing water uses in a river. Babel, et al. (2005) introduced the interactive Integrated Water Allocation Model (IWAM) to aid in decision-making for water use by considering socio-economic, environmental and technical factors using three computational modules for reservoir operation, economic analysis and water allocation. Sadegh, et al. (2010) proposed a methodology based on Shapely Games to be used in water resources allocation among different users for the Karoon River basin in Iran with the goal of developing an equity standard to increase the total net benefit of the system.

A stochastic nonlinear programming model with multiple objectives was used by You, et al. (2011) to aid in multi-objective decision-making considering the Haihe River as a case study. An Inexact Rough-interval Fuzzy Linear Programming IRFLP model was constructed to make a comparison between the IRFLP model and an interval-valued linear programming model for water allocation to provide more conveniences for decision makers. The IRFLP shows distinction in handling the interaction between dual intervals of highly uncertain parameters, as well as their joint impact on the system (Lu et al. 2011). A water resources allocation optimization model (Wang et al. 2015) using multi-objective programming was applied on water deficient of Haihe River basin by embedding land use as a constraint on water allocation. Oxley, et al. (2016) developed a model that defines the net economic benefits calculated in terms of both use and non-use values and sustainability in terms of the risks to water supplies and riverine ecological, environmental and hydrological integrity. An optimization model maximizing the sustainable net economic benefit over a long-term planning horizon was applied by Oxley and Mays (2016) to Prescott Active Management Area. The model evaluates four scenarios to test the validity of the developed model and to provide examples of its potential application.

Fotakis and Sidiropoulos (2012) developed a multi-objective evolutionary algorithm to simultaneously solve the problem of land use planning and resource allocation which performs optimization on a cellular automaton domain, applying suitable transition rules on the individual neighborhoods. Fang, et al. (2013) presented a comprehensive solution for water resources allocation in the Wuwei Basin and they concluded that the model can effectively balance the benefits among all regions and sections. Vaghefi, et al. (2015) linked the soil and water assessment tool (SWAT) and the generic river basin management decision support system (MODSIM) for water allocation in the Karkheh river basin. Their analyses indicate that it is possible to use changes in cropping patterns as an effective tool to adapt to the negative impacts of climate change.

Salman, et al. (2014) presented a methodology to maximize the net farm income in Iraq by producing different types of crops. Four water right (allocation) systems were considered: upstream priority, downstream priority, proportional sharing of shortage, and unrestricted water trading. They considered three water supply scenarios including: normal, dry and drought supply conditions. Dry conditions were 50% of normal conditions and drought conditions were 20% of normal conditions. The various conditions were compared in terms of their capacity to minimize losses in net farm water-related income.

One of the limitations in the work by Salman, et al. (2014) was that the Tigris and Euphrates Rivers were considered as one individual basin inside Iraq for irrigation in thirteen provinces. Water managers in Iraq consider the two rivers as two separate basins which irrigate fifteen provinces. Thus, in order to provide water managers more useful information, the model developed by Salman, et al. (2014) was modified considering the two rivers as two separate basins which irrigate fifteen provinces. Furthermore, the Salman, et al. (2014) model considered unrestricted water trading as one of the water allocation priorities. In Iraq, a water trading strategy is inapplicable due to Iraq’s recent political, geographical, and social composition as well as other religious considerations. Therefore, water trading was not considered in the adopted model.

The optimization model utilized in this study was modified and applied to provide guidance for the future water authorities and to sustain water in Iraq's future by using recent water resource data. Based upon the history of Iraq's water resources systems and provincial distribution, changes were made to the mentioned model by Salman, et al. (2014) in order to satisfy the current conditions in Iraq. These changes affected some of the water distribution systems and the irrigated provinces for each river. Most of the data which were used in the original model was from the year 2012.

The model application in this research improves upon the excellent work previously done by Salman, et al. (2014). Improvements include making the model more accurate and applicable by reflecting the Tigris and Euphrates River basins as separate basins, and the use of more recent data to reflect the current irrigation and agricultural conditions inside Iraq. These modifications were made to reflect the experience with Iraq's recent water conditions. These changes can be summarized as follows:

(1) In comparison to Salman, et al. (2014), who considered the Tigris and Euphrates Rivers as one individual basin in Iraq, this modeling effort considers the Rivers as two separate basins. This change was done to the original model in order to satisfy Iraq's current conditions and to investigate a different approach. The updated model optimizes each of the two river basins separately, which is how water is managed in Iraq.

(2) The second modification is to allocate the water of the two rivers over 17 agricultural demand nodes inside Iraq (Table 4-2) in contrast to Salman, et al. (2014) who considered only 13 irrigation provinces (nodes) to be irrigated by only one river basin.

(3) The updated model considers The Tigris River to irrigate eight provinces (nodes) which form the majority of the eastern part of Iraq alongside with its flow path all the way from the north to the south of Iraq. While the Euphrates River basin irrigates nine provinces (nodes) along with its flow path at the western parts of Iraq starting at its entrance at the Iraqi-Syrian border to the Arabian (Persian) Gulf south of Iraq. Both Baghdad and Basra were divided into two sections because they are irrigated from the two rivers at the same time. The eastern parts, Baghdad-A and Basra-A are irrigated from The Tigris River, while the western parts, Baghdad-B and Basra-B, are irrigated from The Euphrates River. Thus, there are seventeen irrigated nodes in contrast to the thirteen provinces (nodes) used by Salman, et al. (2014).

(4) The updated model includes updated data to match the most recent conditions in Iraq. These data were observed from Iraqi Central of Statistical Organization (ICSO) (2015) which include crop production rates, agricultural land per crop, production cost per crop, and associated crop prices.

Table 4-2. Irrigated land in production by province (ICSO, http://cosit.gov.iq/ar/agri-ind).

	The Tigris River							
Province	Mosul	Kurkuk	Salaheldeen	Deyala	Baghdad-A	Wasit	Mesan	Basrah-A
Estimated Irrigated Area (1000 ha)	94.08	189.29	221.02	172.83	52.75	258.51	111.86	29.36

The Euphrates River

Province	Anbar	Baghdad-B	Babylon	Karbala	Najaf	Qadeseeya	Muthana	Thieqar	Basrah-B
Estimated Irrigated Area (1000 ha)	126.25	41.19	132.28	10.38	50.08	160.72	1.93	51.33	23.43

1.7. Data for Optimization Model

The required data used in the optimization model is listed in Tables 4-2 to 4-4. Portions of the data on land in production, crop yields, prices, costs of production, and net farm income per unit land by province for the years 2010-2014, were adopted from select sources including the Iraqi Central Statistical Organization (ICSO, 2015), and Salman, et al. (2014). Others were secured from specific Iraqi institutions including the Ministry of Water Resources and the Ministry of Agriculture. The Tigris and Euphrates Rivers' annual flows were estimated to be 43-52.6 billion m^3/yr and 28.7-30.5 billion m^3/yr respectively based on data from the Iraqi Ministry of Water Resources (2013). The year 2006 was taken as the base year for the current analysis because the supply from the river system water used in crop irrigation was a maximum value. This was based on the 2006-2013 historical data from the Iraqi Ministry of Agriculture showing that the highest total amount of irrigated land in production occurred in 2006 (Al-Ansari 2013). Salman, et al. (2014), calculated the river system water use by irrigated crops using the indirect methods described by Allen, et al. (1998).

Saleh (2010) considered crop irrigation water requirement (ETc) as about 30% of the total water supplied by the Tigris-Euphrates system in Iraq. Therefore, almost 70% of the available surface water inside the country is largely unaccounted for and the exact fate of the water is not certain.

Crop water requirements ETc were adopted from Salman, et al. (2014), which were based on water demands to support maximum yield. Crop production costs in US dollar per hectare ($/ha) were updated to 2015 values, as presented in Table 4-3, based on data secured from the Iraqi Ministry of Agriculture. Therefore, these costs are higher than those which were adopted in the original model by Salman, et al. (2014). The reason for higher costs includes conflicts in Iraq and the rise of all agricultural prices starting from the prices of seeds along with the prices of fuel and fertilizers. The production cost includes soil fertility, weather, and water availability and quality which fluctuated across Iraq. The yield rates of different types of crops in Iraq are provided in Table 4-4.

Table 4-3. Crop production costs exclusive of water costs ($ US per Ha) (ICSO, http://cosit.gov.iq/ar/agri-ind).

Crop	Rice	Wheat	Cotton	Sunflower	Maize	Barley	Tomato	Lettuce	Onion
Cost $	850	820	1300	655	900	720	1300	850	580

Table 4-4. Crop yield tons per hectare (proportional to ET) (ICSO, http://cosit.gov.iq/ar/agri-ind).

Province	Rice	Wheat	Cotton	Sunflower	Maize	Barley	Tomato	Lettuce	Onion
1-Mousil	2.89	3.05	2.40	1.33	4.40	0.90	17.90	19.97	5.89
2-Kurkuk	2.89	3.35	2.50	2.86	5.63	2.76	5.86	15.20	4.80
3-Salaheldeen	2.89	2.49	0.80	1.58	3.57	1.18	12.79	15.44	2.10
4-Deyala	2.89	3.58	1.87	1.67	2.51	2.00	27.90	21.70	11.54
5-Anbar	4.00	2.69	0.36	2.78	2.08	0.8	14.82	23.77	9.24
6-Baghdad	4.00	2.61	0.58	1.45	2.26	1.21	14.60	26.18	20.13
7-Babylon	4.04	3.15	0.94	1.69	2.88	1.78	10.50	16.32	5.32
8-Karbala	4.00	2.35	0.50	1.50	2.66	1.55	9.48	9.07	3.30
9-Najaf	4.88	1.39	0.50	1.50	2.47	1.36	34.65	14.69	20.69
10-Qadeseeya	4.70	2.37	0.40	1.50	2.54	1.74	11.38	9.74	7.05
11-Wasit	2.89	2.81	0.50	1.33	2.58	1.28	7.12	11.91	4.40
12-Muthana	2.51	1.34	0.50	1.50	0.00	1.03	14.10	9.50	1.00
13-Meesan	2.20	2.17	2.42	1.33	3.40	1.41	14.44	11.45	0.01

Province	Rice	Wheat	Cotton	Sunflower	Maize	Barley	Tomato	Lettuce	Onion
14-Thieqar	1.80	1.86	0.50	1.50	2.85	1.66	7.85	18.26	11.31
15-Basra	1.70	1.98	0.50	1.50	0.88	0.87	2.97	11.45	1.00

4.5. Optimization Model

1.7.1. *The Objective Function*

The purpose of this model is to allocate crops on land in order to maximize the net farm income (Nfi) by determining the optimal amount of land ($Ln_{i,k}$) assigned to each crop (k) in each province (i). The ability to generate farm income is constrained by the quantity of water available for agriculture. A mass balance equation was developed for water allocation and then constraints were assigned for the three different water supply scenarios. The optimization model considered eight provinces associated with the Tigris River (Mousil, Kurkuk, Salaheldeen, Deyala, Baghdad-A, Wasit, Meesan, Basra-A) and the nine provinces associated with the Euphrates River (Anbar, Baghdad-B, Babylon, Karbala, Najaf, Qadeseeya, Muthana, Thieqar, Basra-B).

The objective function is to maximize the total income from the crops k= 1, ..., K in provinces i= 1, …, I, expressed as:

$$\text{Max Net Farm Income } (Nf_i) = \text{Max} \sum_i \sum_k Nb_{i,k} \quad (4\text{-}1)$$

where $Nb_{i,k}$ is the total income from crop k in province i expressed as

$$Nb_{i,k} = (P_{i,k}\, Y_{i,k} - C_{i,k})\, Ln_{i,k} \quad (4\text{-}2)$$

where

$P_{i,k}$ is the selling price ($/ton) of crop k in province i

$Y_{i,k}$ is the yield of crop k (tons/ha) in province i

$C_{i,k}$ is the cost ($/ha) of production of crop k in province i

$Ln_{i,k}$ is the land in production (1000 ha/year) of crop k in province i

1.7.2. *Decision Variables and Constraints*

The nonlinear programming (NLP) model contains a number of decision variables which are: water availability ($W_{x,i,k}$) for normal conditions, dry conditions, and drought conditions are ($W_{1,i,k}$), ($W_{2,i,k}$), and ($W_{3,i,k}$) respectively; land assigned ($L_{x,i,k}$) under normal, dry and drought water supply conditions are ($L_{1,i,k}$), ($L_{2,i,k}$), and ($L_{3,i,k}$) respectively.

1.7.3. *Water Availability Conditions/Constraints*

Three water availability conditions Wu_x (m^3) for the upstream entrance of each river are included: availability for normal conditions Wu_1; availability for dry conditions $Wu_2 = 0.5\ Wu_1$; and availability for drought conditions $Wu_3 = 0.2\ Wu_1$. Subscript x=1 represents the water supply under normal conditions, x=2 is the water supply under dry conditions and x=3 is the water supply under drought conditions.

The sum of the total water assigned for each province under a certain water availability condition must be equal to or less than the total amount of water assigned for all the provinces under the same availability conditions (Wu_1, Wu_2, Wu_3). Using non-linear constraints written in terms of the decision variables $W_{x,i,k}$ and $L_{x,i,k}$, the sum of the total water assigned for each province i is expressed as:

$$\sum_i \sum_k W_{x,i,k}\ L_{x,i,k} \leq Wu_x \qquad \text{for } x = 1, 2, 3 \qquad (4\text{-}3)$$

where

$W_{x,i,k}$ is the unknown water use (m^3/ha) of crop k in province i for a certain water supply condition (x=1, 2, 3)

$L_{x,i,k}$ is the unknown land (ha) to cultivate crop (i) in province (k) under the same water supply conditions

1.7.4. *Land in Production Under Various Water Supply Conditions/ Constraints*

The total predicted land in production $Lp_{x,i}$ for a specific water supply condition per province i (1000 ha) is the sum of the unknown irrigated land $L_{x,i,k}$ for each crop k in each province i under the same water supply condition x, expressed as

$$Lp_{x,i} = \sum_k L_{x,i,k} \qquad \text{for } x = 1, 2, 3 \text{ and } i = 1,\ldots., I \qquad (4\text{-}4)$$

The available irrigable farmland for each province is presented in Table 4-2 and represents the maximum farmland that could be used in each province.

1.7.5. *Water Rights by Province Constraints*

The percentage of a basin's water rights by province i (policy of water allocation rule) under certain water supply conditions ($R_{x,i}$) is evaluated using different priorities based on three distinct water sharing rules: upstream priority rule (UPR), downstream priority rule (DPR), and proportional sharing allocation rules (PSR). The sum of the total water rights percentages $R_{x,i}$ for all provinces under a certain water supply condition (x=1, 2, 3) must be equal to 1.0 as expressed in terms of the unknown water use $W_{x,i,k}$ and the irrigated land $L_{x,i,k}$ under the same water supply conditions.

$$R_{x,i} = \frac{\sum_k (W_{x,i,k}\ L_{x,i,k})}{Wu_x} = 1.0 \qquad \text{for } x = 1, 2, 3 \text{ and } i = 1,\ldots., I \qquad (4\text{-}5)$$

1.7.6. *Water Allocation Rules*

a. Upstream Priority Rule (UPR)

The upstream province in the river basin collects its full allocation of water, while the next lower province collects its full allocation of the remaining water as long as water remains in the river system. The remaining water after supplying provinces using the upstream allocation rule with higher priorities $Rsu_{x,i}$, starting from the upstream province traveling to the farthest downstream province under a certain water supply condition (x=1, 2, 3), is defined as:

$$Rsu_{x,i} = (Wu_x - \textstyle\sum_k W_{x,i,k}) \qquad \text{for } x= 1, 2, 3 \text{ and } i = 1, \ldots, I \tag{4-6}$$

$$\textstyle\sum_k W_{x,i,k} = 0 \qquad \text{when } i=1 \text{ for } x= 1, 2, 3 \tag{4-7}$$

b. Downstream Priority Rule (DPR)

Under this water allocation rule, the farthest downstream province receives its full amount of water that would occur under a specific water supply condition while the next upper province takes its full amount of remaining water, sequentially moving from the downstream to the upstream provinces. The water allocation, using DPR, is essentially the opposite of UPR, resulting in an almost identical mathematical expression. The remaining water after supplying provinces using DPR with higher priorities $Rsd_{x,i}$, beginning from the farthest downstream province going to the upstream province, under a certain water supply condition (x=1, 2, 3), is defined as:

$$Rsd_{x,i} = (Wu_x - \textstyle\sum_k W_{x,i,k}) \qquad \text{for } x= 1, 2, 3 \text{ and } i = 1, \ldots, I \tag{4-8}$$

$$\textstyle\sum_k W_{x,i,k} = 0 \qquad \text{when } i=1 \text{ for } x= 1, 2, 3 \tag{4-9}$$

c. Proportional Sharing Rule (PSR)

The water allocation rule for proportional sharing during a shortage allows each province to sustain the burden of water shortages proportionally. Under this arrangement, when shortages are shared, an X% overall shortage of normal supplies reflects an equal X% reduction of each province's full share under normal conditions. The remaining water supply after supplying provinces, using the proportional sharing of shortage allocation rule with higher priorities $Rsp_{x,i}$, starting from the upstream province going to the farthest downstream under a certain water supply condition (x=1, 2, 3), is defined as:

$$Rsp_{x,i} = (Wu_x - \sum_k W_{x,i,k}) \qquad \text{for } x= 1, 2, 3 \text{ and } i = 1, \ldots, I \qquad (4\text{-}10)$$

$$\sum_k W_{x,i,k} = 0 \qquad \text{when } i=1 \ \text{ for } x= 1, 2, 3 \qquad (4\text{-}11)$$

The total paper rights by priority for all provinces is the sum of the percentage of water allocation rule of all provinces. The total paper rights constraint Tp_x, under a certain water supply condition (x=1, 2, 3), is the sum of the total water rights percentages $Rp_{x,i}$ of all provinces under the same conditions:

$$Tp_x = \sum_i Rp_{x,i} \qquad \text{for } x= 1, 2, 3 \qquad (4\text{-}12)$$

The unknown water use assigned to i^{th} province using one of the allocation rules, the UPR, the DPR, and the PSR, under specific water supply conditions (normal, dry, and drought water supply) are defined. The unknown water use $Wwu_{x,i}$ assigned to i^{th} province using UPR, under a certain water supply condition (x=1, 2, 3), is defined as:

$$Wwu_{x,i} = (Rp_{x,i} / Tp_x)\, Rsu_{x,i} \qquad \text{for } x= 1, 2, 3 \ \text{ and } i = 1, \ldots, I \qquad (4\text{-}13)$$

The unknown water use $Wwd_{x,i}$ assigned to the ith province using DPR, under a certain water supply condition (x=1, 2, 3), is defined as:

$$Wwd_{x,i} = (Rp_{x,i} / Tp_x)\, Rsd_{x,i} \qquad \text{for } x= 1, 2, 3 \text{ and } i = 1, \ldots, I \tag{4-14}$$

The unknown water use $Wwp_{x,i}$ assigned to the ith province using PSR, under a certain water supply conditions (x=1, 2, 3), is defined as:

$$Wwp_{x,i} = (Rp_{x,i} / Tp_x)\, Rsp_{x,i} \qquad \text{for } x= 1, 2, 3 \text{ and } i = 1, \ldots, I \tag{4-15}$$

The cumulative water result, after water is assigned to the last province getting water, should match the total supply. Using the UPR, the cumulative water result $Cu_{x,i}$ that is assigned to the last province obtaining water under a certain water supply condition (x=1, 2, 3) is defined in equation 16, which should match the total supply under the same condition x.

$$Cu_{x,i} = \textstyle\sum_k (W_{x,i,k} + Wwu_{x,i}) \qquad \text{for } x= 1, 2, 3 \text{ and } i = 1, \ldots, I \tag{4-16}$$

Using DPR, the cumulative water result $Cd_{x,i}$ that is assigned to the last province obtaining water under a certain water supply condition (x=1, 2, 3) is defined in equation 17, which should match the total supply under the same condition x.

$$Cd_{x,i} = \textstyle\sum_k (W_{x,i,k} + Wwd_{x,i}) \qquad \text{for } x= 1, 2, 3 \text{ and } i = 1, \ldots, I \tag{4-17}$$

Using PSR, the cumulative water result $Cp_{x,i}$ is assigned to the last province receiving water under a certain water supply condition (x=1,2,3), which is defined in equation 18, should match the total supply under the same condition x.

$$Cp_{x,i} = \textstyle\sum_k (W_{x,i,k} + Wwp_{x,i}) \qquad \text{for } x= 1, 2, 3 \text{ and } i = 1, \ldots, I \tag{4-18}$$

The GAMS code used to solve this non-linear water allocation optimization model is described in Appendix A of this dissertation.

1.8. Results and Discussion

The net farm income levels associated with irrigation for the Tigris and the Euphrates Rivers, predicted under each of the three water shortage sharing rules described in the mathematical model, are illustrated in Figures 4-2 and 4-3. The proportional sharing of shortage water allocation rule (PSR) clearly performs with the highest level of flexibility for adapting to shortages. With PSR, all provinces receive water in a severe drought, thus, the water provides a positive advantage enabling the achievement of economic and food security. In contrast, under shortage conditions with UPR, water is used primarily by the upstream provinces and lower value crops will continue to be grown in the upstream provinces while downstream provinces receive lower amounts of water or no water at all. A similar phenomenon is observed with DPR under shortage conditions where the downstream provinces receive the majority of water and lower value crops continue to be grown in the downstream provinces.

The net income losses under PSR during shortages have less economic cost caused by drought when compared with other types of water allocation rules due to the fact that PSR provides the opportunity for all provinces, under dry and drought conditions, to cultivate part of their farmland with higher economical crops. This reflected positively on the maximized net benefit in comparison to the UPR and DPR under the same water availability conditions.

For the dry water supply condition under PSR, farm net income is maintained at 62.3% and 72.3% of the maximum income under normal water availability conditions for the Tigris and Euphrates, respectively, as illustrated in Figures 4-2 and 4-3. When considering PSR under drought water conditions, the farm net income drops approximately 62.2% for the Tigris River and 52.78% for the Euphrates River as compared to normal water supply conditions.

The downstream provinces suffer the most during water shortages under the common water right system typically used in Iraq (which is shown as UPR in the model). This is readily apparent from the model results presented in Figures 4-4 and 4-5. The results show that when drought occurs with UPR, the lands under production are going to be eliminated or reduced to lower values in downstream provinces. For example, the total planted area in Iraq with PSR is greater compared to the UPR water allocation rule by 10% and 21.4% under dry and drought conditions respectively for the Tigris River. This is because rather than the downstream provinces receiving little to none as compared to the other two water availability scenarios, PSR for the Tigris River ensures all provinces receive some water. However, the results for the Euphrates River with UPR result in greater values of the total planted area, approximately 23% and 54% greater for dry and drought conditions respectively, as compared to the results with the PSR. Nevertheless, the water is used more efficiently for net farm income with PSR as more water is focused on higher value crops.

When the dry water availability condition is applied, the model predicts that provinces that do not get water under UPR will obtain the water when DPR is applied with some exceptions, as illustrated in Figures 4-4 and 4-5. The provinces of Salaheldeen, Deyala, Baghdad-A, Karbala and Najaf received water under both UPR and DPR with different quantities since these five provinces are centrally located. Economically inefficient water allocation will occur with either the use of DPR or UPR since there is no motivation for specific provinces receiving the majority of water to change. Under an efficient water sharing system such as PSR, farmers would experience economic incentives to conserve water in a drought season and provide water to higher valued crops in downstream provinces like Thieqar, Meesan and Basra.

Water shadow prices were computed for both the Tigris and Euphrates River. Shadow prices reflect the marginal economic value per unit additional water and can be calculated for different water supplies, provinces, and water allocation systems. Salman et al., (2014), described the importance of shadow prices to assist farmers making investment decisions in developing alternative sources of water, such as groundwater pumping, water importation, or water conservation. Where the economic values of water are specified, these water shadow prices represent useful tools for identifying water policies (Rosegrant et al. 2000; Doppler et al. 2002; Richmond et al. 2007).

For the Tigris River, the marginal value of water is approximately US$64.75 for each additional 1,000 cubic meters of water, as illustrated in Figure 6, for both the dry and drought water availability scenarios. For the Euphrates River (Figure 4-7), the marginal value of water is approximately US$43.19 for each additional 1,000 cubic meters of water under the dry water availability scenario and approximately US$47.06 when the drought water availability scenario is adopted. Salman, et al. (2014), demonstrated that the marginal value of water is approximately US$32 for each additional 1,000 cubic meters of water in dry conditions and approximately US$93 when severe shortage occurs.

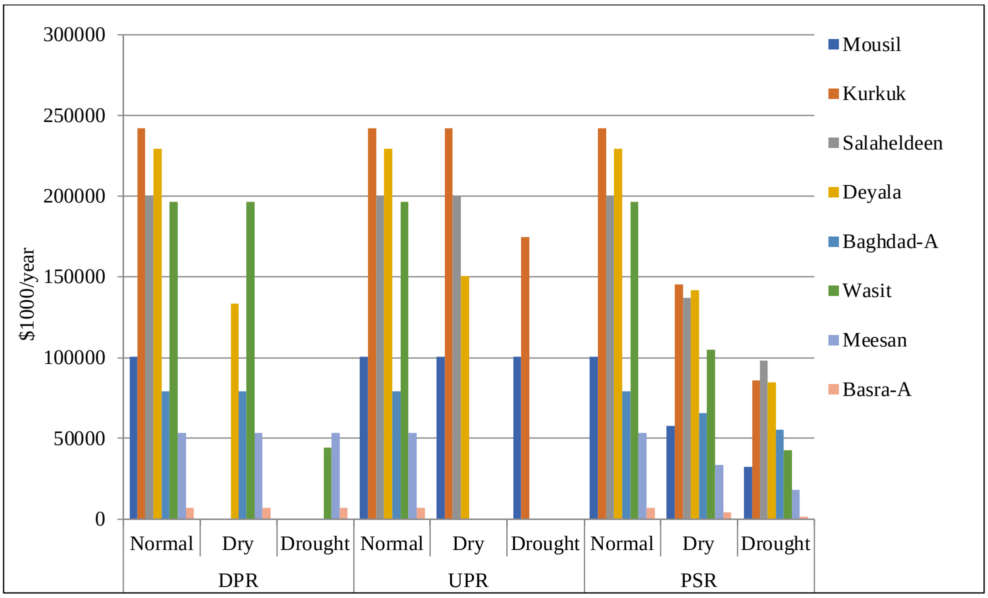


Figure 4-2. Model results of the regional province income by water sharing arrangement, water supply, and province, Tigris River, Iraq ($1000/year).

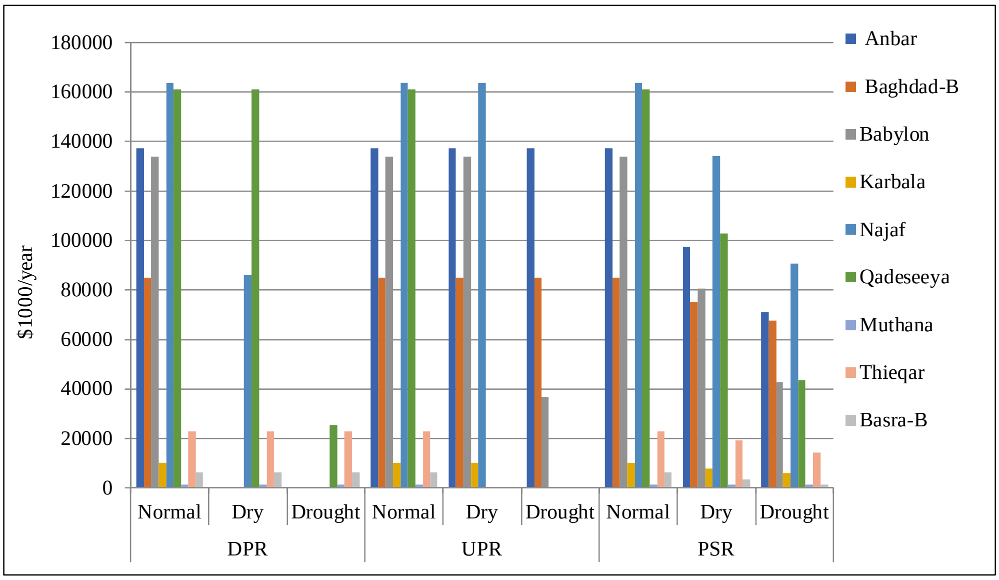


Figure 4-3. Model results of the regional province income by water sharing arrangement, water supply, and province, Euphrates River, Iraq ($1000/year).

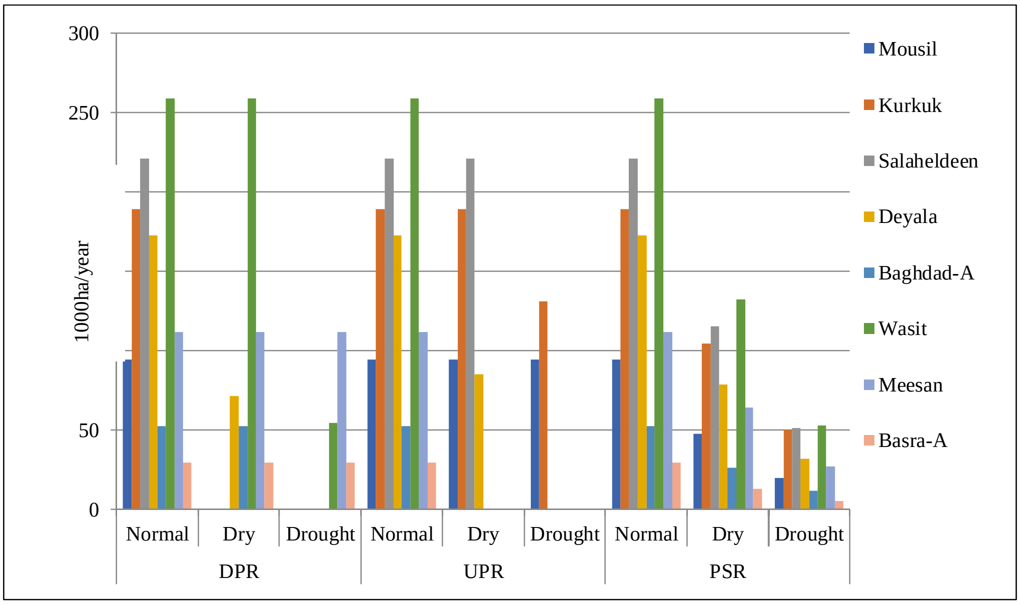


Figure 4-4. Model results of the irrigated land in production by province, crop, shortage sharing arrangement-water supply scenario, Tigris River Basin, Iraq, 2013 (1000ha/year).

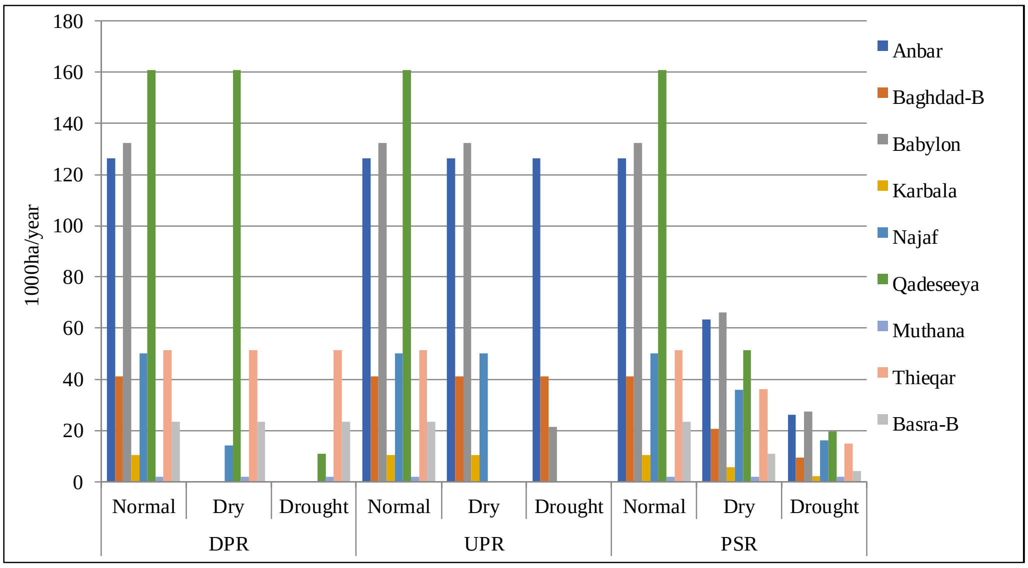


Figure 4-5. Model results of the irrigated land in production by province, crop, shortage sharing arrangement-water supply scenario, Euphrates River Basin, Iraq, 2013 (1000ha/year).

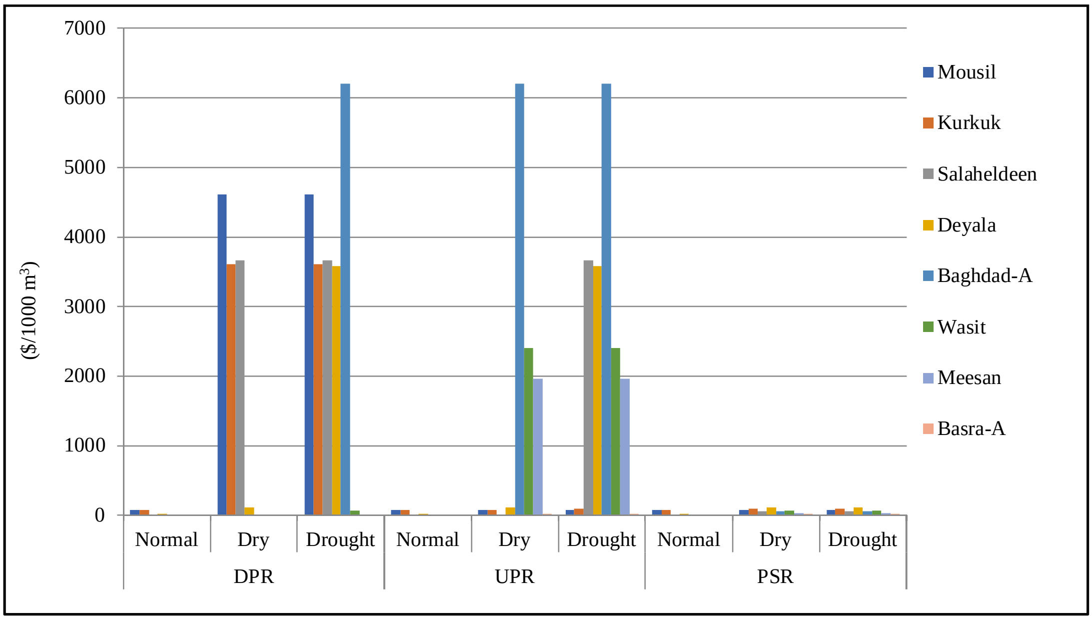


Figure 4-6. Model results of the shadow price of water by province, crop, shortage arrangement, and water supply scenario, Tigris River Basin, Iraq, 2013 ($/1000m^3).

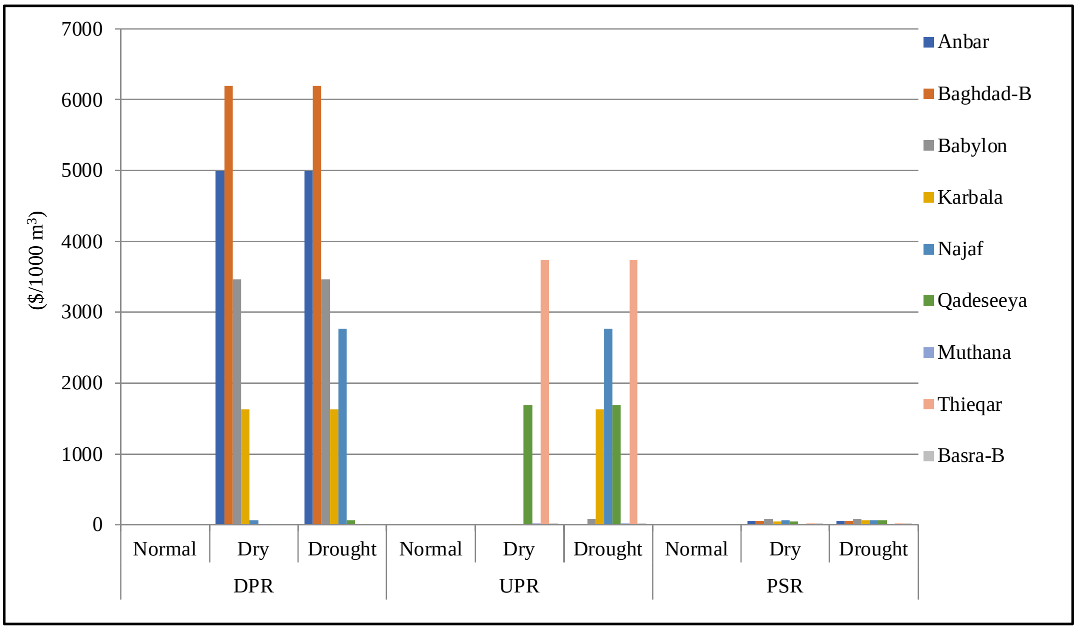


Figure 4-7. Model results of the shadow price of water by province, crop, shortage arrangement, and water supply scenario, Euphrates River Basin, Iraq, 2013 ($/1000m^3).

This study indicates that the process of adopting Tigris and Euphrates Rivers as individual basins results in the reduction of shadow prices under the drought condition while it provides similar values under the dry water availability condition. Under drought conditions, treating the Tigris and Euphrates Rivers as individual basins as performed in this study, provides greater flexibility leading to reduce shadow prices.

1.9. Potential for Implementation of PSR in Iraq

Due to the frequent droughts and water shortages which have occurred in Iraq in the last decade, the potentiality of using PSR is clear based on the model results. Iraq has the majority of the required hydraulic infrastructure to control and manage its water resources, thus implementation of further advanced and integrated water management strategies are feasible. Iraq has its own water legislation and laws which control and manage its water sources to allocate them for users. For instance, the 2008 law of the Ministry of Water Resources (MoWR) No. 50 provides the MoWR the ability to plan and invest Iraq’s water resources for greater optimal usage. Furthermore, MoWR has the right to identify and develop water users to obtain optimal usage. Thus, MoWR has the full right to control the available water sources and to adopt an optimal water allocation strategy which assures the best investment of water resources.

Technically, the adoption of PSR needs advanced control technology to estimate water demand and to control water release to consumers to ensure water sharing for each one of the partnered provinces. The development of the recent water management system on both the administrative and technical aspects is one of the mandatory requirements not only for water conservation, but it is also required to satisfy the optimum distribution to maximize the potential benefits and to minimize water losses. Key investments are needed to satisfy that goal, which means more financial support for the water sector in Iraq to manage future's water issues. The elimination of ISIS and such other depleting factors will be necessary before key investments such as advanced control technology can be made.

Iraq is one of the richest water countries in the region; its people have the entrenched belief that the water supply will never be exhausted. Unfortunately, the water situation is becoming worse due to well-known reasons such as climate change, rapid population growth, dams in Turkey on the Tigris and the Euphrates Rivers, water pollution, water resource mismanagement, and the lack of awareness. Thus, adopting PSR as an alternative strategy, to allocate water among partnered provinces, will create wide debate and objections, especially among the riparian provinces. This may occur because of the belief that the river's upstream provinces have the right to obtain their full water share regardless of the downstream impacts. While on the agricultural farmlands level, the farmers who are on the upstream sections of the water distribution canals may object to the adoption of PSR if adopting such a strategy is optional. However, if it is mandatory, farmers may be persuaded that PSR assures fair distribution among them and their canal's tail farmers. Public acceptance of PSR requires a change in the public's perception of the facts regarding recent water shortages, which can be performed by the adoption of capacity building programs to educate the public. Capacity building programs should not only be limited to farmers, they should also include representatives of Iraqi provinces, local councils, and water related decision makers. The federal government currently has the right to apply laws which can appropriate the optimum distribution of water resources among riparian governorates. Due to Iraq having most of the required scientists and practical ingredients, in addition to the water infrastructure, Iraq has the appropriate environment to apply PSR by adopting developed approaches and technologies to handle the potential future shortages. An effective example of applied PSR water management strategy among riparian consumers is the one adopted allocating the Colorado River water resources in the United States. The management strategy allocates water among eight of the US states, in addition to Mexico, to handle the shortages proportionally (USBR, 2012). Thus, from this example we can determine that PSR in Iraq would benefit the agricultural sector.

1.10. Summary and Conclusions

A continuous challenge in water governance is studied through the recent research by examining how various water appropriation systems may affect profitability at both the farm and basin levels. Three water allocation systems are compared to measure their impacts on farm income under each of three different water supply scenarios. An optimization model was applied using general algebraic modeling system (GAMS) to maximize the net benefit of land production by computing the optimum farm income depending on the producing of different types of crops.

It is obvious that the proportional sharing of the shortage water allocation rule is the most economically feasible solution to be adopted because it provides the opportunity to all provinces to share water proportionally in order to share profits accordingly. It allowed for a 32% and 75% increase in the total farm income for the Tigris River under dry and drought supply conditions, respectively, as compared to UPR. In the same way, it allowed for 47% and 83.5% increase in the total farm income for the Euphrates River under dry and drought supply conditions, respectively, as compared to UPR. Even when severe droughts occurred, this water allocation rule secured some water for all provinces in a proportional sharing. It assures some water for all provinces in comparison to all for some, and none for others. On the other hand, the net income losses under the proportional allocation rule are less influenced by drought when compared with other types of water allocation rules.

For the case of dry water availability, farm net income is maintained at 62.25% and 72.32% of the maximum income, for the Tigris and Euphrates respectively, under PSR. Farm net income dropped from US$1.11 billion and US$0.72 billion in the normal supply scenario to US$0.69 billion and US$0.52 billion for Tigris and Euphrates River respectively, maintaining an impressive 62.25% and 72.32% of base income levels over all provinces when shortages are shared proportionally.

For the case of drought water availability considering the proportional shortage sharing rule, farm net income falls from US$1.11 billion and US$0.72 billion in the normal supply conditions to US$0.42 billion and US$0.34 billion annually for both of the rivers respectively. The flexibility in the use of the proportional sharing rule grants the incentive to all provinces to eliminate their lowest value crops from production, while continuing to cultivate the highest valued specialty crops that require specialized soils, management, and market access. With respect to the percent of lands in production, the same behavior is followed by provinces with cultivated farms. The conclusion of eliminating the low-income value crops and cultivating crops with a higher value is also described by Salman, et al. (2014).

Finally, according to the computed shadow prices, water allocation rules, that are closest to economically efficient, produce shadow prices which are close to equal among provinces. This similarity of shadow prices is revealed clearly for the system of proportional sharing of shortages for both dry and severe water shortage conditions.

The results from this study are intended to provide guidance for decision makers in Iraq for potential future conditions where water supplies are reduced and demonstrate how it is feasible to adopt the PSR as an alternative and efficient water allocation rule due to its flexibility of providing fair water resource allocation in drought seasons. Adopting such an optimization modelling approach can assist decision makers, ensuring that decisions will benefit the economy by taking the advantage of the followed global experiences to control water allocations in Iraq especially with concern to diminished water supplies. There will be a need to utilize the modelling tools with changing constraints as water supplies, crops, and agricultural lands transform in the future.

CHAPTER 5 A RECLAIMED WASTEWATER ALLOCATION OPTIMIZATION MODEL FOR AGRICULTURAL IRRIGATION

5.1. Introduction

Climate change, pollution, civil conflicts, political instability, and a high rate of population growth all contribute to water shortages in Iraq which are predicted to increase in the future. Due to the importance of agriculture in Iraq which forms more than 75 percent of total demand, a sustainable agricultural water allocation scheme is necessary to find practical and applicable water conservation measures that helps mitigate the impact of potential droughts and water shortages. An agricultural irrigation reclaimed wastewater allocation optimization model was developed to optimally allocate crops and reclaimed wastewater (RW) on cultivated farmlands in order to maximize the net benefit.

The optimization model was formulated using mixed-integer nonlinear programming (MINLP) solved by the branch and reduce optimization navigator (BARON) in the general algebraic mathematical solver (GAMS). The model maximizes the net farm income to determine the cultivated crop assigned to each farmland using three types of reclaimed wastewater (RW); tertiary treated wastewater; secondary treated wastewater; and primary treated wastewater. Constraints in the optimization model include: (1) reclaimed wastewater availability constraints and (2) irrigated farmlands constraints. The optimization model has been applied to 7045 hectares of farms located in the Alrustumia district to the south east of Baghdad, Iraq with 5.5×10^5 m^3/d of treated wastewater. The use of tertiary treated wastewater provided the greatest net benefit under most scenarios evaluated while primary effluent provided the lowest net benefit as only low value crops could be cultivated.

Water scarcity in Iraq is between truth and fiction. For thousands of years, Iraq has been known as Mesopotamia with abundant water from the Tigris and the Euphrates Rivers available for the Fertile Crescent. The Tigris and the Euphrates Rivers have experienced a significant reduction in their annual transboundary water flow since 1999. In 1998, the International Water Management Institute (IWMI) addressed Iraq as one of the critical water scarce countries (Seckler 1998). Most of Iraq’s water is transboundary water. The Euphrates River gets 88 percent of its water from Turkey and 9 percent from Syria. While 56 percent of the Tigris River water is from Turkey and 12 percent is from Iran. Those two rivers also experience significant water demands before they cross the Iraqi border.

More severe shortages in surface water resources are projected as flow in Iraq’s rivers decreases and demands increase in Turkey, Syria, Iran, and Iraq along with the uncertainty associated with climate change. A water shortage in Iraq is an expected consequence due to the 50% or greater decline in transboundary water supplies from Turkey and Iran (FAO, 2016), as shown in Figure 5-1.

Water shortage forms a significant concern in Iraq that should be evaluated precisely. The previously mentioned factors have left negative impacts on the infrastructures, economy, and renewable water resources. Iraq experiences both water quality and quantity problems that are not being addressed by water resources management and thereby adversely affect the agricultural sector especially in the southern provinces downstream Baghdad. For instance, due to the water shortage in 2007-2009, there was a severe decline in agricultural productivity along the Tigris and Euphrates river basins (Shean 2008). Crop production was reduced to one half of its usual rate of production and many farmers abandoned their agricultural lands. Consequently, agricultural crops, meats and many other related products are currently imported into Iraq resulting in elevated costs to consumers (UNDP, 2009). It has been projected that water scarcity may influence the relationship among Iraq's southern provinces due to their total reliance on agriculture.

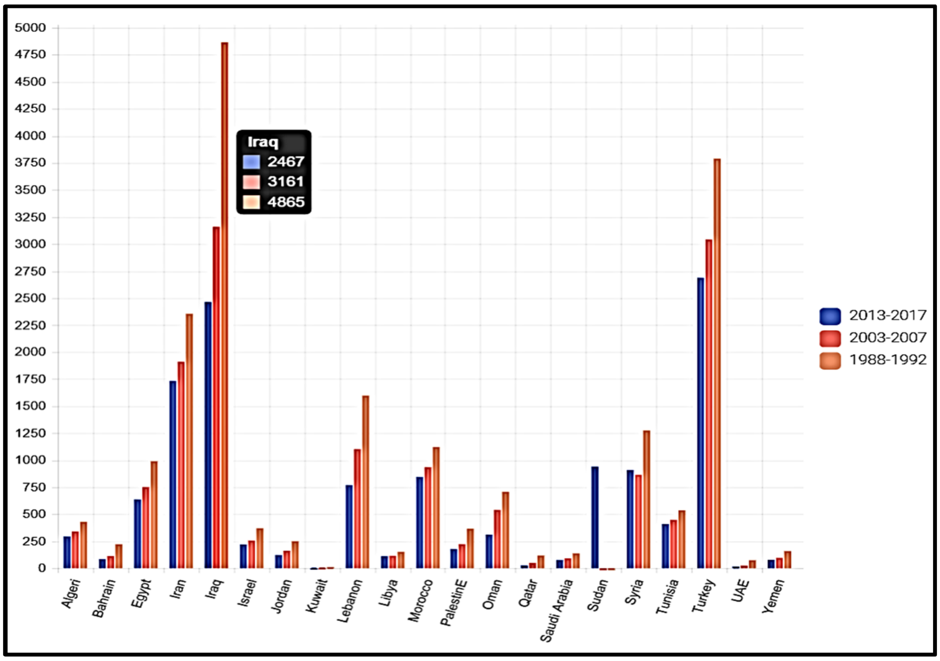


Figure 5-1. Annual renewable water resources in MENA countries (m^3/capita/yr) (FAO, 2016).

Agricultural irrigation is the major consumptive use of water in many regions around the world and there is significant interest to optimize water use to maximize its economic outcomes and avoid water scarcity (Moradi-Jalal et al. 2007). In Iraq, agricultural water demand forms more than 75 percent of total demand (MoWR, 2015).

Rapid and comprehensive solutions must be considered to provide sustainable and reliable water resources which also meet quality standards. An integrated agricultural irrigation water management system requires a robust infrastructure to assure sustainability to avoid recent and future expected water shortages in Iraq. This may be achieved fairly allocating water for agricultural among farmlands. Many integrated water allocation systems have been practiced in many regions around the world which have an obvious role in balancing agricultural demand with other demands with positive economic and societal impacts. Thus, it is of great significance to take land use as a critical factor along with water allocation in river basins.

The practice of wastewater reuse in many regions around the world has bloomed due to the lack of fresh water sources. Reusing wastewater has gained an increased acceptance among people around the world as a reliable alternative and sustainable source of water for many applications. A high demand for agriculture along with proximity to wastewater treatment plants make reuse of wastewater for agriculture logical in many cases. Other uses for treated wastewater include environmental restoration, toilet flushing, cars washes, cooling towers and various industrial uses are practiced today in almost all arid and semi-arid regions all over the world. Consequently, wastewater treatment technologies have been developed accordingly to satisfy the quality standards required for different uses. Therefore, the traditional impression and concerns about wastewater reuse due to its low quality has changed. Wastewater reuse has been practiced in many applications and has even been integrated into drinking water supplies through groundwater recharge and indirect potable reuse.

In the Middle East, there has been a significant increase in reuse of wastewater as an alternative and reliable water resource. However, Iraq has not implemented planned wastewater reuse even though Baghdad produces more than 1.0×10^6 m^3 of treated wastewater that is discharged to the Tigris River after secondary treatment. Iraq's renewable water supply comes primarily from the Tigris and the Euphrates Rivers, groundwater sources, rainwater harvesting, and limited desalination plants. Over the recent history, Iraq has been suffering a lot from political instability which has reflected negatively on its economic stability.

About 8 million hectares is the agricultural area in Iraq, which forms 70% of the total cultivated area. About 40% - 50% of this area is irrigable and is located along river basins while the remainder is rain feed and is in the northeastern plains and mountain valleys (Al-Ansari 2013). The irrigated area is mainly supplied by water from the main rivers, and only 7% of the area is supplied by ground water (World Bank, 2006). Due to fallow practices and the unstable political situation, only 3 to 5 million hectares are now cultivated annually. In 1993, the estimated cultivated land were only 3.73 million hectares of which 3.46 and 0.27 million hectares consisted of annual and permanent crops respectively (Al-Ansari et al. 2012). In 2014, the World Bank estimated the cultivated farmland area in Iraq is about 9.27×10^6 hectares (World Bank, 2017).

Although Iraq's agricultural water demand is predicted to decrease by 55 percent by 2030 if irrigation is modernized, agriculture will still be the largest user of water going into the future (Evans and Sadler 2008). At the same time, the demands for municipal, industrial and tourism are predicted to increase, leading to an increase of the total water demand in the future. Wastewater reuse should be a primary player to mitigate water shortages for irrigation purposes. This is particularly true since agricultural lands south of Baghdad that have been deserted could be reliably irrigated with wastewater.

5.2. Literature Review

Developing an integrated reclaimed wastewater allocation optimization model for agricultural irrigation purpose is crucial in water scarce regions to mitigate water shortages, to control water wastage, and to maximize agricultural net benefit. This topic has led many researchers to focus on the development of agricultural irrigation models that consider economics, regional water resource allocation, and/or to test new water appropriation rules and policies (Benetti 2008). A Computer Aided and Management Simulation of Irrigation Systems model (CAMSIS) to simulate farm income was developed (Burton 1994b). The model applied different water allocation rules and polices under water shortage or drought scenarios in East Africa. Paul, et al. (2000) developed a multi-level approach to solve problems related to seasonal and intra-seasonal agricultural irrigation water allocation in a semiarid region of Punjab, India. The approach considers the competition of the crops for irrigation water and farmed area. Dynamic programming approaches were developed to optimize irrigation scheduling (Rao et al. 1988, Naadimuthu et al. 1999). An agricultural water allocation system (SAWAS) model was developed by Salman, et al. (2001) to be used as a decision-making tool for planners of agricultural production on both local and regional levels adopting an agricultural water allocation system model using linear programming. The model is based on the analysis of inter-seasonal irrigation water allocation and their effects on the net farm income. An agricultural irrigation water allocation optimization model was presented by Shangguan, et al. (2002) using multiple water resources allocation. The model shows that the obstacles in using dynamic programming with multiple dimensions could be overcome. Brown, et al. (2002) developed an AQUARIUS model to evaluate temporal and spatial allocation of flows among competing water uses in a river. A stochastic dynamic programming optimization model was developed by Ghahraman and Sepaskhah (2004) which optimizes the agricultural water allocation to a predetermined multiple cropping pattern in Iran. Álvarez, et al. (2004) described the MOPECO model for irrigation water management in a semi-arid area of Spain and drew a conclusion that the irrigation depth for maximum benefits is lower than that necessary to obtain maximum production.

Georgiou and Papamichail (2008) developed a non-linear programming optimization model to maximize the total farm income using an integrated soil water balance. The model was applied on the Havrias River in Northern Greece to determine the optimal reservoir releases, the water allocation for irrigation purposes, and the optimal cropping pattern for irrigated farmlands. An irrigation scheduling problem was evaluated using a Genetic Algorithm (GA) (Haq et al. 2008). Solving the same problem, the powerful role of using a GA was demonstrated in comparison to the use of an integer programing. A methodology was proposed by Sadegh, et al. (2010) based on Shapely games to be used in water resources allocation among different users for the Karoon River basin in Iran with the goal of developing an equity standard to increase the total net benefit of the system. Simultaneous irrigation scheduling was evaluated using a GA comparing the stream tube model with the time block model (Haq and Anwar 2010). A stochastic nonlinear programming model with multiple objectives was used by You, et al. (2011) to aid in multi-objective decision-making considering the Heihe River as a case study. An Inexact Rough-interval Fuzzy Linear Programming IRFLP model was constructed by Lu, et al. (2011) to make a comparison between the IRFLP model and an interval-valued linear programming model for water allocation to provide more information for decision makers. The IRFLP was capable of handling the interaction between dual intervals of highly uncertain parameters, as well as their joint impact on the system.

Fotakis and Sidiropoulos (2012) developed a multi-objective evolutionary algorithm to simultaneously solve the problem of land use planning and resource allocation which performs optimization on a cellular automaton domain, applying suitable transition rules on the individual neighborhoods. Xuan, et al. (2012) developed an optimal water allocation model based on water resources security assessment.

Fang, et al. (2013) presented a comprehensive solution for water resources allocation in the Wuwei Basin and they concluded that the model can effectively balance the benefits among all regions and sections. Ward, et al. (2013) provided a framework for identifying, designing, and implementing water allocation rules for food security in the developing world’s irrigated areas. Kang and Park (2014) developed a combined simulation-optimization model for simulating reservoir operations by adopting the Shuffled Complex Evolution Method. They concluded that the model is useful for assessing reservoirs’ irrigation water supply capacities when establishing operation plans and providing feasible alternatives for new operation rules. Salman, et al. (2014) presented a methodology to maximize the net farm income in Iraq by producing different types of crops. Four water right (allocation) systems and three water supply scenarios were considered. The various conditions were compared in terms of their capacity to minimize losses in net farm water-related income. Fotakis and Sidiropoulos (2014) integrated land-use and water allocation planning to maximize economic benefit, while minimizing water extraction and transportation cost under ecological constraints. A review of agricultural irrigation water allocation optimization models using different programming for optimizing irrigation management was done by Singh, (2014).

Vaghefi, et al. (2015) linked the soil and water assessment tool (SWAT) to the generic river basin management decision support system (MODSIM) for water allocation in the Karkheh river basin. Their analyses indicate that it is possible to use changes in cropping patterns as an effective tool to adapt to the negative impacts of climate change. The optimization of water resources allocation in a typical river basin was proposed by Wang, et al. (2015) using multi-objective programming. It was applied on the water deficient of Heihe River Basin by embedding land use as a constraint on water allocation. Their results demonstrate that the optimal program can predicate the actual situation of water allocation in the future. A multi-objective water allocation optimization model to maximize crop yields was developed by Lalehzari, et al. (2015).

Oxley, et al. (2016) developed a model that defines the net economic benefits calculated in terms of both use and non-use values and sustainability in terms of the risks to water supplies and riverine ecological, environmental and hydrological integrity. An optimization model maximizing the sustainable net economic benefit over a long-term planning horizon was applied by Oxley and Mays (2016) to the Prescott Active

Management Area. The model evaluates four scenarios to test the validity of the developed model and to provide examples of its potential application.

Nguyen, et al. (2016A) developed an improved agricultural crop and water allocation model using ant colony optimization (ACO) by enabling the dynamic decision variable option (DDVO). The model maximizes the net benefit from allocating a fixed total volume of water to cultivated selected kinds of crops. Davijani, et al. (2016) developed a water allocation optimization model using the particle swarm optimization (PSO) algorithm maximizes the number of the generated jobs in both agricultural and industrial sectors in the central desert region of Iran. The model gives water policy makers an indication about the optimal solution in case of certain policies to be adopted. Nguyen, et al. (2016B) introduced a general optimization framework by optimizing crop and water allocation using ant colony optimization and dynamic decision variable option (ACO - DDVO). The model reduced search space size and increasing the computational efficiency of evolutionary algorithm application. Abdulbaki, et al. (2017) developed an integer linear programming decision support model to optimally allocate water resources by minimizing water treatment, allocation, and environmental costs. The model has the flexibility to consider multiple water sources (seawater, surface water, groundwater and reclaimed wastewater) that allocated to different consumers (irrigation, potable, and industrial) with different quality requirements.

A genetic simulation-optimization framework for optimal irrigation and fertilizer scheduling was developed by Nguyen, et al. (2017) using ant colony optimization (ACO). Anwar and Haq (2013) presented a GA to solve sequential irrigation scheduling problems.

Four different consecutive irrigation scenarios were adopted using four GA models allocating irrigation water to 94 users.

An agricultural irrigation water allocation optimization model using a GA was developed to be applied on the Sri Ram Sagar project in India (Raju and Kumar 2004). Kumar, et al. (2006) presented a water allocation optimization model for agricultural irrigation using GA. The model maximizes the net benefit from the use of certain types of crops following cropping pattern in Karnataka, India. Sadati, et al. (2014) presented a nonlinear programming optimization model using a GA to maximize farm income by determining optimal reservoirs release and optimal cropping pattern.

Aljanabi, et al. (2018) developed a nonlinear water allocation optimization model to maximize the net farm income from the cultivation of different types of crops irrigated by the Tigris and the Euphrates Rivers in Iraq. The model examines how profitability, at both the farm and basin levels, is affected by various water appropriation systems.

5.3. The Mathematical Model

5.3.1. *Objective Function*

The objective function of this model is to maximize the total net benefit by comparing the results of using three different qualities of reclaimed wastewater, RW type A, type B, and type C, to irrigate farms (x=1 to X) cultivating crops (c=1 to C). The model also assumes a proportional water sharing rule (PSR) to allocate RW among observed farmlands proportionally by considering the ratio of the observed farm's area in the entire system to the total farms' observed area. Each RW_i irrigates certain types of crops depending on the quality requirements of that crop. The model computes the net benefit

Nb_i ($) from the use of RW_i by allowing only one crop c to be cultivated in each farm x using the PSR. The objective function maximizes net benefits is:

$$\text{Max. } Nb_i = \sum_x Nb_{i,x} \qquad i = 1, \ldots, I \tag{5-1}$$

Where $Nb_{i,x}$ represents the computed net benefit ($) for each farm x cultivating crop c using RW type i. In general, the net benefit is usually computed by subtracting the cost of production from the selling price.

The total cost $CP_{i,x,c}$ ($) to produce crop c cultivated in farm x using RW type i is the sum of crop's production cost plus the cost of the assigned RW type i to cultivate crop c, which is:

$$CP_{i,x,c} = \sum_c (FA_{i,x,c}\, CCost_c + RW_{i,x,c}\, RWC_i) \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \tag{5-2}$$

Where

$FA_{i,x,c}$ is the assigned area (ha) of farm x in hectare to cultivate crop c using RW type i

$CCost_c$ is crop c production cost ($/ha); $RW_{i,x,c}$ is the assigned RW (m^3) of type i to irrigate farm x cultivating crop c

RWC_i is the cost ($\$/m^3$) of RW type i

A crop's production cost is based on updated data including the cost of seeds, land preparation cost, labor cost, and fertilizer cost. A crop's yield is computed by considering the yield of each crop Y_c (ton/ha) multiplied by the selling price of that crop P_c ($/ton) times the cultivated area $FA_{i,x,c}$ (ha), which is as follows:

$$Re_{i,x,c} = Y_c\, P_c\, FA_{i,x,c} \tag{5-3}$$

By re-arranging equations (5-2) and (5-3), the net benefit, $Nb_{i,x,c}$, of cultivating crop c in farm x using RW type i is:

$$Nb_{i,x,c} = (Y_c\,P_c\,FA_{i,x,c}) - \left(FA_{i,x,c}\,CCost_c\right) - \left(RW_{i,x,c}\,RWC_i\right) \qquad c=1, \ldots, C,$$

$$x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}4)$$

For any RW type i, assuming that each crop c has a coefficient of connectivity, $CRw_{i,c}$, according to the crop's quality standards and salinity tolerance. Then, equation (4) can be re-written as:

$$Nb_{i,x,c} = \qquad c=1, \ldots, C \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}5)$$

In this water allocation system, for any farm x, there is only one crop c that can be cultivated using RW type i. By considering the connectivity coefficient $M_{i,x,c}$ of crop c to farm x and RW type i as a binary variable, the net benefit $Nb_{i,x,c}$ from the cultivation of crop c in farm x using RW type i can be re-written as:

$$Nb_{i,x,c} = \qquad c=1, \ldots, C, \; x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}6)$$

To compute the net benefit $Nb_{i,x}$ of cultivating farm x using RW type i , the total net benefit equation is written as:

$$Nb_{i,x} = \sum_c \Big[\left(Y_c\,P_c\,FA_{i,x,c}\,M_{i,x,c}\,CRw_{i,c}\right) - \big[\left(RW_{i,x,c}\,RWC_i\,M_{i,x,c}\,CRw_{i,c}\right) +$$

$$\left(FA_{i,x,c}\,CCost_c\,M_{i,x,c}\,CRw_{i,c}\right)\big]\Big] \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}7)$$

5.3.2. *Decision Variables*

The optimization model allocates farmland areas and RW to cultivate different types of crops, so the decision variables are:

a) $FA_{i,x,c}$ assigned area of farm x to cultivate crop c using RW type i (ha)

b) $RW_{i,x,c}$ assigned RW of type i to farm x farming crop c (m^3)

c) $M_{i,x,c}$ connectivity of RW type i to farm x and crop c (binary variable)

5.3.3. *Constraints*

Whenever a given amount of RW from a certain type i is allocated to irrigate crop c, it is important to optimally be allocated by considering the season of growth water requirements to satisfy a crop's real water consumption. Adopting this strategy will produce a reasonable irrigation scheme which reflects positively on crop yield and on the conservation of the consumed water to irrigate more lands. The available amount of RW type i should optimally be allocated to irrigate part or all of the observed farmlands considering the following constraints:

5.3.3.1. RW availability constraints

Three RW availabilities related to their quality are considered. The availability of RW type A (i=1) from tertiary treated wastewater; availability of RW type B (i=2) from secondary treated wastewater; and availability of RW type C (i=3) from primary treated wastewater.

1) Consumed RW type i

The sum of the total use of RW ($RW_{i,x,c}$) of a certain type i must be equal or less than the total amount of RW (QRw_i) of the same type i released from the same WWTP in the same cultivation season.

$$\sum_x \sum_c RW_{i,x,c} \leq QRw_i \qquad i = 1, \ldots, I \qquad (5\text{-}8)$$

Where QRw_i is the total amount of assigned RW type i (m^3).

2) Consumed RW by type i and farm x

The sum of the assigned RW type i to irrigate farms (x=1 to X) cultivating crops (c=1 to C) must be equal or less than the hydraulic loading $\mathrm{Lw_c}$ (m^3/ha) of each crop c times the cultivated area $\mathrm{FA_{i,x,c}}$ (ha), which is:

$$\sum_c \mathrm{RW_{i,x,c}} = \sum_c \mathrm{Lw_c}\, \mathrm{FA_{i,x,c}} \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}9)$$

By applying RW-farm-crop connectivity coefficient ($\mathrm{M_{i,x,c}}$) and RW-crop coefficient ($\mathrm{CRw_{i,c}}$) on both sides of equation (5-9), it yields to:

$$\sum_c \mathrm{RW_{i,x,c}}\, \mathrm{M_{i,x,c}}\, \mathrm{CRw_{i,c}} = \sum_c \mathrm{Lw_c}\, \mathrm{FA_{i,x,c}}\, \mathrm{M_{i,x,c}}\, \mathrm{CRw_{i,c}} \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}10)$$

The hydraulic loading $\mathrm{Lw_c}$ (m^3/ha) considering each cultivated crop c is computed as:

$$\mathrm{Lw_c} = \frac{\mathrm{NR_c}}{\frac{\mathrm{E_c}}{100}}\left(\frac{10000}{1000}\right) = \mathrm{ETc_{k,j}} \times \left(1 + \frac{\mathrm{LR_c}}{100}\right) \times \left(\frac{100}{\mathrm{E_c}}\right)\left(\frac{10000}{1000}\right) \qquad c=1, \ldots, C \qquad (5\text{-}11)$$

Where

$\mathrm{ETc_c}$ is the evapotranspiration requirements (mm/season) to cultivate crop c

$\mathrm{E_c}$ is the irrigation efficiency to cultivate crop c

$\mathrm{NR_c}$ is the net irrigation requirements (mm/season) to cultivate crop c

$\mathrm{LR_c}$ is the leaching requirement to cultivate crop c

(10000/1000) is a conversion factor to m^3/ha

3) Consumed RW from source i by farm x irrigating crop c

$$\sum_c \mathrm{RW_{i,x,c}} = \mathrm{RLn_{i,x}}\, \mathrm{QRw_i} \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}12)$$

By applying RW-farm-crop connectivity coefficient ($M_{i,x,c}$) and RW-crop coefficient ($CRw_{i,c}$) on both sides of equation (5-12), it yields to:

$$\sum_c RW_{i,x,c}\, M_{i,x,c}\, CRw_{i,c} = RLn_{i,x}\, QRw_i \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}13)$$

where $RLn_{i,x}$ is the ratio of the observed area of farm x (Ln_x) to the total observed area in the system (TLn_i), defined as:

$$RLn_{i,x} = Ln_x / TLn_i \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}14)$$

Equation (13) assures the proportionality in water allocation among farmlands considering the ratio of their areas in the system.

5.3.3.2. Irrigated farmlands constraints

1) Irrigated area of farm x

The area in production $FA_{i,x,c}$ (ha) of farm x cultivating crop c using RW type i must be equal or less than the observed area Ln_x (ha) of farm x, as:

$$\sum_c FA_{i,x,c} \leq Ln_x \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}15)$$

By applying RW-crop coefficient ($CRw_{I,c}$) in equation (5-5 to 5-15), it yields to:

$$\sum_c FA_{i,x,c}\, CRw_{i,c} \leq Ln_x \qquad x=1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (5\text{-}16)$$

2) Total irrigated farmlands area per RW type i

The sum of the total irrigated area in the system must be equal or less than the area of the total observed farmlands, which is:

$$\sum_x \sum_c FA_{i,x,c} \leq \sum_x Ln_x \qquad i = 1, \ldots, I \qquad (5\text{-}17)$$

3) Maximum farmlands area to be cultivated by crop c

In order not to exceed the upper limit of the area cultivated using crop c to avoid the domination of the most economic crop on others and to force the model to select as many crops as it could to satisfy the variety in production, the following constraint is considered:

$$\sum_x FA_{i,x,c} \leq FARWC_{i,c} \qquad i = 1, \ldots, I \text{ and } c = 1, \ldots, C \qquad (5\text{-}18)$$

where $FARWC_{i,c}$ is the maximum area (ha) allowed to be cultivated with crop c using RW type i.

5.3.3.3. Connectivity of RW type i to farm x and crop c constraint

This binary variable coefficient $M_{i,x,c}$ assures that only one crop c is to be cultivated in farm x irrigated using RW type i. So, the sum of $M_{i,x,c}$, for the same farm x irrigated from the same RW type i, must be equal to 1.0, as in the following

$$\sum_i \sum_x M_{i,x,c} = 1 \qquad c = 1, \ldots, C \qquad (5\text{-}19)$$

The GAMS code used to solve the previously described MINLP reclaimed water allocation optimization model is described in Appendix B of this dissertation.

5.4. Baghdad as a Case Study

The location of the wastewater treatment plant (RW source), locations and types of the potential RW uses, water quality consideration, the need for additional treatment, and the cost of competing for alternative sources are the main local conditions which influence the economics of RW reuse. Producing RW suitable for agricultural irrigation is less costly than to provide a higher level of treatment, such as nutrient removal, necessary for discharge into ecological sensitive surface waters (Metcalf et al. 2007).

Reuse of wastewater in Baghdad is logical as the wastewater treatment plants are located in the southern portion of Baghdad and there is land available for irrigation south of Baghdad. Furthermore, the RW can be delivered by gravity using mostly existing irrigation canals. Two wastewater treatment plants can treat a total of 1.0×10^6 m^3/d by secondary treatment. The Alrustumia wastewater treatment can treat 5.5×10^5 m^3/d in a three different treatment trains and this is the plant that is being considered for production of RW in this study. The total land available for irrigation that is being considered is 7,045 ha divided into 106 individual farms. Each farm is based on land ownership and are therefore of different land areas.

5.5. Data for Optimization Model

Crop water requirements ETc were adopted from Salman, et al. (2014) and updated from the Strategy for Water and Land Resources in Iraq (MoWR, 2015). Crop production costs in US dollar per hectare ($/ha), presented in Table 5-1, based on data secured from the Iraqi Ministry of Agriculture. The production cost includes soil fertility, weather, and water availability and quality which fluctuated across Iraq. The yield rates of different types of crops in Iraq are provided in Table 5-1.

There is a variety of 33 strategic crops which can be cultivated in Iraq (MoWR, 2015) which can be irrigated using RW as an alternative source considering its quality, crop type, and the irrigation method. Those crops can be divided into human edible and inedible crops in addition to the industrial crops. So, the optimization maximizes the net benefit of 14 crops of the 33 strategic crops to measure their profitability. Table 5-1 shows the strategic crops which are adopted in the optimization model.

Table 5-1. Crop production costs exclusive of water costs ($ US per ha).

Crop	Cotton	Wheat	Maize	Potato	Tomato	Barley	Clover	Cucumber	Alfalfa	Onion	Eggplant	Sunflower	Sesame	Okra
Cost ($/ha)	1200	820	900	750	1300	720	320	1350	500	580	1250	550	475	1230

In order to force the model not exceed a maximum area for each crop, maximum allowed areas were assigned to each crop for different types of RW (Table 5-2).

Table 5-2. Maximum allowed areas (ha) to be cultivated by certain types of crops irrigated using three RW qualities.

	Cotton	Wheat	Maize	Potato	Tomato	Barley	Clover	Cucumber	Alfalfa	Onion	Eggplant	Sunflower	Sesame	Okra
RW$_A$	1500	1500	1500	1250	750	1500	1000	300	1000	300	250	1000	500	200
RW$_B$	1500	2000	1500	0	750	1500	1000	300	1000	0	250	250	500	200
RW$_C$	1500	0	0	0	0	1500	2000	0	2000	0	0	1500	0	0

5.6. Results and Discussion

The results of the solution of the 0/1 mixed integer nonlinear programming (MINLP) optimization model are presented in Figures 5-2 to 5-4. The branch and reduce optimization navigator (BARON) solver (Tawarmalani & Shahinidis, 2005) in the general algebraic modeling system (GAMS) (GAMS, 2017) was implemented. The net farm income was predicted by maximizing the net benefit by allocating RW type A, type B, and Type C to irrigate a variety of 14 strategic crops to be cultivated in 106 farms of 7,045 (ha) in Baghdad under the use of proportional water sharing rule (PSR).

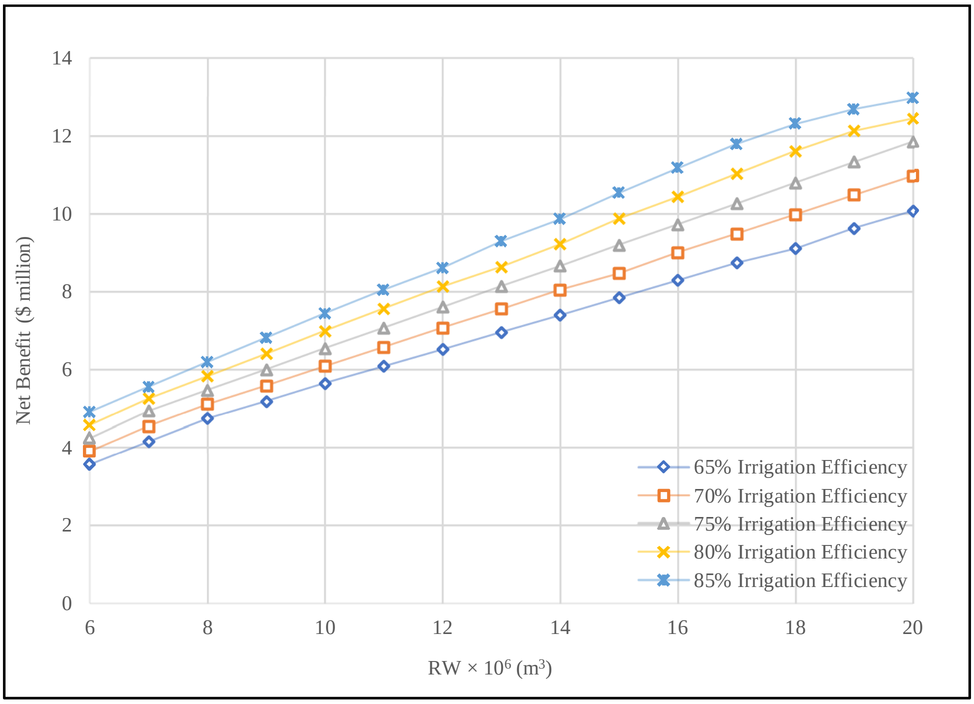


Figure 5-2. Computed net benefit ($) comparing irrigation efficiencies using RW type A.

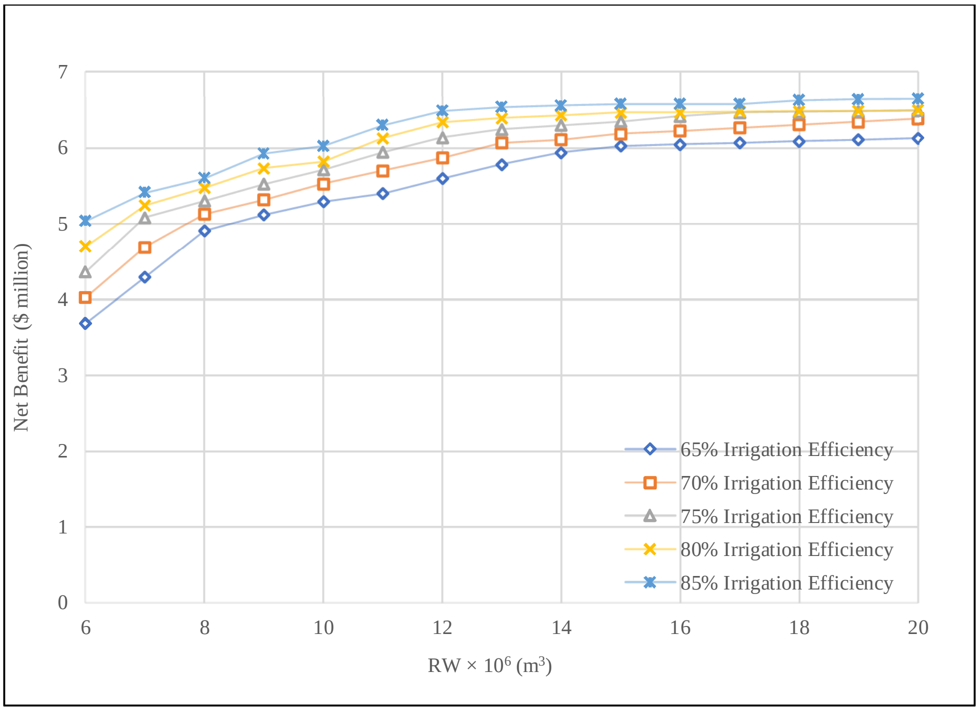


Figure 5-3. Computed net benefit ($) comparing irrigation efficiencies using RW type B.

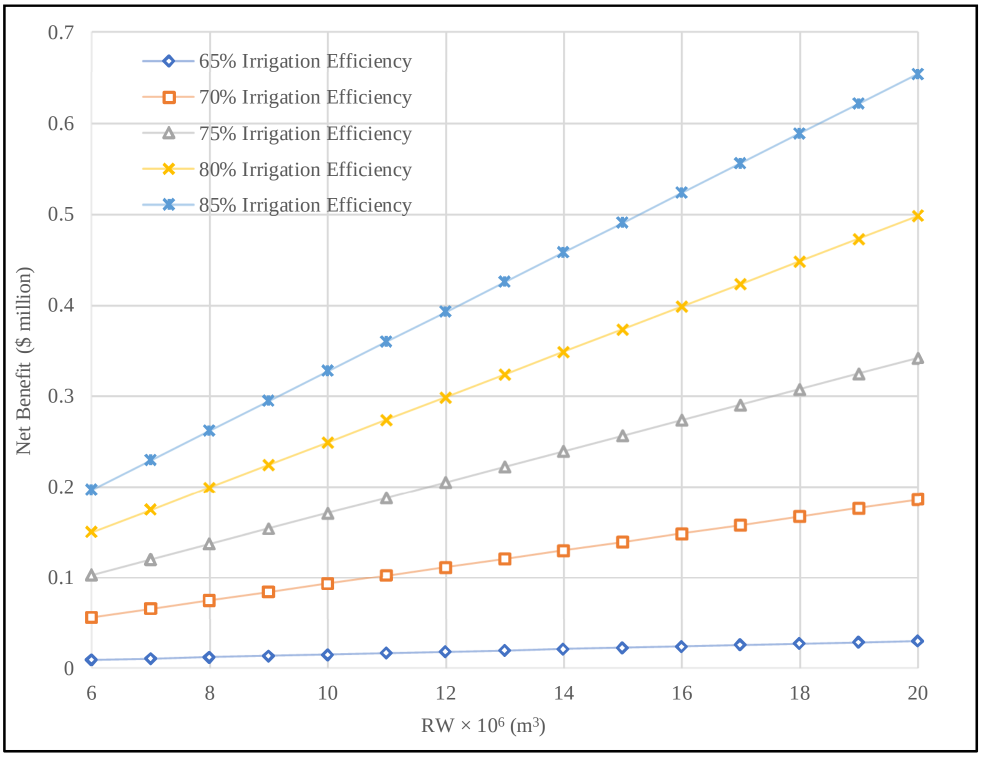


Figure 5-4. Computed net benefit ($) comparing irrigation efficiencies using RW type C.

The predicted net benefit results of using RW type A, type B, and type C respectively, under five different irrigation efficiencies are illustrated in Figures 5-2 to 5-4 respectively. It is obvious that the increase of irrigation efficiency reflects positively on the net income due to the decrease in the RW requirement which gives the opportunity to cultivate larger areas selecting the highest value crops.

As illustrated in Figure 5-2, the optimization model results show a consistent net benefit increase corresponding with the increase of irrigation efficiencies for most assumed quantities of RW type A because the crops which are selected by the model are close to each other in their net benefit. Using 6×10^6 m^3 of RW type A and 65% irrigation efficiency, the predicted net benefit was $\$3.56\times10^6$ irrigating 556 ha of tomato. Using 20×10^6 m^3 of

RW type A and 85% irrigation efficiency, there was 1248 ha of potato, 747 ha of tomato, and 202 ha of onion with a predicted net benefit of about \$13.0×10^6.

RW type B shows a slightly different behavior (Figure 5-3) because it has a lower range of crops to be cultivated which reduces the maximized net benefit. The crops which were computed by the model to be irrigated using RW type B above the level of 12 ×10^6 m^3 have a lower marginal net benefit than okra, eggplant, and cucumber. Using 6×10^6 m^3 of RW type B and 65% irrigation efficiency predicted a net benefit of \$3.68×10^6 irrigating 556 ha of tomato. In comparison, there were 748 ha of tomato, 248 ha of eggplant, 200 ha of okra, 298 ha of cucumber, and 530 ha of clover resulting in a \$6.64×10^6 net benefit.

RW type C maintained the same trend with the maximized net benefit (Figure 5-4) because it can only irrigate a small selection of crops. Using 6×10^6 m^3 of RW type C and 65% irrigation efficiency, the model irrigated 556 ha of clover. When the model used 20×10^6 m^3 of RW type C with 85% irrigation efficiency, only 1,551 ha of clover was irrigated. This is because clover is one of the highest water demand crops among the selected list of crops (Table 5-2) but it has the highest net benefit per hectare.

In this model, RW type A can select from all the 14 strategic crops, RW type B and RW type C are capable of selecting 12 and 5 crops, respectively, of the 14 selected crops shown in Table 2. On the other hand, each crop has its own evapotranspiration, production cost, yield, and selling price, which causes the variation in the predicted farms economic benefits. For instance, the predicted benefit of using 14×10^6 m^3 of RW type A adopting 80% irrigation efficiency is about \$9.23×10^6 cultivating a total of 1,499 ha farming 736 ha of tomato and 763 ha of potato. The model predicted the net benefit of using the same amount of RW type B under the same irrigation efficiency is about $\$6.43\times10^6$ cultivating 750 ha of tomatoes, 285 ha of cucumber, 250 ha of eggplant, 177 ha of okra, and 30 ha of clover. While the net benefit is predicted to be $\$3.49\times10^6$ using RW type C irrigating 1,022 ha of clover. It is obvious that the use of RW type C provide the lowest net benefit due to the limited number of crops which are irrigated, due to quality standards, and the low marginal benefit of those crops in comparison to RW types A and B.

The results show that RW type A provides the highest net benefit of RW to be used since it allowed for irrigation of crops with the highest net benefit. The capability of RW type A to irrigate all the suggested crops, due its high quality, has promoted the model the opportunity of selecting the high value crops for cultivation. A similar phenomenon is observed under the use of RW type B where it has fewer options for crops to be cultivated as compared to RW type A.

Figures 5-5 to 5-9 compare the net benefit from the use of RW types A, B and C under 65%, 70%, 75%, 80% and 85% irrigation efficiencies respectively. Figure 5-5 shows that using 6×10^6 to 8.5×10^6 m^3 availability of reclaimed wastewater, RW type B performs better than RW types A and C. This domination of RW type B over RW type A is because the model selected the same type of crop, which is tomato, to be cultivated in same areas using RW type A and B, but the difference occurred because the cost of RW type B is less than RW type A. The domination of RW type B on RW type A decreases with the increase in RW volumes, as the model allocates water on farmlands to cultivate the most economic crop (Figures 5-8 and 5-9). For instance, under a certain amount of RW availability, the model selected tomatoes and then potatoes to be cultivated using RW type A, while tomato, cucumber, eggplant and okra were selected to be irrigated by RW type B.

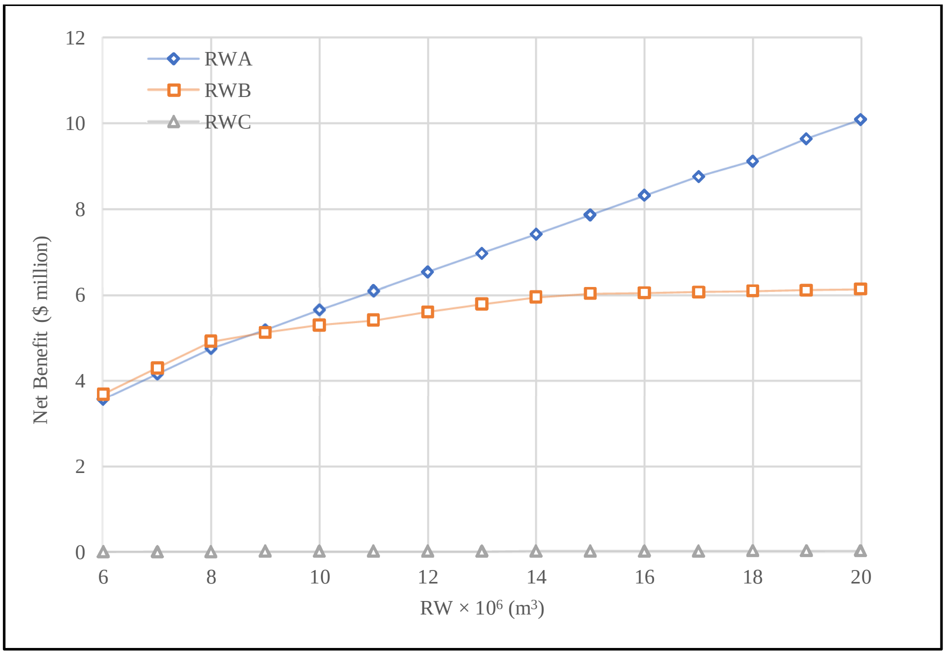


Figure 5-5. Computed net benefit ($) adopting 65% irrigation efficiency.

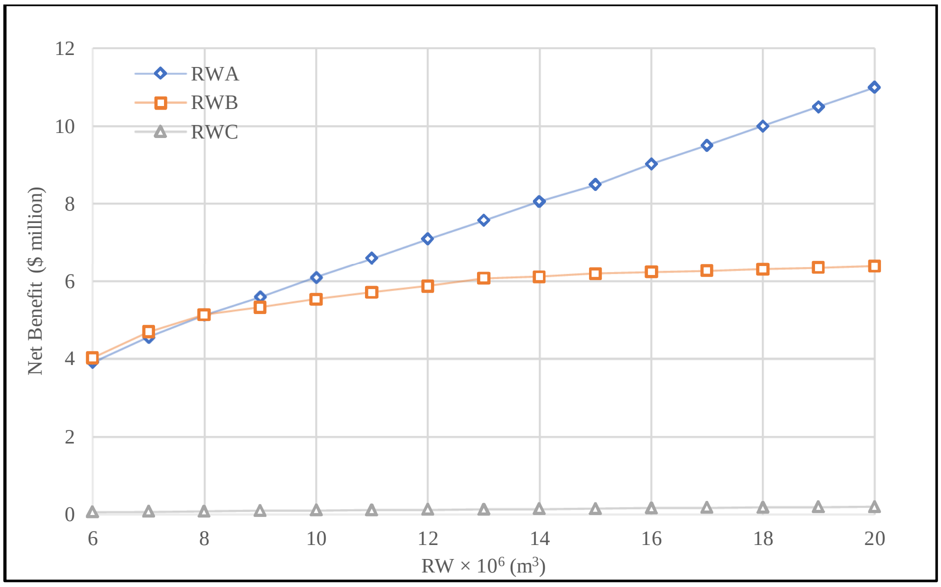


Figure 5-6. Computed net benefit ($) adopting 70% irrigation efficiency.

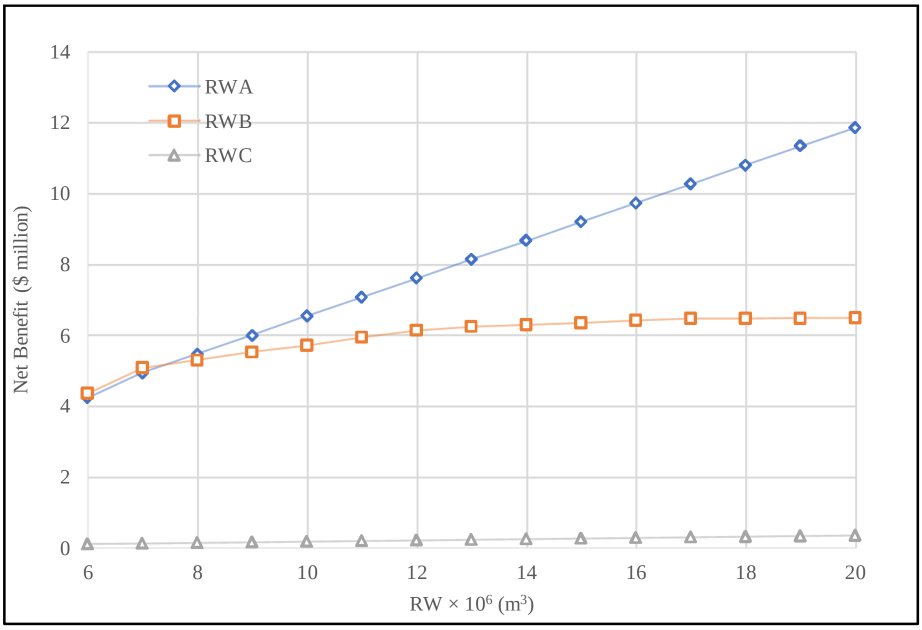


Figure 5-7. Computed net benefit ($) adopting 75% irrigation efficiency.

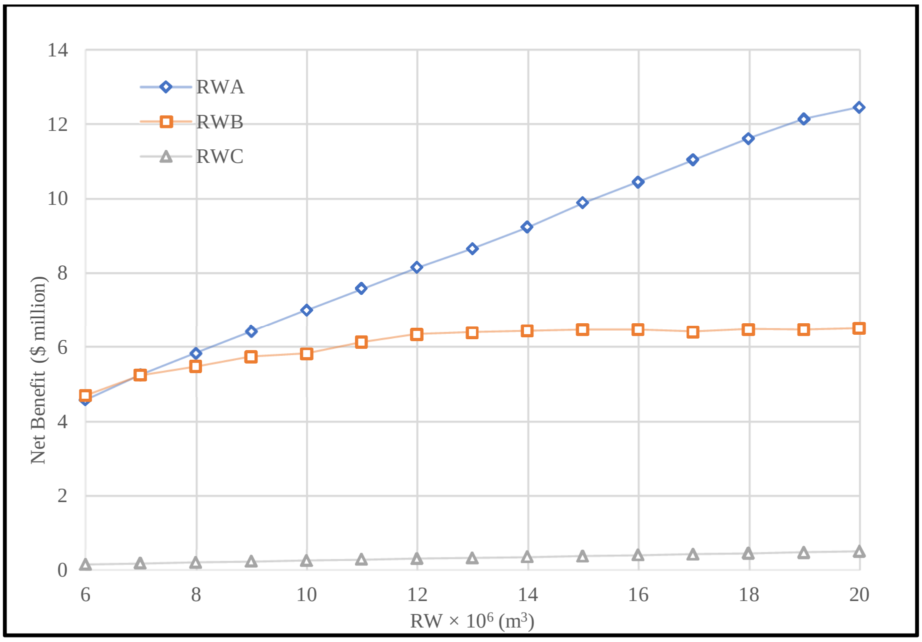


Figure 5-8. Computed net benefit ($) adopting 80% irrigation efficiency.

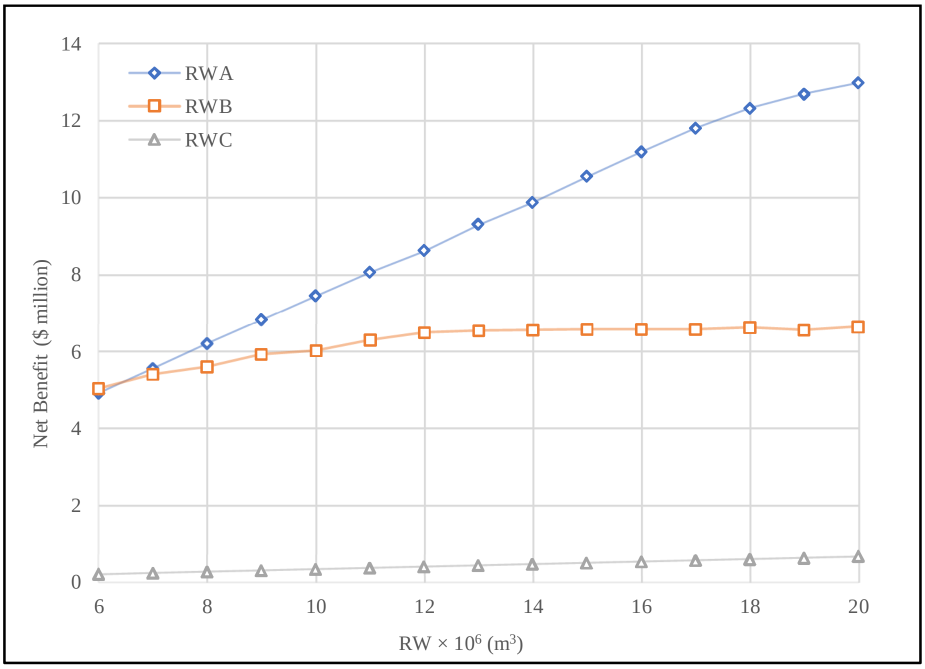


Figure 5-9. Computed net benefit ($) adopting 85% irrigation efficiency.

5.7. Summary

The positive results from comparing the use of different RW qualities under different irrigation efficiencies helps in the evaluation of the Alrustumia WWTP, and others in Iraq, to show how it is efficient to invest in treated wastewater for agricultural irrigation instead of deposition to the environment. On the other hand, this study helps the decision makers take advantage of promoting wastewater treatment efficiencies of the recently rebuilt WWTPs by considering tertiary treatment for the existing and potential new WWTPs to employ their reclaimed wastewater for agricultural irrigation or other practices. In addition, the available wide range of selected crops considering RW type A offered the model a flexibility in selecting the highest economic crops to satisfy the maximum limit of the allowable cultivated area by each crop.

CHAPTER 6 OPTIMIZATION MODEL FOR AGRICULTURAL RECLAIMED WATER ALLOCATION USING MIXED-INTEGER NONLINEAR PROGRAMMING

6.1. Introduction

Reclaimed water (RW) is a reliable alternative water supply for agricultural irrigation which is the predominant consumer of water in Iraq. A mixed-integer nonlinear programming reclaimed water allocation optimization model was developed to maximize the net benefit generated from the cultivation of different types of crops, comparing the use of reclaimed water type A (tertiary treated), and reclaimed water type B (secondary treated).

The model was solved using Algorithms for coNTinuous/ Integer Global Optimization of Nonlinear Equations (ANTIGONE) optimizer in the general algebraic modeling system (GAMS). A total of 84 agricultural farms located on 5300 hectares to the south of Baghdad, Iraq were available for irrigation with reclaimed water. Analysis considered varying quantities of available reclaimed water and different irrigation efficiencies (45-85%). The net benefits from using lower quantities of reclaimed water were similar for both types of reclaimed water as the highest net benefit crop was cultivated on 384 ha. As the quantities of water increased, the amount of cultivated land increased and the net benefit per hectare decreased as the model required the cultivation of more crops with lower economic value. Irrigation with reclaimed water has potential to increase agricultural and economic activity adjacent to Baghdad.

Mesopotamia, present day Iraq, has been proud of its abundance of water in the Tigris and the Euphrates Rivers which has historically enabled the development of a vibrant civilization and economy. Recently, Iraq survived a serious threat from ISIS on its water supplies. The Tigris and the Euphrates Rivers originate in the eastern and the southeastern part of Turkey, respectively, flowing downstream through Syria to Iraq. The Tigris River also includes many tributaries originating in Iran and Iraq. For many reasons, Iran and Turkey have been reducing and/or eliminating Iraq's water resources to gain the economic benefits associated with increased water resources. Turkey recently completed most of the hydraulic structures for the Southeastern Anatolia Project (GAP) which includes 22 dams and 19 hydropower facilities that impact flows in both the Tigris and Euphrates Rivers. Iran has fully or partially cut or diverted water from more than 45 small rivers and tributaries that were supplying the eastern part of Iraqi rivers and marshlands with water, which forms about 12 % of Iraq's transboundary water supplies.

These water supply issues have resulted in a deterioration in both water quantity and quality in Iraq. The gravest impact is on the agricultural sector south of Baghdad along the Tigris and the Euphrates Rivers resulting in enormous economic losses. During water shortage crises there is a need for management to distribute existing water supplies for the greatest societal benefit while satisfying the water demands in various sectors. It is a common practice for arid and semiarid regions (Metcalf et al. 2007), such as in Iraq, to use reclaimed water for agricultural irrigation and thereby create an alternative water resource without importing water.

Use of reclaimed water (RW), as an alternative source, has emerged as common practice to meet the demands of increasing populations in many arid and semi-arid regions around the world. Many water demands are currently met with reclaimed water as the main or alternative water resource depending on quality and availability. Industrial, municipal, agricultural and recreational uses are the most common applications for reclaimed water use. In Iraq, there is a daily flow of more than 6.0 MCM (million cubic meters) of treated, untreated, or partially treated wastewater that is currently discharged directly to the environment. For instance, in Baghdad, there is secondary treated wastewater of more than 1.0 MCM that is discharged to the Tigris River. These large quantities of treated wastewater contribute to the pollution of the receiving waters. The treated wastewater could be a significant source of water for a variety of applications. This paper explores the opportunity to use these large flows of treated wastewater for agriculture in lands directly south of Baghdad where the majority of treated wastewater could be delivered by gravity.

The goal of this research project is the development of an optimization model for the allocation of reclaimed water for agriculture. Specifically, the objective function maximizes the net benefit generated from the cultivation of different types of crops using reclaimed water. The mixed integer nonlinear optimization programming problem (MINLP) was solved using Algorithms for coNTinuous / Integer Global Optimization of Nonlinear Equations (ANTIGONE) optimizer (Misener and Floudas 2014) in the general algebraic modeling system (GAMS) (GAMS Development Corporation n.d.). Different solvers including Branch-And-Reduced Optimization Navigator (BARON) (Tawarmalani and Sahinidis 2005), Basic Open-source Nonlinear Mixed Integer (BONMIN) (Bonami and Lee 2007), Convex Over and Under ENvelopes for Nonlinear Estimation (COUENNE) (Belotti, 2013), and DIscrete and Continuous OPTimizer (DICOPT) (Grossmann et al. 2002), were also investigated for solving the MINLP problem.

In this MINLP water allocation optimization model, reclaimed water was allocated proportionally on farms where each farm's water share was equal to the ratio of its agricultural area to the total agricultural area of all farms. Two reclaimed water qualities were compared, reclaimed water type A (tertiary treated) and reclaimed water type B (secondary treated). Different RW availabilities and irrigation efficiencies were evaluated to determine the sensitivity of the results on these parameters. Reclaimed water availability and the cultivated area form the main constraints in this model in addition to the farm-crop connectivity, farm-RW connectivity, and minimum net benefit constraints.

6.2. Literature Review

With the development of wastewater treatment technologies, the quality of the reclaimed water has been enhanced to allow for a wide variety of applications. For decades, many countries have been practicing reclaimed water use in common applications such as in agricultural irrigation, cooling towers, recreational uses, etc. Iraq is a country that faces a severe shortage in its water supplies due to the previously mentioned reasons and it is crucial to determine how to mitigate the impacts of water shortages by implementing water conservation measures and developing alternative water supplies. Reclaimed water use is one of these alternative resources which has not been developed in Iraq even though there is excellent potential for water reuse if developed properly. Implementing integrated and sustainable water management strategies in arid regions helps to mitigate water stresses and has led to the development of a variety of water allocation optimization models.

An assessment of water appropriations in Iraq was previously modeled by developing a non-linear water allocation optimization programming model that maximizes the agricultural net benefit from the cultivation of different kinds of crops in the Tigris and Euphrates Rivers basin (Salman et al. 2014). The maximization of the net farm income in Iraq producing different types of crops presented by the development of a water allocation optimization model (Aljanabi et al. 2018a). Three water allocation strategies and three water supply scenarios were considered. The various conditions were compared in terms of their capacity to minimize losses in net farm water-related income. The proportional sharing water allocation strategy consistently resulted in the greatest agricultural net benefit under the different water supply scenarios which included drought conditions. Proportional sharing ensures that water is allocated to all provinces that use the Tigris and Euphrates rivers as water sources for irrigation. A mixed integer non-linear programming water allocation optimization model solved using the branch and reduce optimization navigator (BARON) was developed by Aljanabi, et al. (2018b) for water allocation in Iraq. The model compares the maximized net benefit from the use of reclaimed water type A, reclaimed water type B, and reclaimed water type C for cultivating different types of crops on 106 agricultural farms. Crop selection considered applicable water quality standards and different irrigation efficiencies. The model showed the excellency of reclaimed water type A on the other two types of reclaimed water.

Water allocation models have been used to address a variety of different water supply needs around the world. Different water allocation rules were tested by the development of a Computer Aided and Management Simulation of Irrigation Systems model (CAMSIS) which simulates farm income for an irrigation scheme in East Africa (Burton 1994b). A decision-making tool for agricultural production sector was developed by the development of a linear water allocation optimization model considering the local and the regional levels by analyzing the inter-seasonal irrigation water allocation and their effects on the net farm income applied to the Jordan Valley in Jordan (Salman et al. 2001). An optimization model maximizing the sustainable net economic benefit over a long-term planning horizon was applied to the Prescott Active Management Area in Arizona, USA (Oxley and Mays 2016). The validity of the developed model that incorporated unique measures of sustainability was evaluated by testing four different scenarios. Chong, et al. (2018) developed and applied linear programming water allocation optimization model based on water resources sustainability. The model tends to improve the water use benefits in the Zhangjiakou Region of northern China in 2020. The eco-environmental and socio-economic benefits were considered to meet the domestic and environmental water demand and to assure sustainable water use at the regional scale.

Different agricultural irrigation water allocation optimization models maximizing the net benefit were developed using a variety of allocation scenarios. Singh (2014) reviewed agricultural irrigation water allocation optimization models which were implemented using different programming for optimizing irrigation management. Multiple agricultural water resources allocation was presented using a dynamic programming optimization model applied on Yangling, China (Shangguan et al. 2002). Multiple cropping patterns were tested using a stochastic dynamic programming water allocation optimization model developed for the Ardak area, Iran (Ghahraman and Sepaskhah 2004). The total farm income on the Havrias River in Northern Greece was maximized using an integrated soil water balance non-linear programming optimization model (Georgiou and

Papamichail 2008). The Shapely games methodology was proposed (Sadegh et al. 2010) to be used in Karoon River basin water resources allocation with the goal of developing an equity standard to increase the total net benefit of the system.

Models have been developed with the specific goal of aiding water supply decision makers who face complex decisions that require consideration of many different factors. Bekri, et al. (2015) developed an optimal water allocation optimization model using fuzzy-boundary-interval linear programming methodology. The model adopted the uncertainty of the random water inflows through the simultaneous generation of stochastic equal-probability hydrologic scenarios using various inflow scenarios applied on Alfeios River Basin (Greece) to enhance the attitude of decision makers. Lu, et al. (2011) constructed an Inexact Rough-interval Fuzzy Linear Programming IRFLP and the IRFLP model was compared with an interval-valued linear programming model for water allocation to provide more information for decision-makers. The results proved the IRFLP can handle the interaction between dual intervals of highly uncertain parameters, as well as their joint impact on the system. An integer linear programming decision support model was developed to optimally allocate water resources by minimizing water treatment, allocation, and environmental costs (Abdulbaki et al. 2017). The model has the flexibility of including multiple water sources to be allocated for different uses constrained by different quality requirements.

Multi-objective programming has been developed to analyze water allocation where more than one objective must be considered. A fuzzy Multi-Objective Particle Swarm Optimization (f-MOPSO) was presented by Rezaei, et al. (2017) to improve conjunctive surface water and groundwater management in Najafabad Plain, Iran. The model used a weighting method to define the partial performance of each objective's potential solution to reach an optimal solution on the Pareto-front. A multi-objective programming was applied to analyze the water deficit of the Heihe River Basin by optimizing the allocation of water resources and embedding land uses as constraints (Wang et al. 2015). Results demonstrate that the optimal program can predict the actual situation of water allocation in the future. A multi-objective evolutionary algorithm to simultaneously solve the problem of land use planning and resource allocation was developed (Fotakis and Sidiropoulos 2012). The model performs optimization on a cellular automaton domain, applying suitable transition rules on the individual neighborhoods. Lalehzari, et al. (2015) developed a multi-objective water allocation optimization model to maximize crop yields applied on farmlands located at Baghmalek plain, Iran. A multi-objective cropping pattern optimization model was developed by Yousefi, et al. (2018) to maximize the benefits and minimize the potential negative quantitative-qualitative impacts of agricultural reclaimed water and groundwater uses. The developed model maximizes the benefits from crop patterns, reducing nitrogen leaching, and improves the rate of groundwater recharge in the Varamin irrigation network in Iran.

Other models have included a comprehensive list of objectives regarding water allocation in water-constrained regions considering the water/food/energy nexus. Fang, et al. (2013) concluded it is possible to effectively balance the benefits among all regions and sections in the Wuwei Basin using a comprehensive optimization model for water resources allocation. Maximizing the economic benefits considering integrated land-use and water allocation planning while minimizing water extraction and transportation cost under ecological constraints was also developed (Fotakis and Sidiropoulos 2014). A framework for identifying, designing, and implementing water allocation rules for food security in the developing world's irrigated areas was developed considering Afghanistan as a case study (Ward et al. 2013).

Ant colony optimization is another modeling technique that can be applied for the allocation of water for agricultural purposes. An agricultural crop and water allocation model using ant colony optimization (ACO) was developed by enabling the dynamic decision variable option (DDVO) (Nguyen et al. 2016b). The model maximizes the net benefit from allocating a fixed total volume of water to cultivate selected kinds of crops on an irrigation district located in Loxton, South Australia. While, a general optimization framework was introduced by Nguyen, et al. (2016a), optimizing crop and water allocation using ant colony optimization and dynamic decision variable option (ACO -DDVO) which reduces search space size and increase the computational efficiency of evolutionary algorithm application. Another ant colony optimization (ACO) program was used under genetic simulation-optimization framework to optimize irrigation and fertilizer scheduling applied for corn production using different water availabilities with various rates of fertilizer application in eastern Colorado, USA (Nguyen et al. 2017).

The particle swarm optimization (PSO) algorithm was used in a water allocation optimization model (Davijani et al. 2016). The number of the generated jobs in both agricultural and industrial sectors in the central desert region of Iran were maximized to provide an indication about the optimal solution which should be followed in case of certain policies.

Genetic algorithms (GA) provide another useful optimization technique for water allocation models. For the Sri Ram Sagar project in India, a genetic algorithm agricultural irrigation water allocation optimization model was developed (Raju and Kumar 2004). The water allocation optimization model for agricultural irrigation was presented which maximizes the net benefit from the use of certain types of crops and cropping patterns in Karnataka, India (Nagesh Kumar et al. 2006). By optimizing reservoir releases and cropping patterns, Sadati, et al. (2014) presented a nonlinear programming optimization model using a GA to maximize farm income around Doroudzan Dam in the South-West of Iran. Anwar and Haq (2013) presented a sequential irrigation scheduling problem using GA models allocating water on 94 agricultural farms adopting four different consecutive irrigation scenarios.

6.3. Problem Definition and Objective

The Euphrates River has suffered severe water quality deterioration which has negative impacts on human health and the environment (Frenken, 2009 and Rahi and Halihan, 2010), so that the majority of the flow in the river south of Baghdad is considered unsuitable for irrigation. The strategy study for water and land resources in Iraq (Iraqi Ministry of Water Resources 2014) concluded that the suitability of Iraq’s surface water for irrigation decreases as it flows downstream. According to reports from the Iraqi Ministry of Environment for 2009, waterborne diseases are widespread due to bacteriological contamination as 16% of the water supply exceeded both Iraq’s National

Drinking Water Standards and World Health Organization Guidelines for Drinking Water (Iraqi Ministry of Water Resources 2014). Diverting the majority of wastewater flows through treatment plants allowing for the irrigation with reclaimed water will not only provide benefits to the agricultural economy, but also improve the water quality in the Euphrates River south of Baghdad.

In Iraq, extended droughts have previously exhausted significant amounts of water stored in reservoirs, such as the drought which occurred between 2007 and 2009, that strongly affected the agricultural sector. In June 2018, Iraq has been subjected to the most recent water shortage due to Turkey diverting flow to fill the reservoirs behind Ilisu dam. Fortunately, Turkey has been temporarily reduced the flow diversions in response to Iraq’s need to avoid water shortages. The filling of the reservoir has stopped due to the agreement between the two countries which will allow the reservoir to be filled while still allowing adequate water supplies to Iraq. The fact that Mesopotamia is currently experiencing water shortages needs to be recognized by the Iraqi people who are keeping inefficient practices and traditional habits of water use including the use of conventional flooding irrigation techniques. Furthermore, they should recognize that water is a source of national wealth which must be conserved and used sustainably to satisfy both recent and future demands.

One of the fastest and most efficient methods to develop alternative water sources is to adopt reclaimed water as a sustainable source of drought-resistant water to satisfy agricultural irrigation requirements and mitigate pressure on surface water resources. In Iraq, the main wastewater treatment plants were built on rivers and streams close to agricultural farmlands (Figure 6-1).

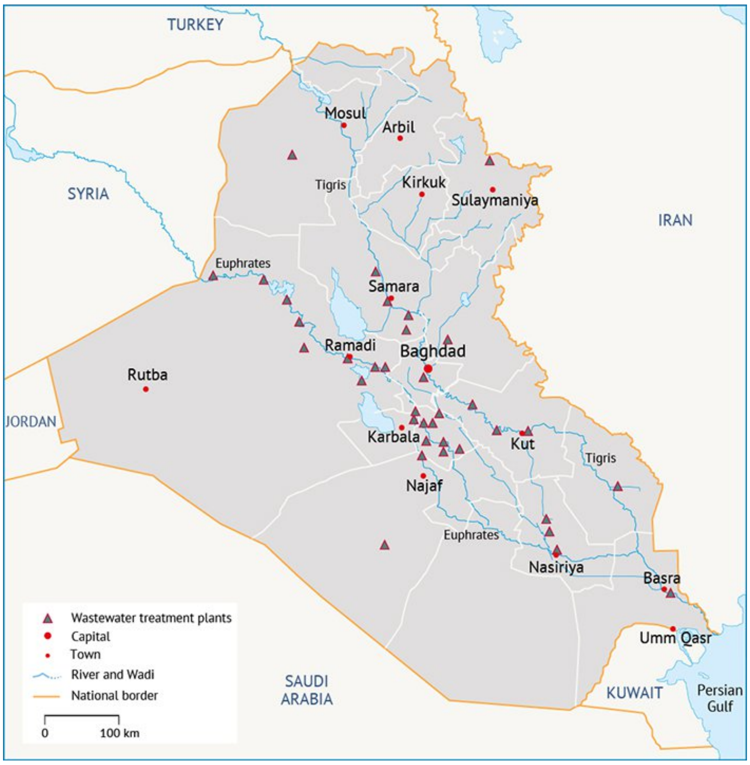


Figure 6-1. Locations of wastewater treatment plants in Iraq.

The Karkh and the Rustumia wastewater treatment plants treat received inflows from the western and the eastern regions of Baghdad, respectively. The Karkh WWTP's daily treatment capacity is 0.375 MCM (million cubic meters) and it is expected to reach 0.55 MCM with a proposed expansion. Currently, it produces only 0.2 MCM of treated wastewater, due to the need for extensive repairs and maintenance, which is discharged to the Tigris River south of Baghdad. The Rustumia WWTP treats a daily flow of 0.575 MCM of wastewater, which is discharged directly to the Diyala River a few kilometers before it confluences with the Tigris River to the south of Baghdad about 5 kilometers downstream of the Karkh WWTP. Downstream villages and cities mostly suffer from the deterioration of the water quality in the Tigris River. The implementation of tertiary treatment in these

WWTPs has the potential to enhance the reclaimed water quality and increases its potential uses.

6.4. Mathematical Formulation of the Optimization Model

6.4.1. *The Objective Function*

The objective function of this optimization model is to maximize the net benefit predicted from the cultivation of different types of crops using reclaimed water. The maximized net benefit $\mathrm{Nb_i}$ using reclaimed water ($\mathrm{RW_i}$) type i is:

$$\mathrm{Max.\,Nb_i} = \sum_{x} \mathrm{Nb_{i,x}} \qquad i = 1, \ldots, I \tag{6-1}$$

Where

$\mathrm{Nb_{i,x}}$ is the computed net benefit ($) for each farm x cultivating crop c using RW type i.

The total cost to produce crop c which is cultivated in farm x using RW type i is the sum of the crop's production cost plus the cost of the assigned RW type i to cultivate crop c. The production cost $\mathrm{CC_{i,x,c}}$ ($) of crop c in farm x using RW type i is written as:

$$\mathrm{CC_{i,x,c}} = \sum_{c}(\mathrm{FA_{i,x,c}\,CCost_c}) \qquad x= 1, \ldots, X \text{ and } i = 1, \ldots, I \tag{6-2}$$

While, the cost $\mathrm{CRW_{i,x,c}}$ ($) of RW type i used to irrigate farm x cultivating crop c is expressed as:

$$\mathrm{CRW_{i,x,c}} = \sum_{c}(\mathrm{RW_{i,x,c}\,RWC_i}) \qquad x= 1, \ldots, X \text{ and } i = 1, \ldots, I \tag{6-3}$$

By merging equations (6-2) and (6-3), the total production cost $\mathrm{CP_{i,x,c}}$ ($) of crop c in farm x using RW type i yields to:

$$\mathrm{CP}_{\mathrm{i,x,c}} = \sum_c (\mathrm{CC}_{\mathrm{i,x,c}} + \mathrm{CRW}_{\mathrm{i,x,c}}) \qquad x= 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (6\text{-}4)$$

Where

$\mathrm{FA}_{\mathrm{i,x,c}}$ is the assigned area of farm x in hectare (ha) to cultivate crop c using RW type i

$\mathrm{CCost}_{\mathrm{c}}$ is crop c production cost (\$/ha)

$\mathrm{RW}_{\mathrm{i,x,c}}$ is the assigned RW of type i to irrigate farm x cultivating crop c (m^3)

$\mathrm{RWC}_{\mathrm{i}}$ is the cost of RW type i (\$/m^3).

Farm's x revenue $\mathrm{Re}_{\mathrm{i,x,c}}$ is computed by considering the crop's c yield Y_{c} (ton/ha) multiplied by the selling price P_{c} (\$/ton) of that crop times the cultivated area $\mathrm{FA}_{\mathrm{i,x,c}}$ (ha) of farm x, which is as follows:

$$\mathrm{Re}_{\mathrm{i,x,c}} = \mathrm{Y}_{\mathrm{c}} \mathrm{P}_{\mathrm{c}}\, \mathrm{FA}_{\mathrm{i,x,c}} \qquad (6\text{-}5)$$

The net benefit $\mathrm{Nb}_{\mathrm{i,x,c}}$ generated from the cultivation of crop c in farm x using RW type i is:

$$\mathrm{Nb}_{\mathrm{i,x,c}} = \sum_c [\mathrm{Re}_{\mathrm{i,x,c}} - \mathrm{CP}_{\mathrm{i,x,c}}] \qquad x= 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (6\text{-}6)$$

Considering the quality of the RW used and the quality standard and salinity tolerance of each cultivated crop, a binary 0/1 coefficient of connectivity, $\mathrm{CRw}_{\mathrm{i,c}}$, is used allowing crop c to get its appropriate RW type i. So, equation (6-6) yields to:

$$\mathrm{Nb}_{\mathrm{i,x,c}} = \sum_c \left[[\mathrm{Re}_{\mathrm{i,x,c}} - \left(\mathrm{CC}_{\mathrm{i,x,c}} + \mathrm{CRW}_{\mathrm{i,x,c}}\right)]\, \mathrm{CRw}_{\mathrm{i,c}}\right] \qquad x= 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (6\text{-}7)$$

In this model, more than one crop is allowed to be cultivated in farm x, which can be satisfied using the 0/1 binary variable $\mathrm{M}_{\mathrm{x,c}}$. On the other hand, the model assumes that there is only RW type i is available to irrigate farm x which is implemented using the second binary variable $N_{x,i}$. By considering the two connectivity binary variables, $M_{x,c}$ and $N_{x,i}$, the net benefit $Nb_{i,x}$ equation can be re-arranged as:

$$Nb_{i,x,c}=\sum_{c}\left[\left[Re_{i,x,c}\, M_{x,c} - \left(CC_{i,x,c}\, M_{x,c} + CRW_{i,x,c}\, N_{x,i}\right)\right] CRw_{i,c}\right] \qquad x= 1, \ldots., X \text{ and } i = 1, \ldots., I \qquad (6\text{-}8)$$

6.4.2. *Decision variables*

Since the optimization model allocates farmland areas and RW to cultivate different types of crops, the decision variables are:

d) $FA_{i,x,c}$ assigned area of farm x to cultivate crop c using RW type i (ha)

e) $RW_{i,x,c}$ assigned RW of type i to farm x farming crop c (m^3)

f) $N_{x,i}$ defines the connectivity of RW type i to farm x (binary variable)

g) $M_{x,c}$ defines the connectivity of crop c to farm x (binary variable)

6.4.3. *Constraints*

6.4.3.1. Reclaimed water availability constraints

Two types of RW are considered in this optimization model: RW type A (i=1) from tertiary treated wastewater and RW type B (i=2) from secondary treated wastewater.

a. Total consumed RW type i

The sum of the total use of reclaimed water ($RW_{i,x,c}$) of a certain type i must be equal to or less than the total amount of RW (QRw_i) of the same type i released from the same WWTP in the same cultivation season.

$$\sum_{x} \sum_{c} \mathrm{RW}_{i,x,c} \leq \mathrm{QRw}_{i} \qquad i = 1, \ldots, I \qquad (6\text{-}9)$$

Where QRw_i represents the total amount of RW type i (m^3) discharged from the WWTP.

b. Consumed RW from source i by farm x irrigating crop c

$$\sum_{c} \mathrm{RW}_{i,x,c}\, \mathrm{N}_{x,i}\ \ \mathrm{CRw}_{i,c} \leq\ \mathrm{RLn}_{i,x}\, \mathrm{QRw}_{i} \qquad x= 1, \ldots, X \text{ and } i = 1, \ldots, I \quad (6\text{-}10)$$

Where

$\mathrm{RLn}_{i,x}$ is the ratio of the observed area of farm x (Ln_x) to the total observed area in the system (TLn_i), defined as

$$\mathrm{RLn}_{i,x} = \mathrm{Ln}_{x} / \mathrm{TLn}_{i} \qquad x= 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (6\text{-}11)$$

which assures that each farm x will get its share of water proportionally to the ratio of its observed area to the total observed farmlands' areas in the system.

c. Consumed RW by type i and farm x

The sum of the assigned RW type i to irrigate farms (x=1 to X) cultivating crops (c=1 to C) must be equal to or less than the hydraulic loading Lw_c (m^3/ha) of each crop c times the cultivated area $\mathrm{FA}_{i,x,c}$ (ha), which is:

$$\sum_{c} \mathrm{RW}_{i,x,c}\, \mathrm{N}_{x,i}\ \ \mathrm{CRw}_{i,c} =\ \sum_{c} \mathrm{Lw}_{c}\, \mathrm{FA}_{i,x,c}\, \mathrm{N}_{x,i}\, \mathrm{CRw}_{i,c} \qquad x= 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (6\text{-}12)$$

The hydraulic loading Lw_c (m^3/ha) considering each cultivated crop c is computed as:

$$\mathrm{Lw}_{c} = \frac{\mathrm{NR_c}}{\frac{\mathrm{IE_c}}{100}} \left(\frac{10000}{1000}\right) = \mathrm{ETc}_{c} \times \left(1 + \frac{\mathrm{LR_c}}{100}\right) \times \left(\frac{100}{\mathrm{IE_c}}\right) (10) \qquad c= 1, \ldots, C \qquad (6\text{-}13)$$

Where

ETc_c is the evapotranspiration requirements (mm/season) to cultivate crop c

IE_c is the irrigation efficiency to cultivate crop c

NR_c is the net irrigation requirements (mm/season) to cultivate crop k

LR_c is the leaching requirements to cultivate crop c

10 is a conversion factor to m^3/ha

6.4.3.2. Irrigated farmlands constraints

a. Irrigated area of farm x

The area (ha) in production $FA_{i,x,c}$ of farm x cultivating crop c using RW type i must be equal to or less than the observed area Ln_x (ha) of farm x, as:

$$\sum_c FA_{i,x,c}\ M_{x,c}\ N_{x,i}\ CRw_{i,c} \leq Ln_x \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (6\text{-}14)$$

b. Total irrigated farmland area per RW type i

The sum of the total irrigated area in the system must be equal to or less than the area of the total observed farmlands, which is:

$$\sum_x \sum_c FA_{i,x,c} \leq \sum_x Ln_x \qquad i = 1, \ldots, I \qquad (6\text{-}15)$$

c. Minimum farmlands area to be cultivated with crop c in farm x

This constraint assures the cultivated area with each crop c must be more than the minimum limit of hectares to satisfy the feasible investment, which represented as follows:

$$\sum_c FA_{i,x,c} \geq FAmin_{i,c} \qquad i = 1, \ldots, I \text{ and } c = 1, \ldots, C \qquad (6\text{-}16)$$

d. Maximum farmlands area to be cultivated by crop c

In order not to exceed the upper limit of the area cultivated using crop c, to avoid the domination of the most economic crop over all others, and to force the model to select as many crops as it could to satisfy the variety in production, the following constraint is considered:

$$\sum_x FA_{i,x,c} \leq FAmax_{i,c} \qquad i = 1, \ldots, I \text{ and } c = 1, \ldots, C \qquad (6\text{-}17)$$

Where

$FAmin_{i,c}$ is the minimum area (ha) to be cultivated by crop c using RW type i

$FAmax_{i,c}$ is the maximum area (ha) to be cultivated by crop c using RW type i

6.4.3.3. Connectivity Constraints

a. Connectivity of crop c to farm x constraint $M_{x,c}$

The $M_{x,c}$ binary variable assures at least one crop is cultivated at farm x. So, the sum of $M_{x,c}$ binary variable, for the same farm x, must be equal to or greater than 1. On the other hand, the model allows a maximum number of crops to be cultivated on each farm x. Up to four crops are allowed to be cultivated on the same farm. So, the farm-crop connectivity constraint is written as:

$$1.0 \leq \sum_c M_{x,c} \leq 4.0 \qquad x = 1, \ldots, X \qquad (6\text{-}18)$$

b. Connectivity of RW type i to farm x constraint $N_{x,i}$

The $N_{x,i}$ binary variable assures that farm x will be irrigated by one source of RW type i. So, the sum of $N_{x,i}$ binary variable, for the same RW type i, must be equal to 1.0, as in the following

$$\sum_{x} N_{x,i} = 1 \qquad i = 1, \ldots, I \qquad (6\text{-}19)$$

6.4.3.4. Minimum allowed net benefit by farm x constraint

To assure a suitable minimum margin of net benefit per farm x, the computed net benefit from cultivating crop/s must be at least 20 % of the total cultivation cost of the same farm, which can be satisfied as:

$$Nb_{i,x} \geq 1.20 \sum_{c} CP_{i,x,c} \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (6\text{-}20)$$

The GAMS code used to solve this MINLP agricultural reclaimed water allocation optimization model is described in Appendix C of this dissertation.

6.5. Baghdad as a Case Study

In Baghdad, there are two main wastewater treatment plants; the Karkh WWTP and the Rustumia WWTP which provide daily secondary treatment to a total of 1.0 MCM of wastewater that discharges to the Tigris River south of Baghdad. Several kilometers downstream of Baghdad, there are towns, villages, and cities which get their municipal and agricultural water supplies from the Tigris River. Furthermore, these WWTPs are surrounded by agricultural farmlands which are suitable to cultivate a wide variety of crops. Some of the best citrus and date palm orchards are located on the banks of the Tigris River, which enhances the beauty and the environment of the region along with contributing to the local economy. These two WWTPs may have negative environmental impacts on the people and the aquatic life downstream when the treated wastewater does not meet the basic standards for organic matter and pathogens. Utilization of the treated wastewater for agricultural irrigation has the potential to improve water quality in the river and to further develop the local agricultural economy. Both the Karkh and the Rustumia WWTPs provide secondary treatment for their influent and plans to implement tertiary treatment have been made recognizing the need for further treatment for agricultural reuse.

In this water allocation optimization model, reclaimed water type A (RW_A) (tertiary treated wastewater), and reclaimed water type B (RW_B) (secondary treated wastewater) are to be allocated on a total of 84 farms with a total area of 5,300 hectares (ha) to the south of Baghdad allowing up to four crops to be cultivated in each farm. Each cultivated farm is based on actual land ownership and is therefore of different land areas starting from a minimum area of 17.5 ha up to a maximum area of 193 ha.

6.6. Data Input for the Model

The Iraqi Ministry of Water Resource has specified a variety of 34 strategic crops which were chosen to be cultivated in Iraq (Iraqi Ministry of Water Resources 2014) that can be irrigated using RW as an alternative source considering water quality, crop type, and the irrigation method. Those crops can be divided into human edible and inedible crops in addition to the industrial crops. In this study, two groups of crops were chosen to be cultivated (Table 6-1). Group A crops are to be irrigated using RW_A, and group B crops are to be irrigated using RW_B. RW_A will be tertiary treated water with both filtration and disinfection to reduce both pathogens and suspended solids. RW_B will be secondary treated water that includes basic disinfection and this water cannot be used on root crops including potatoes and onions. To limit the cultivated area of each crop to ensure a variety in production, the maximum area to be cultivated by each crop is listed in Table 6-1.

Table 6-1. Maximum allowed areas (ha) to be cultivated by certain types of crops irrigated using two reclaimed water (RW) qualities.

	Cotton	Wheat	Maize	Potato	Tomato	Barley	Clover	Cucumber	Alfalfa	Onion	Eggplant	Sunflower	Sesame	Okra
Group A	1000	1000	1000	500	500	1000	750	200	750	150	150	750	250	100
Group B	1000	1000	1000	0	500	1000	750	200	750	0	150	750	250	100

Each crop's water requirements (ETc) were adopted from Salman, et al. (2014) and updated from the Iraqi Ministry of Water Resources (2014). Each crop's and production costs in US dollar per hectare ($/ha) are presented in Table 6-2, based on data secured from the Iraqi Ministry of Agriculture and the Iraqi Central Statistical Organization (ICSO).

Table 6-2. Crop production costs exclusive of water costs ($ US per ha).

Crop	Cotton	Wheat	Maize	Potato	Tomato	Barley	Clover	Cucumber	Alfalfa	Onion	Eggplant	Sunflower	Sesame	Okra
Cost ($/ha)	1200	820	900	750	1300	720	320	1350	500	580	1250	550	475	1230

In Iraq, farm productivity fluctuates due to soil fertility, weather, and water availability and quality. Each crop's yield, as shown in Table 6-3, were secured from the Iraqi Central Statistical Organization (ICSO) considering Baghdad as the case study.

Table 6-3. Crop yield (ton per ha).

Crop	Cotton	Wheat	Maize	Potato	Tomato	Barley	Clover	Cucumber	Alfalfa	Onion	Eggplant	Sunflower	Sesame	Okra
Yield (ton/ha)	2.0	2.6	2.26	15.7	19.0	1.2	16.25	9.2	22.4	7.9	23.0	1.32	1.0	7.8

6.7. Results and Discussion

The optimization model was solved using ANTIGONE in GAMS allowing up to four crops to be cultivated in each farm. Before choosing ANTIGONE to run the model, an investigation of different MINLP solvers, including the Branch-And-Reduced Optimization Navigator (BARON) computational system for the solution of nonlinear programming problems (NLPs) and mixed-integer nonlinear programming problems (MINLPs), was performed. An Intel Core i7 2.2 GHz with Turbo Boost up to 3.2 GHz computer, with 16 GB Double Data Rate Type 3 (DDR3) memory, was used. Computed values of the net benefit using ANTIGONE were higher than the predicted values using BARON. For instance, solving the same problem, the computed net benefit using BARON is about $\$7 \times 10^5$ lower than the computed value using ANTIGONE. ANTIGONE was 11.6 times faster than BARON for solving the same optimization model. For example, BARON took about 186 seconds to solve the problem to find the optimal solution after 109 iterations by exploring 109 nodes. While ANTIGONE took only 17 seconds to solve the same problem exploring only 1 node. Other models such as BONMIN, COUENNE, and DICOPT were also evaluated solving the same MINLP optimization problem, but all these solvers resulted in infeasible solutions.

The current optimization model has 3946 variables and 956 constraints with 31936 Jacobian elements, 27552 of which are nonlinear. The Hessian of the Lagrangian has 0 elements on the diagonal, 5880 elements below the diagonal, and 3612 nonlinear variables. The total CPU time which was taken for one optimization attempt ranged from about 12 seconds to less than 1 minute depending on the number of iterations used to find the optimal solution.

The analysis was completed using two different reclaimed water qualities with different reclaimed water availabilities and different irrigation efficiencies. The analysis generated the maximum net benefit, total cultivated area, net benefit per hectare, and the area dedicated to each crop. The selected irrigation efficiencies were proposed regarding the irrigation technique used. In Iraq, the vast majority of agricultural irrigation is done using the traditional flooding system with an estimated irrigation efficiency (IE) ranging from 45-55% (Iraqi Ministry of Water Resources 2014). The irrigation efficiency should increase with the development of modern irrigation techniques which could reach up to 85 % with the use of automated drip irrigation systems. While there is debate regarding the impact of increasing irrigation efficiency on water consumption at the basin scale (Grafton et al. 2018), increasing irrigation efficiency should increase water availability in Iraq at the basin scale. In Iraq, agricultural return flows are considered unsuitable for irrigation and they are diverted into drains that transport the water into the Arabian (Persian) Gulf. Furthermore, groundwater is currently not used extensively in Iraq. Increasing irrigation efficiency will decrease irrigation return flows and flows to groundwater, however, the infrastructure in Iraq does not currently utilize these flows so the basin-scale impact on water resources should be positive. The model was run for different irrigation efficiencies ranging from 45% to 85% to help determine the potential benefits of improving the irrigation systems.

The maximized net benefits using RW_A and RW_B on the proposed 84 farms for different irrigation efficiencies and different quantities of water are presented in Figures 6-2 and 6-3. Results showed that the net benefit of using RW_A and RW_B increases with the increase of the amount of reclaimed water used. The use of 6.0 MCM of RW_A with a 45% irrigation efficiency (IE) has a net benefit of $\$2.21 \times 10^6$ from the cultivation of approximately 384 hectares of tomatoes. For the use of 6.0 MCM of RW_A with 85% IE, the model predicts a net benefit of $\$4.55 \times 10^6$ while cultivating a total of 701.2 ha comprised of 500 ha of tomatoes and 201.2 ha of potatoes. The model demonstrates that the use of higher irrigation efficiencies, which means more water availability due to advanced irrigation techniques, can produce a higher net benefit and greater crop diversity. The use of the same 6.0 MCM of RW_A with irrigation efficiencies of 55, 65, 75, and 85%, the net benefit increases by 30.7, 57.3, 81.7, and 106.1%, respectively, as compared to the results for a 45% IE. Small increases in irrigation efficiency are clearly beneficial. The use of 6.0 MCM of RW_A with 65% IE has a net benefit increase of 20.4% as compared to a 55% IE, and the 75% IE has a net benefit increase of 15.5% higher as compared to a 65% IE. Finally, the use of 85% IE has a net benefit increase of about 13.4% as compared to a 75% IE. The increase in net benefit will decrease as higher IEs are achieved.

The optimum maximized net benefit using RW_B was $\$4.46 \times 10^6$ with 20.0 MCM of RW_B with an 85% IE while cultivating 2031 ha with 10 different types of crops. As illustrated in Figure 6-3, optimizing the use of RW_B results in lower net benefit values in comparison to RW_A (Figure 6-2), due to the difference in the crops allowed to be cultivated using both RW types.

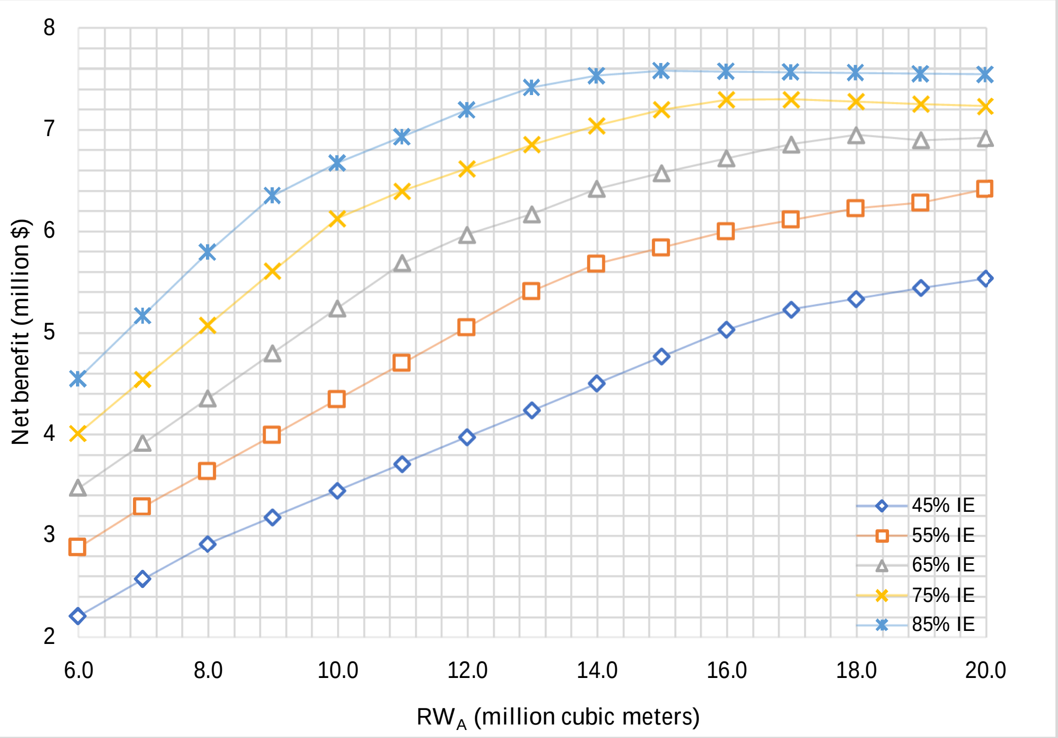


Figure 6-2. Total net benefit (million $) predicted using reclaimed water type A (RW_A) with five different irrigation efficiencies (IE).

The maximization of the net benefit from the use of RW_B has followed a different trend than that observed with RW_A. Using 6.0 MCM of RW_B with a 45% IE produces a net benefit of $\$2.33 \times 10^6$. In contrast, the use of 6.0 MCM of RW_B with 55, 65, 75, and 85 % IEs results in an increase of about 29.1, 46.9, 58.7, 69.8%, respectively, in comparison to a 45% IE. The increase in net benefit decreases as the quantity of RW_B used increases and the same is true for the increases in IEs. Using 12.0 MCM of RW_B with 55, 65, 75, and 85% IEs have an increase in net benefit of 12.3, 18.9, 24.5, 30.1 as compared to a 45% IE which has a net benefit of about $\$3.4 \times 10^6$. The decreases in the ratio of the net benefit with higher irrigation efficiencies is due to the increase in the practically employed amount of water which tends to irrigate the maximum allowed area of the most economic crops first and later to find crops of lower economic values. The most economic crops identified by the water allocation optimization model using RW_B are tomatoes, eggplant, cucumber, okra, and clover.

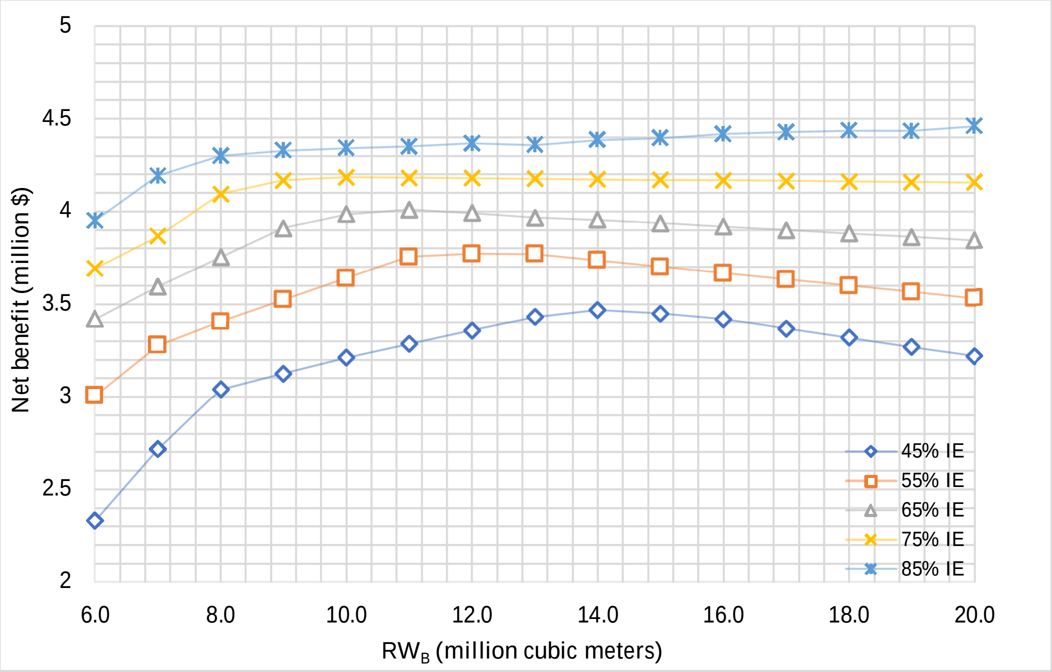


Figure 6-3. Total net benefit (million \$) predicted using reclaimed water type B (RW_B) with five different irrigation efficiencies (IE).

Using 6.0 MCM of RW_B with 45% IE has a computed net benefit of \$2.33 × 10^6, which is higher than the net benefit computed using RW_A, cultivating the same area of 384 ha of tomatoes. RW_B has shown a significant advantage over RW_A when both are used to cultivate the same types of crops on the same areas as with the cultivation of tomatoes using of 6.0 MCM of RW_B with 45, and 55% IE and using 7.0 and 8.0 MCM of RW_B with 45% IE. The advantage of RW_B over RW_A is because the cultivation cost and the selling price of the cultivated crops are the same except RW_B is less expensive than RW_A.

The higher quantities of reclaimed water in combination with higher irrigation efficiencies result in the cultivation of more land which produces a higher net benefit when crops with higher economic value are cultivated. In this study, the maximized net benefit from using RW_A had a peak value of $\$7.6 \times 10^6$ when 15.0 MCM of RW_A has been used with 85% IE, as illustrated in Figure 6-2. Thereafter, the maximized net benefit declined with an increase in the quantity of water used because the model reached the maximum area for the highest economic value crops (Table 6-1), such as tomatoes, while lower economic value crops are cultivated until crops with negative economic value, such as clover, are the only crops available for cultivation. Optimizing the use of higher water availabilities with RW_B results in a similar decline in the net benefit with higher irrigation efficiencies, as illustrated in Figure 6-3, due to the previously mentioned reason.

The cultivated areas predicted from optimizing the allocation of RW_A are presented in Figure 6-4. Increasing the quantities of RW_A used results in a commensurate increase in the cultivated area. Using 6.0 MCM of RW_A with 45, 55, 65, 75, and 85% IEs results in irrigated areas of 384.8, 470.3, 549.5, 625.3, and 701.2 ha, respectively. The model satisfies the maximum allowed area of the most economic crop then it starts cultivating the crop with the next higher economic value and so on. Therefore, tomatoes were selected first by the model to be cultivated using RW_A followed by potatoes, onion, eggplant, cucumber, and okra. For instance, using 6.0 MCM of RW_A with 45% IE, the model selected tomatoes to be cultivated first and when the quantity of RW_A reached 8.0 MCM with 45% IE, the model cultivated 500 ha of tomatoes then 11.6 ha of potatoes, which is the second most economic crop in the system.

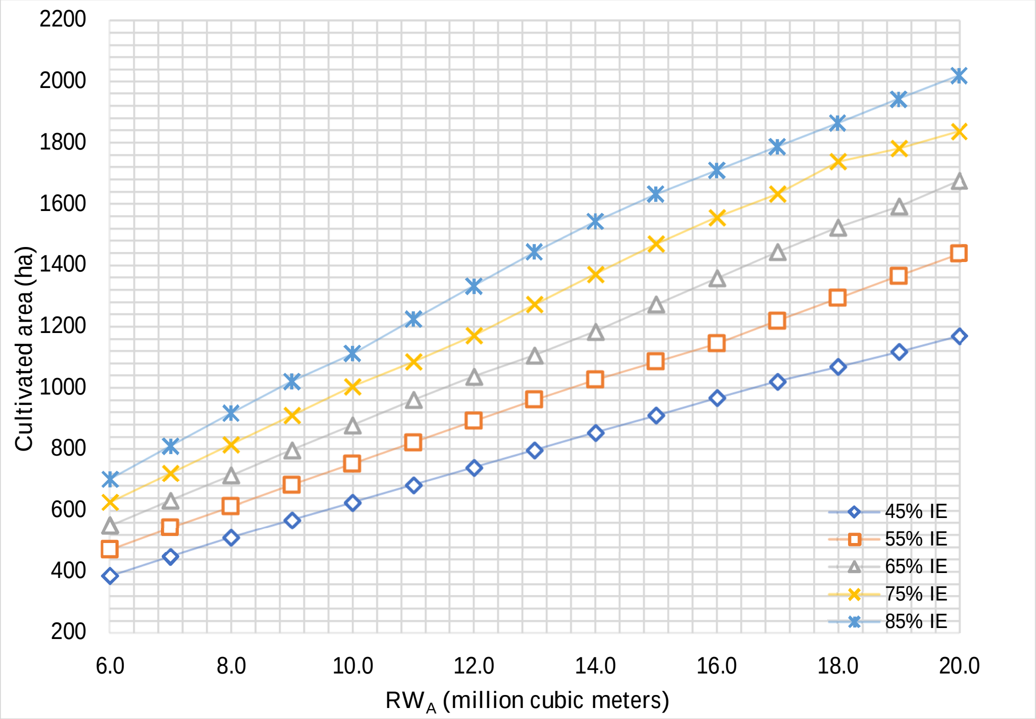


Figure 6-4. Total cultivated area (ha) predicted using reclaimed water type A (RW$_A$) with five different irrigation efficiencies (IE).

The total cultivated areas using RW$_B$ with different irrigation efficiencies are presented in Figure 6-5. The results show that the increase in the reclaimed water quantities used, the served area will increase accordingly depending on the evapotranspiration of the crops cultivated. The model predicts the maximum net benefit by cultivating the optimum area using a variety of crops as a function of the available quantity of water. Using 10.0 MCM of RW$_B$ with 85% IE results in the cultivation of the maximum allowable hectares of tomatoes, eggplant, cucumber, and okra followed by the cultivation of 131.7 ha of clover (Table 6-1). Meanwhile, using 11.0 MCM of RW$_B$ with 85% IE results in the cultivation of the maximum allowable area of tomatoes, eggplant, and cucumber, followed by 176.3 ha of clover, 93.5 ha of sesame, and 9.3 ha of alfalfa. Instead of cultivating only 209.3 ha of clover, the model maximizes the net benefit by including sesame and alfalfa which provide a similar net benefit to clover (Figure 6-5). The same trend was predicted by the model using from 13.0 MCM to 19.0 MCM of RW_B with 85% IE. One of the features of the model is to allow for cultivating as many crops as possible which satisfy the maximum net benefit. In addition, the minimum allowed area of crops to be cultivated may be adjusted based on specific conditions to provide constraints in the model consistent with supply and demand.

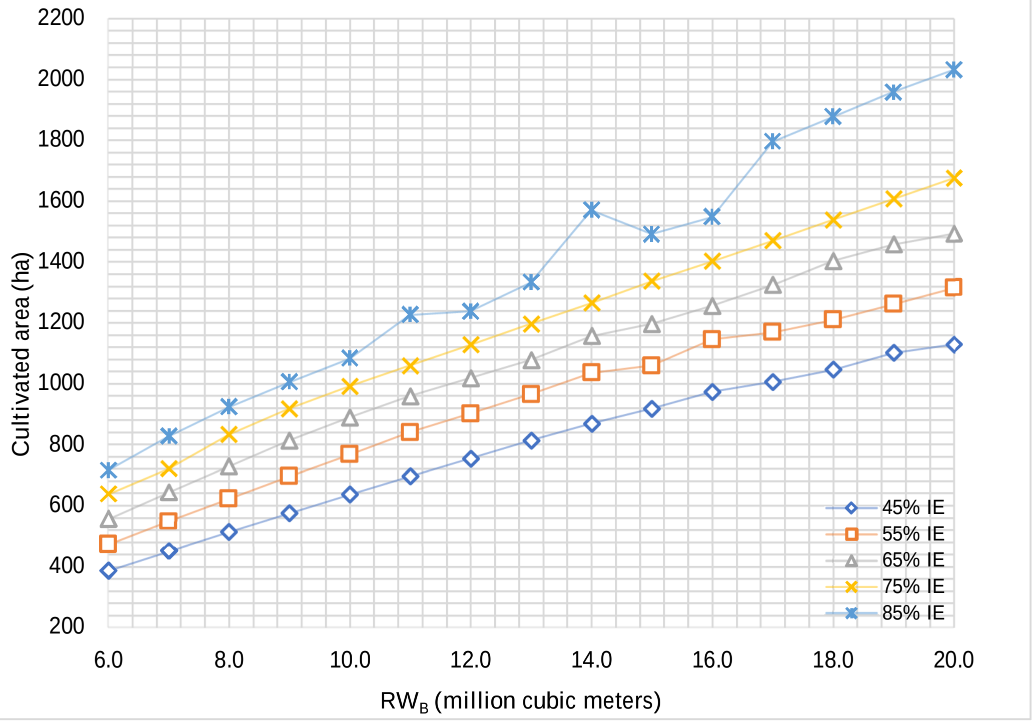


Figure 6-5. Total cultivated area (ha) predicted using reclaimed water type B (RW_B) with five different irrigation efficiencies (IE).

The average net benefit per hectare ($/ha) predicted from optimizing the allocation of RW_A and RW_B is presented in Figures 6-6 and 6-7, respectively. With an increase in irrigation efficiency using a specific quantity of water, the computed net benefit per cultivated hectare of crops increased until a limit was reached. The factors that limit the net benefit are the increase in the cultivated area along with the requirement to grow more lower economic value crops. For instance, using 6.0 MCM of RW_A with 45% IE has predicted a net benefit of about $5732/ha when only tomatoes are cultivated on 384 ha. While, the model predicted a net benefit of $6483/ha when it cultivated 500 ha of tomatoes, and 201 ha of potatoes using 6.0 MCM of RW_A with 85% IE. In contrast, the model results experienced a significant decline in the predicted net benefit per hectare with the increase in irrigation efficiencies using higher quantities of water due to the increase in the cultivated area, and the decrease of the total maximized net benefit computed from the cultivation of crops with a lower net benefit. Using 20.0 MCM of RW_A with 45% IE has predicted a net benefit of about $4734/ha while cultivating 500 ha of tomatoes, 500 ha of potatoes, 15 ha of onion, and 19 ha of eggplant. A net benefit of $3737/ha was predicted by cultivating 500 ha of tomatoes, 500 hectares of potatoes, 200 ha of eggplant, 150 ha of onion, 150 ha of cucumber, 100 of okra, and 419 ha of clover using 20.0 MCM of RW_A with 85% IE (Figure 6-6). The net benefit per hectare using different availabilities of RW_B with different irrigation efficiencies, as illustrated in Figure 6-7, decreases with the increase in the quantities of RW_B with the increase in IEs due to the same reasons mentioned under the use of RW_A.

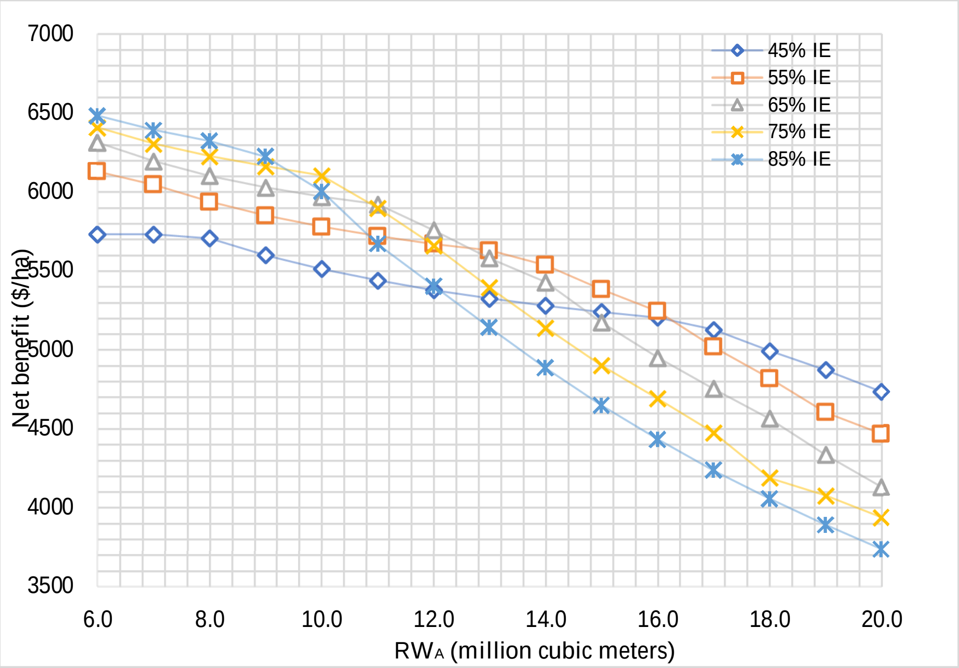


Figure 6-6. Net benefit per hectare ($/ha) predicted using reclaimed water type A (RW_A) with five different irrigation efficiencies (IE).

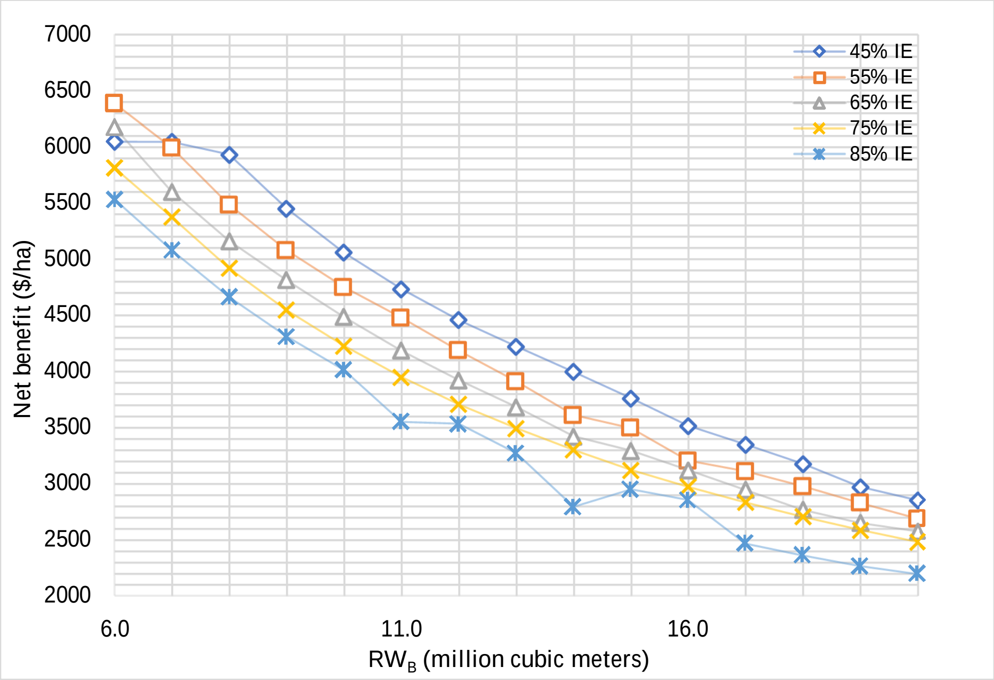


Figure 6-7. Net benefit per hectare ($/ha) predicted using reclaimed water type B (RW_B) with five different irrigation efficiencies (IE).

The cultivated crops using different availabilities of RW_A with 45, 65, and 85% IEs are presented in Figures 6-8 to 6-10, respectively. There are 14 different types of crops available for cultivation using RW_A as listed in group A in Table 6-1. Each crop has its own evapotranspiration value, selling price, production cost, and yield per hectare. Starting with 6.0 MCM with 45% IE, the model predicted cultivation of 384 ha of tomatoes. Tomato is the crop which satisfied the highest net benefit per hectare as compared to the other competitive crops in Table 6-1. All of the 84 cultivated farms of the system have the opportunity to cultivate tomatoes depending on the ratio of their areas to the total observed area of farms. Increasing the quantity of RW_A and/or increasing the irrigation efficiency, increases the quantity of water which is allocated on farms cultivating more crops. With 45% IE using different RW_A availabilities, tomatoes, potatoes, onion, and eggplant have been cultivated, respectively, starting from the highest economic value crop then next highest and so on, as illustrated in Figure 6-8. Increasing the irrigation efficiencies using a certain quantity of reclaimed water provides the opportunity to cultivate more crops after cultivating the maximum allowed area for each crop. For example, at 65% IE the model predicts the cultivation of up to 8 crops (Figure 6-9). While, with 85% IE using certain availabilities of RW_A, the model has predicted the cultivation of up to 7 different crops when 20.0 MCM of RW_A was used (Figure 6-10).

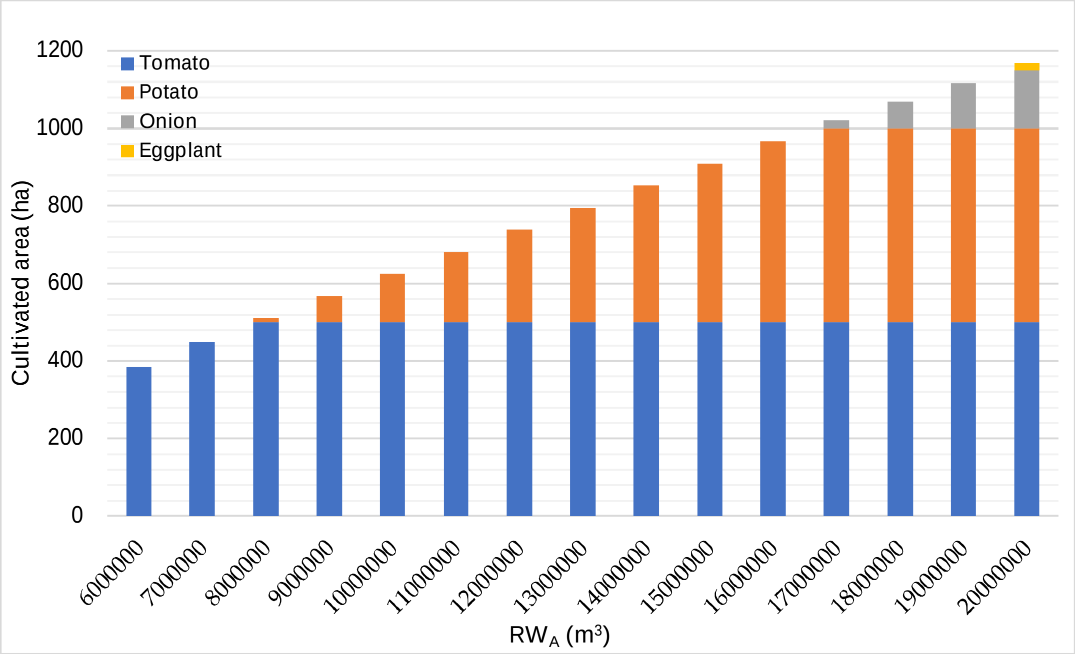


Figure 6-8. Predicted area (ha) of crops irrigated using reclaimed water type A (RW$_A$) with 45% IE.

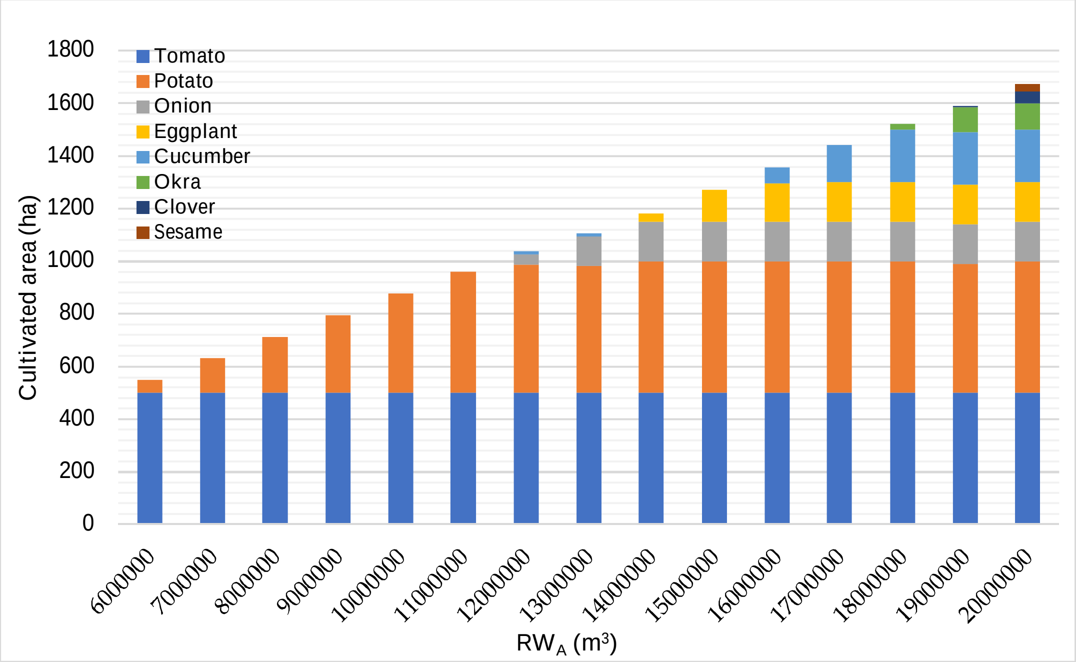


Figure 6-9. Predicted area (ha) of crops irrigated using reclaimed water type A (RW$_A$) with 65% IE.

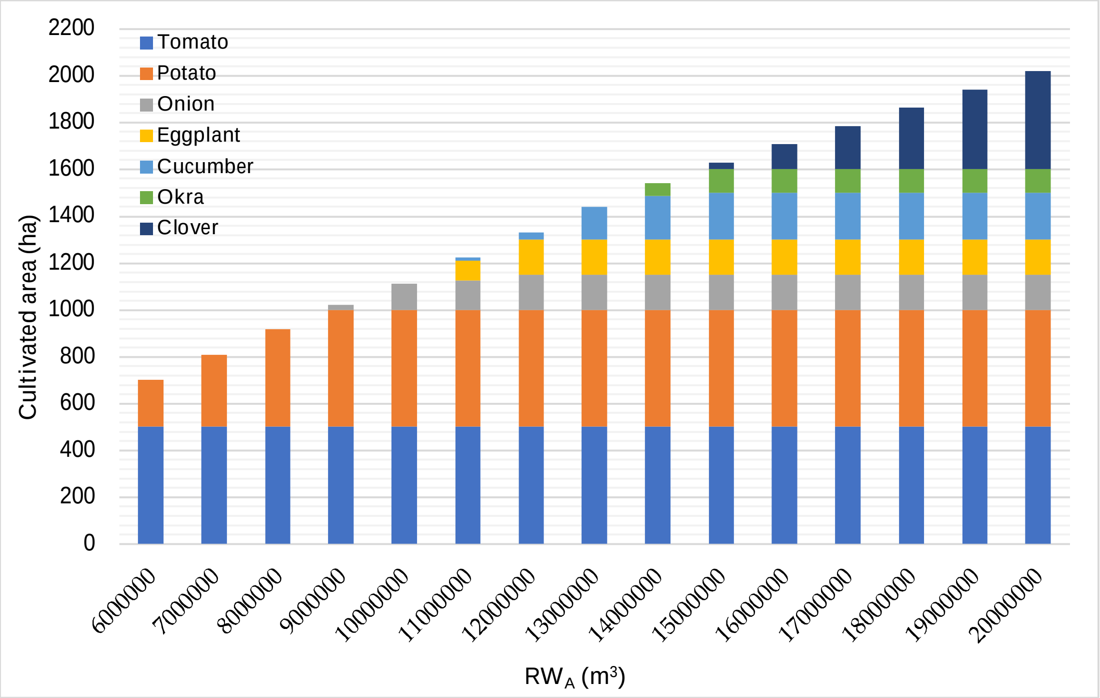


Figure 6-10. Predicted area (ha) of crops irrigated using reclaimed water type A (RW$_A$) with 85% IE.

The cultivated crops using different availabilities of RW$_B$ with 45, 65, and 85% IEs are illustrated in Figures 6-11 to 6-13, respectively. The use of RW$_B$ has followed the same trends observed with RW$_A$ by cultivating the highest economic value crop then the next highest and so on while selecting from the 12 crops listed in group B in Table 6-1. Starting from irrigating only 384 ha of tomatoes using 6.0 MCM of RW$_B$ with 45% IE reaching to the irrigation of 500 ha of tomatoes, 150 ha of eggplant, 200 ha of cucumber, 100 ha of okra, 177 ha of clover, and 1.6 ha of sesame by using 20.0 MCM of RW$_B$, as illustrated in Figure 6-11. Figures 6-12 and 6-13 illustrate the cultivated crops using different RW$_B$ availabilities with 65% and 85% IEs, respectively. Even though the optimization model allows up to 4 crops to be cultivated simultaneously on the same farm, results showed that most of the farms cultivated up to 2 crops depending on the RW availability and the IE implemented.

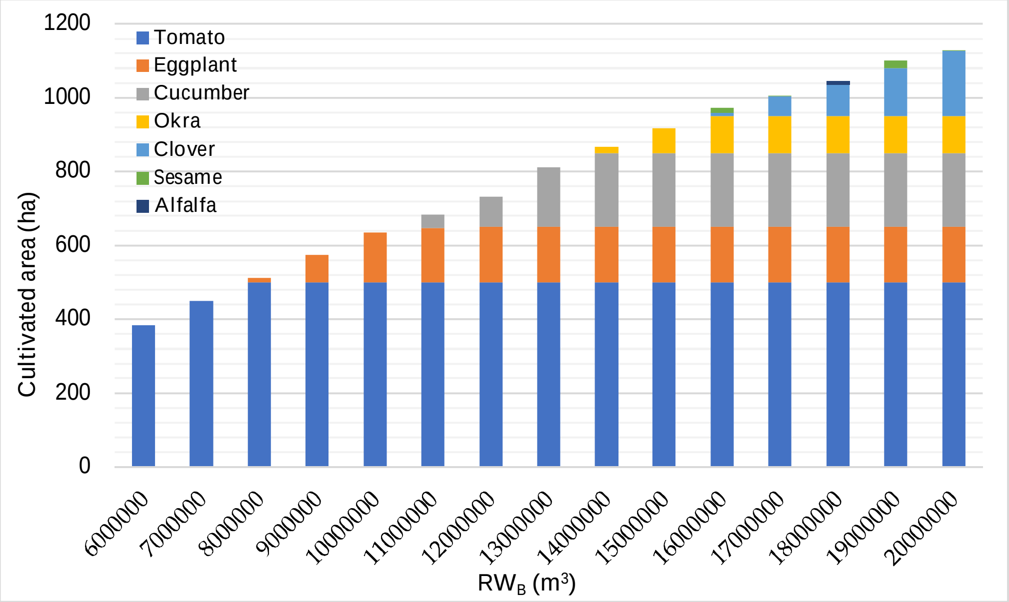


Figure 6-11. Predicted area (ha) of crops irrigated using reclaimed water type B (RW_B) with 45% IE.

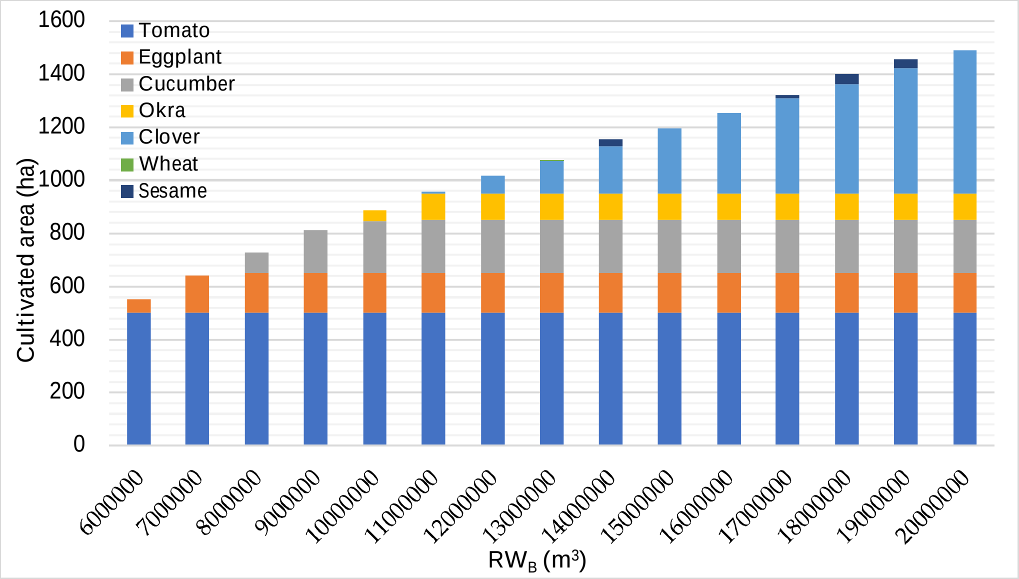


Figure 6-12. Predicted area (ha) of crops irrigated using reclaimed water type B (RW_B) with 65% IE.

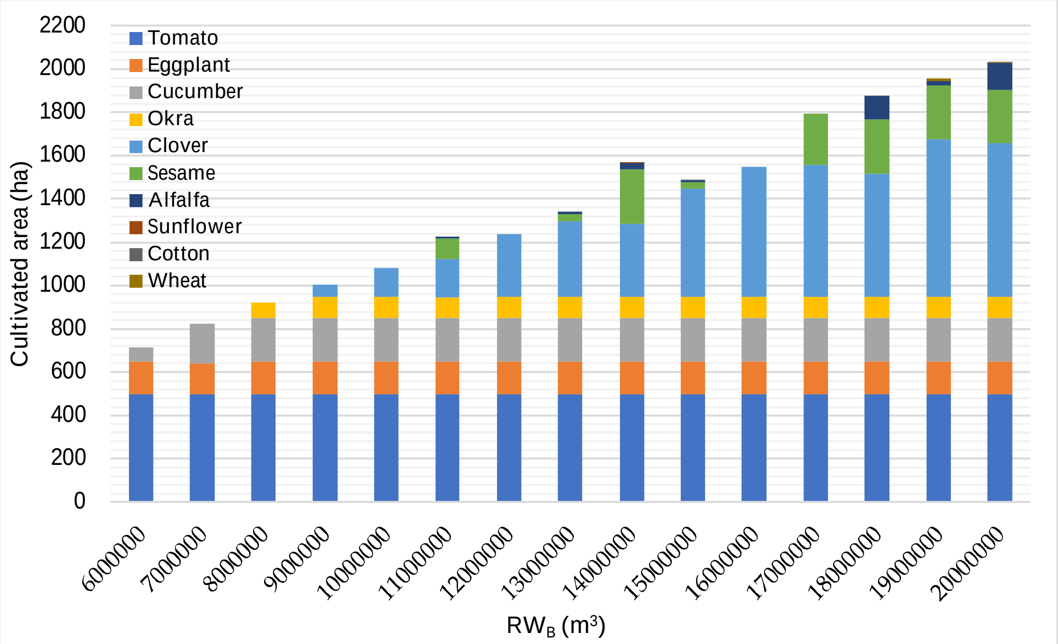


Figure 6-13. Predicted area (ha) of crops irrigated using reclaimed water type B (RW$_B$) with 85% IE.

6.8. Summary and Conclusion

The reclaimed water allocation optimization model (mixed-integer nonlinear programming problem) was used to determine the optimum allocation of water on 84 proposed farms south of Baghdad. It was demonstrated that increasing irrigation efficiencies can produce a higher net benefit and greater crop diversity. Even small increases in irrigation efficiency is clearly beneficial as increasing the irrigation efficiency from 45% to 55% can result in a net benefit increase of 30.7%. The net benefit per hectare of cultivated land increases until high irrigation efficiencies (>75%) are used as the increase in the available water allows for irrigation of the maximum allowed area for the most economic crops. Therefore, crops with lower economic value are cultivated with increased water availability while at lower irrigation efficiencies, only the highest economic value crops are selected. The model demonstrated that RW_A generally results in a higher net benefit as compared to RW_B. With lower quantities of available water, only the most economic crops are grown with both RW_A and RW_B while the cost of RW_B is less than RW_A. For instance, using 6.0 MCM of RW_B with 45% IE has a predicted a net benefit of $\$2.33 \times 10^6$, which is higher than the net benefit of $\$2.21 \times 10^6$ using RW_A while cultivating the same area of 384 ha of tomatoes.

Even though most Iraqi WWTPs use secondary treatment, the model predicts it is more efficient to upgrade to tertiary treatment to produce RW_A. Using reclaimed water for irrigation will help in reducing the potential negative environmental impacts of wastewater discharges while increasing the potential uses of RW for agriculture. Since most of Iraq's built or under construction WWTPs are located in or adjacent to agricultural lands, it is logical and efficient to invest in using their secondary or tertiary treated wastewater for agricultural irrigation to enhance the economy of farmers and the environment while providing a diversity of crops.

CHAPTER 7 AGRICULTURAL RECLAIMED WATER ALLOCATION OPTIMIZATION MODEL MAXIMIZES INDIVIDUAL FARM'S NET BENEFIT

7.1. Goals and Objectives

The goal of this chapter is the development of an optimization model for agricultural water allocation using reclaimed water. The objective function is to maximize the net benefit, taking into consideration individual farm level, generated from the cultivation of different types of crops using reclaimed water with different qualities. The optimization model, a mixed integer nonlinear programming (MINLP) problem, was solved using both the general algebraic modeling system (GAMS) (GAMS Development Corporation, 2016) and Algorithms for coNTinuous / Integer Global Optimization of Nonlinear Equations (ANTIGONE) (Misener and Floudas, 2014).

In this MINLP water allocation optimization model, reclaimed water was allocated proportionally to all farms. The water share of each farm was equal to the ratio of farm's agricultural area to the total agricultural area of all farms. Two reclaimed water qualities were compared, reclaimed water type A (tertiary treated) and reclaimed water type B (secondary treated), considering different RW availabilities with different irrigation efficiencies to evaluate the sensitivity of the computed results to these variables. The objective function of this model is subjected to constraints of reclaimed water availabilities and cultivated areas, the farm-crop connectivity and farm-RW connectivity, and a minimum net benefit.

7.2. Mathematical Formulation of the Optimization Model

7.2.1. *The Objective Function*

The objective function of this optimization model is to maximize the individual farm net benefit predicted from the cultivation of different types of crops using reclaimed water. The maximized net benefit $\mathrm{Nb_i}$ using reclaimed water ($\mathrm{RW_i}$) type i is:

$$\mathrm{Max.\,Nb_{i,x}} = \sum_c \mathrm{Nb_{i,x,c}} \qquad x = 1, \ldots, X \qquad (7\text{-}1)$$

Where

$\mathrm{Nb_{i,x}}$ is the computed net benefit ($) for each farm x cultivating crop c using RW type i.

The total production cost $\mathrm{CP_{i,x,c}}$ ($) to produce crop c which is cultivated in farm x using RW type i is the sum of the crop's production cost plus the cost of the assigned RW type i to cultivate crop c. The total production cost $\mathrm{CP_{i,x,c}}$ ($) is defined as:

$$\mathrm{CP_{i,x,c}} = \sum_c [(\mathrm{FA_{i,x,c}\,CCost_c}) + (\mathrm{RW_{i,x,c}\,RWC_i})] \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (7\text{-}2)$$

Where

$\mathrm{FA_{i,x,c}}$ is the assigned area of farm x in hectare (ha) to cultivate crop c using RW type i

$\mathrm{CCost_c}$ is the production cost ($/ha) of crop c

$\mathrm{RW_{i,x,c}}$ is the assigned RW of type i to irrigate farm x cultivating crop c (m^3)

$\mathrm{RWC_i}$ is the cost of RW type i ($/$m^3$)

The revenue of farm x, $\mathrm{Re}_{i,x,c}$, is computed by considering crop c yield, Y_c (ton/ha), times the selling price P_c ($/ton) of that crop times the cultivated area $FA_{i,x,c}$ (ha) of farm x, which is:

$$\mathrm{Re}_{i,x,c} = Y_c P_c\, FA_{i,x,c} \tag{7-3}$$

The individual farm net benefit, $Nb_{i,x,c}$, generated from the cultivation of crop c at farm x using RW type i is:

$$Nb_{i,x,c} = \sum_c [\mathrm{Re}_{i,x,c} - CP_{i,x,c}] \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \tag{7-4}$$

Considering the quality of the RW used and the quality standard and salinity tolerance of each cultivated crop, a binary 0/1 coefficient of connectivity, $CRw_{i,c}$, is used allowing crop c to get its appropriate RW type i. Equation (7-4) can be expressed as:

$$Nb_{i,x,c} = \sum_c \big[[\mathrm{Re}_{i,x,c} - \big((FA_{i,x,c}\, CCost_c) + (RW_{i,x,c}\, RWC_i) \big) \big]\, CRw_{i,c} \big] \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \tag{7-5}$$

In this model, more than one crop is allowed to be cultivated at farm x, which can be satisfied using the 0/1 binary variable $M_{x,c}$. On the other hand, the model assumes that only RW type i is available to irrigate farm x which is implemented using the second binary variable $N_{x,i}$. By considering the two connectivity binary variables, $M_{x,c}$ and $N_{x,i}$, the net benefit $Nb_{i,x}$ equation can be re-arranged as:

$$Nb_{i,x,c} = \sum_c \big[[\mathrm{Re}_{i,x,c}\, M_{x,c} - \big((FA_{i,x,c}\, CCost_c)\, M_{x,c} + (RW_{i,x,c}\, RWC_i)\, N_{x,i} \big) \big]\, CRw_{i,c} \big] \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \tag{7-6}$$

7.2.2. *Decision variables*

Since the optimization model allocates RW on farmland areas to cultivate a variety of crops on different areas, the decision variables are:

$FA_{i,x,c}$ is the assigned area of farm x to cultivate crop c using RW type i (ha)

$RW_{i,x,c}$ is the assigned RW of type i to farm x farming crop c (m^3)

$N_{x,i}$ defines the connectivity of RW type i to farm x (binary variable)

h) $M_{x,c}$ defines the connectivity of crop c to farm x (binary variable)

7.2.3. *Constraints*

7.2.3.1. Reclaimed water availability constraints

Two types of RW are considered in this optimization model: RW type A (i=1) from tertiary treated wastewater and RW type B (i=2) from secondary treated wastewater.

a. Total consumed RW type i

The sum of the total use of reclaimed water ($RW_{i,x,c}$) of a certain type i must be equal to or less than the total amount of RW (QRw_i) of the same type i released from the same WWTP in the same cultivation season.

$$\sum_x \sum_c RW_{i,x,c} \leq QRw_i \qquad i = 1, \ldots, I \qquad (7\text{-}7)$$

Where

QRw_i is the total amount of RW type i (m^3) discharged from the WWTP

b. Consumed RW from source i by farm x irrigating crop c

$$\sum_c RW_{i,x,c}\, M_{x,c}\, CRw_{i,c} \leq RLn_{i,x}\, QRw_i \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (7\text{-}8)$$

Where

$RLn_{i,x}$ is the ratio of the observed area of farm x (Ln_x) to the total observed area in the system (TLn_i), defined as

$$RLn_{i,x} = Ln_x / TLn_i \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (7\text{-}9)$$

assures that each farm x receives its share of water proportionally to the ratio of its observed area to the total observed farmlands’ areas in the system.

c. Consumed RW by type i and farm x

The sum of the assigned RW type i to irrigate farms (x=1 to X) cultivating crops (c=1 to C) must be equal to or less than the hydraulic loading Lw_c (m^3/ha) of each crop c times the cultivated area $FA_{i,x,c}$ (ha), expressed as:

$$\sum_c RW_{i,x,c}\, M_{x,c}\, CRw_{i,c} = \sum_c Lw_c\, FA_{i,x,c}\, M_{x,c}\, CRw_{i,c} \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (7\text{-}10)$$

Where

Lw_c the hydraulic loading (m^3/ha) considering each cultivated crop c, which is computed as:

$$Lw_c = \frac{NR_c}{\frac{IE_c}{100}}\left(\frac{10000}{1000}\right) = ETc_c \times \left(1 + \frac{LR_c}{100}\right) \times \left(\frac{100}{IE_c}\right)(10) \qquad c = 1, \ldots, C \qquad (7\text{-}11)$$

Where

ETc_c is the evapotranspiration requirements (mm/season) to cultivate crop c

IE_c is the irrigation efficiency to cultivate crop c

NR_c is the net irrigation requirements (mm/season) to cultivate crop k

LR_c is the leaching requirements to cultivate crop c

10 is the conversion factor for m^3/ha

7.2.3.2. Irrigated farmlands constraints

a. Irrigated area of farm x

The area (ha) in production $\mathsf{FA}_{i,x,c}$ of farm x cultivating crop c using RW type i must be equal to or less than the observed area Ln_x (ha) of farm x, as:

$$\sum_c \mathsf{FA}_{i,x,c}\ \mathsf{CRw}_{i,c} \leq \mathsf{Ln}_x \qquad x = 1, \ldots, X \text{ and } i = 1, \ldots, I \qquad (7\text{-}12)$$

b. Total irrigated farmland area per RW type i

The sum of the total irrigated area in the system must be equal to or less than the area of the total observed farmlands, expressed as:

$$\sum_x \sum_c \mathsf{FA}_{i,x,c} \leq \sum_x \mathsf{Ln}_x \qquad i = 1, \ldots, I \qquad (7\text{-}13)$$

c. Minimum farmlands area to be cultivated with crop c in farm x

This constraint assures the cultivated area with each crop c must be more than the minimum limit of hectares to satisfy the feasible investment, which is expressed as:

$$\sum_c \mathsf{FA}_{i,x,c} \geq \mathsf{FAmin}_{i,c} \qquad i = 1, \ldots, I \text{ and } c = 1, \ldots, C \qquad (7\text{-}14)$$

d. Maximum farmlands area to be cultivated by crop c

In order not to exceed the upper limit of the area cultivated using crop c, to avoid the domination of the most economic crop over all others, and to force the model to select as many crops as possible to satisfy a variety in production, the following constraint is used:

$$\sum_x FA_{i,x,c} \leq FAmax_{i,c} \qquad i = 1, \ldots, I \text{ and } c = 1, \ldots, C \qquad (7\text{-}15)$$

Where

$FAmin_{i,c}$ is the minimum area (ha) to be cultivated by crop c using RW type i

$FAmax_{i,c}$ is the maximum area (ha) to be cultivated by crop c using RW type i

7.2.3.3. Allocation Constraints

a. Allocation of crop c to farm x

The $M_{x,c}$ binary variable assures that at least one crop is cultivated at farm x. So, the sum of $M_{x,c}$ binary variable, for the same farm x, must be equal to or greater than 1. On the other hand, the model allows a maximum number of crops to be cultivated on each farm x. Up to four crops are allowed to be cultivated on the same farm. So, the farm-crop connectivity constraint is written as:

$$1.0 \leq \sum_c M_{x,c} \leq 4.0 \qquad x = 1, \ldots, X \qquad (7\text{-}16)$$

b. Allocation of RW type i to farm x

The following constraint assures that farm x will be irrigated by one source of RW type I, so, the sum of $N_{x,i}$ binary variable for the same RW type i must be equal to 1.0.

$$\sum_x N_{x,i} = 1 \qquad i = 1, \ldots, I \qquad (7\text{-}17)$$

7.2.3.4. Minimum allowed net benefit by farm x constraint

To assure a suitable minimum margin of net benefit per farm x, the computed net benefit from cultivating crop(s) must be at least 20 % of the total cultivation cost of the same farm, which can be satisfied using:

$$Nb_{i,x} \geq 1.20 \sum_{c} CP_{i,x,c} \qquad x= 1, \ldots., X \text{ and } i = 1, \ldots., I \qquad (7\text{-}18)$$

The GAMS code used to solve this MINLP agricultural reclaimed water allocation optimization model is described in Appendix D of this dissertation.

7.3. Baghdad as a Case Study

In Baghdad, there are two main wastewater treatment plants; the Karkh WWTP and the Rustumia WWTP, which provide daily secondary treatment to a total of 1.0 million cubic meters (MCM) of wastewater that is presently discharged into the Tigris River south of Baghdad. The WWTPs are surrounded by agricultural farmlands which are suitable to cultivate a wide variety of crops. Furthermore, some of the best citrus and date palm orchards are located on the banks of the Tigris River, adjacent to the Karkh WWTP, which enhances the beauty and the environment of the region along with contributing to the local economy. The Karkh and the Rustumia WWTPs provide secondary treatment for their influent, using different treatment processes. The Mayoralty of Baghdad intends to implement tertiary treatment and preliminary designs have been made recognizing the need for further treatment for agricultural reuse.

In this water allocation optimization model, reclaimed water type A (RW_A) (tertiary treated wastewater), and reclaimed water type B (RW_B) (secondary treated wastewater) are to be allocated on a total of 84 farms with a total area of 5,300 hectares (ha) to the south of Baghdad allowing up to four crops to be cultivated on each farm. Each cultivated farm is based on actual land ownership and is therefore of different land areas starting from a minimum area of 17.5 ha up to a maximum area of 193 ha (Table 7-1).

Table 7- 1. The areas in hectares (ha) of the 84 farms modeled in the optimization model.

Farm	Area (ha)	Farm	Area (ha)	Farm	Area (ha)	Farm	Area (ha)
FA_{1}	111.90	FA_{22}	59.80	FA_{43}	36.40	FA_{64}	84.70
FA_{2}	120.40	FA_{23}	59.40	FA_{44}	30.70	FA_{65}	88.20
FA_{3}	193.00	FA_{24}	58.80	FA_{45}	31.40	FA_{66}	77.30
FA_{4}	128.50	FA_{25}	54.70	FA_{46}	26.40	FA_{67}	80.90
FA_{5}	75.80	FA_{26}	57.90	FA_{47}	30.90	FA_{68}	109.50
FA_{6}	116.90	FA_{27}	54.40	FA_{48}	31.70	FA_{69}	72.80
FA_{7}	121.60	FA_{28}	53.70	FA_{49}	80.50	FA_{70}	64.90
FA_{8}	94.40	FA_{29}	68.40	FA_{50}	78.40	FA_{71}	64.50
FA_{9}	34.30	FA_{30}	56.80	FA_{51}	17.50	FA_{72}	56.85
FA_{10}	74.90	FA_{31}	60.20	FA_{52}	66.90	FA_{73}	56.00
FA_{11}	68.50	FA_{32}	44.80	FA_{53}	60.00	FA_{74}	138.90
FA_{12}	64.30	FA_{33}	51.10	FA_{54}	65.70	FA_{75}	49.40
FA_{13}	62.00	FA_{34}	43.40	FA_{55}	56.50	FA_{76}	54.95
FA_{14}	59.20	FA_{35}	42.20	FA_{56}	59.90	FA_{77}	54.50
FA_{15}	57.10	FA_{36}	43.30	FA_{57}	52.90	FA_{78}	59.30
FA_{16}	41.45	FA_{37}	45.60	FA_{58}	67.80	FA_{79}	90.50
FA_{17}	43.50	FA_{38}	43.40	FA_{59}	76.90	FA_{80}	61.15
FA_{18}	42.90	FA_{39}	22.50	FA_{60}	51.80	FA_{81}	56.68
FA_{19}	42.90	FA_{40}	35.40	FA_{61}	46.90	FA_{82}	54.08
FA_{20}	44.50	FA_{41}	39.20	FA_{62}	78.40	FA_{83}	46.60
FA_{21}	60.60	FA_{42}	34.20	FA_{63}	96.50	FA_{84}	46.55
						Total	5,300.00

7.4. Data Input for the Model

The Iraqi Ministry of Water Resource has specified a variety of 34 strategic crops which were chosen to be cultivated in Iraq (Iraqi Ministry of Water Resources 2014) that can be irrigated using RW as an alternative source considering water quality, crop type, and irrigation method. Those crops can be divided into human edible and non-edible crops in addition to the industrial crops. In this study, two groups of crops were chosen to be cultivated (Table 6-1). Group A crops are to be irrigated using RW_A, and group B crops are irrigated using RW_B. RW_A is tertiary treated water with both filtration and disinfection to reduce both pathogens and suspended solids. RW_B will be secondary treated water that includes basic disinfection and this water cannot be used on root crops including potatoes and onions. To limit the cultivated area of each crop to ensure a variety in production, the maximum area to be cultivated with each crop is listed in Table 6-1.

Each crop's water requirements (ETc) were adopted from Salman, et al. (2014) and updated from the Iraqi Ministry of Water Resources (2014). Each crop's production costs in US dollar per hectare ($/ha) are presented in Table 6-2, based on data secured from the Iraqi Ministry of Agriculture and the Iraqi Central Statistical Organization (ICSO).

In Iraq, farm productivity fluctuates due to soil fertility, weather, and water availability and quality. Each crop's yield, as shown in Table 6-3, were secured from the Iraqi Central Statistical Organization (ICSO) considering Baghdad as the case study.

7.5. Results and Discussion

The optimization model was solved using ANTIGONE in GAMS allowing up to four crops to be cultivated on each farm. An Intel Core i7 2.2 GHz with Turbo Boost up to 3.2 GHz computer, with 16 GB Double Data Rate Type 3 (DDR3) memory, was used.

The optimization model has 3,956 variables and 1,054 constraints with 29,416 Jacobian elements, 20,160 of which are nonlinear. The Hessian of the Lagrangian has 0 elements on the diagonal, 3528 elements below the diagonal, and 3612 nonlinear variables. The total central processing unit (CPU) time based upon one optimization attempt ranged from about 4 seconds to less than 1 minute depending on the number of iterations used to find the optimal solution.

The analysis was completed using two different reclaimed water qualities with different reclaimed water availabilities and different irrigation efficiencies by implementing the model for 100 iterations. The analysis predicted the maximum individual farm net benefit, total net benefit, individual farm cultivated area, total cultivated area, net benefit per hectare, and the area dedicated to each crop. Different irrigation efficiencies were selected taking into account the irrigation technique used. In Iraq, the traditional flooding system with an estimated irrigation efficiency (IE) ranging from 45-55% is the most dominant irrigation techniques used (Iraqi Ministry of Water Resources 2014). It is obvious that with the development of modern irrigation techniques, the irrigation efficiency should increase accordingly reaching up to 85 % using advanced irrigation systems. While there is debate regarding the impact of increasing irrigation efficiency on water consumption at the basin scale (Grafton et al. 2018), increasing irrigation efficiency should increase water availability in Iraq at the basin scale. In Iraq, agricultural return flows are unsuitable for irrigation and groundwater is not used extensively in Iraq, therefore, enhancing irrigation efficiency will reduce irrigation return flows and flows to groundwater. However, the infrastructure in Iraq does not currently utilize these flows so the basin-scale impact on water resources should be positive. The model was run using two reclaimed water types with different quantities considering five different irrigation efficiencies ranging from 45% to 85% to help determine the potential benefits of improving the irrigation systems.

The maximized individual farm net benefits using RW_A and RW_B on the proposed 84 farms for different irrigation efficiencies and different quantities of water are presented in Figures 7-1 and 7-2. Results showed that the net benefit of using RW_A and RW_B increases with the increase of the amount of reclaimed water used. The use of 6.0 MCM of RW_A with a 45% irrigation efficiency (IE) satisfied an individual farm net benefit of $7282 cultivating up to 4 crops on each farm. While the total net benefit, which is computed from the multiplication of the individual farm net benefit times 84 farms, using the same quantity of RW_A with 45% IE is $\$0.612 \times 10^6$ from the cultivation of all the 14 crops listed in Table 6-1, except for barley. Approximately 314.5 hectares of the 13 crops were cultivated on the 84 farms (Table 7-1) up to 4 crops on each individual farm. For the use of 6.0 MCM of RW_A with 85% IE, the model predicts an individual farm net benefit of $16220 with a total net benefit of $\$1.363 \times 10^6$ while cultivating a total of 570.34 ha comprised of 13 out of the 14 crops listed in Table 6-1.

The maximization of the individual farm net benefit from the use of RW_B has followed a different pattern than that observed with RW_A. The use of the same quantity of RW_A with irrigation efficiencies of 55, 65, 75, and 85%, had individual farm net benefit increases by 26.6, 47.0, 63.0, and 76.1%, respectively, as compared to the results for a 45% IE. While, using RW_B of the same amount with irrigation efficiencies of 55, 65, 75, and 85% had an individual farm net benefit

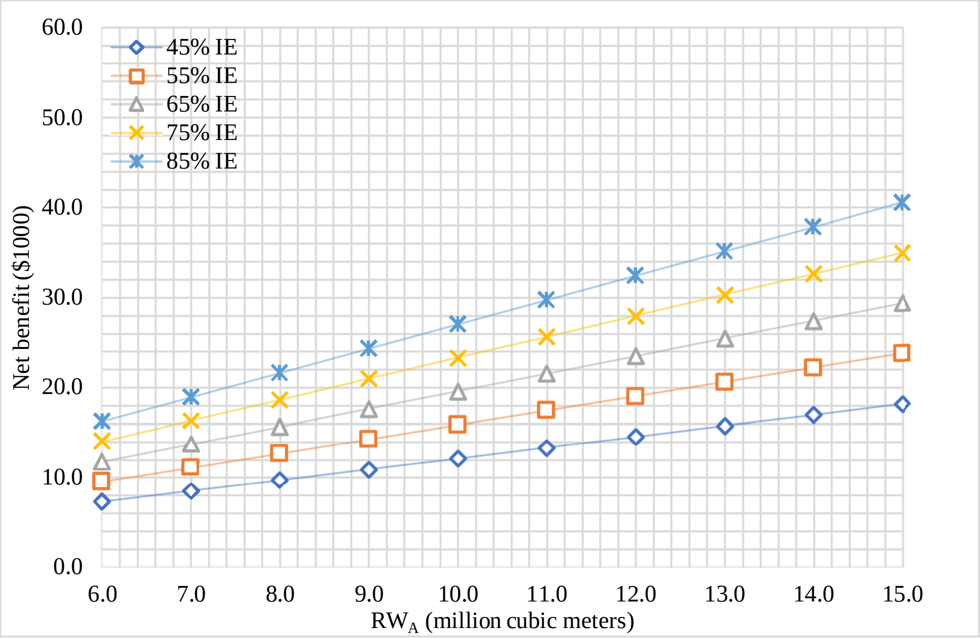


Figure 7-1. Individual farm net benefit (thousand $) predicted using reclaimed water type A (RW$_A$) with five different irrigation efficiencies (IEs).

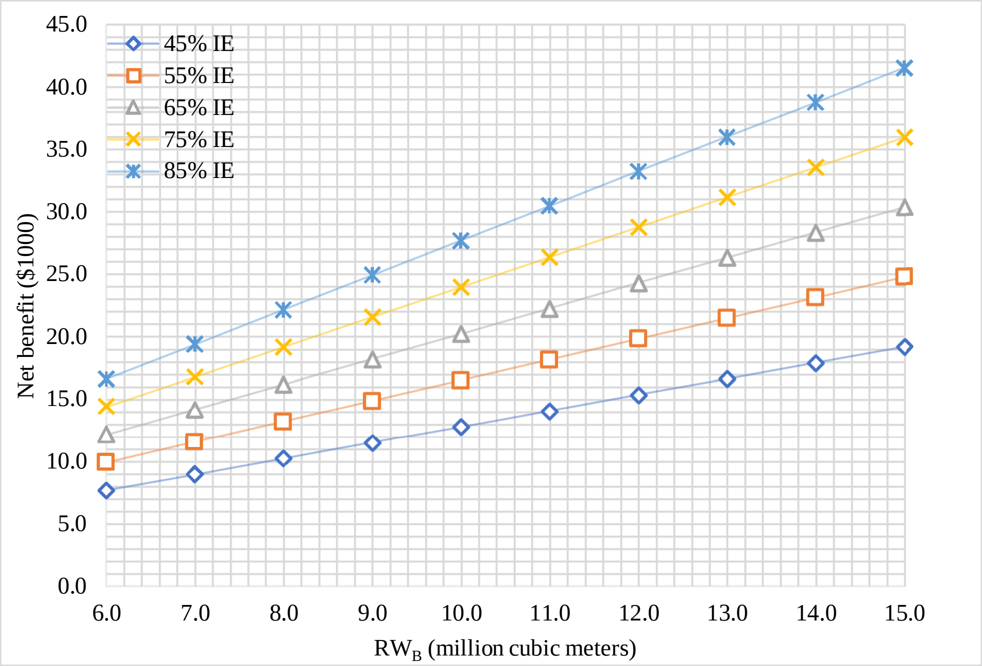


Figure 7-2. Individual farm net benefit (thousand $) predicted using reclaimed water type B (RW$_B$) with five different irrigation efficiencies (IEs).

increases by 25.4, 45.1, 60.8, and 73.6%, respectively in comparison to the computed results for a 45% IE. Small increases in irrigation efficiency are clearly beneficial which increase the individual farm net benefit as well as the total farms net benefit. The model demonstrates that the use of higher irrigation efficiencies, which means more water availability due to advanced irrigation techniques, can produce a higher net benefit and greater crop diversity.

The optimum maximized individual farm net benefits using RW_A was $40,550 using 15.0 MCM of RW with an 85% IE while cultivating 1,624 ha of the 14 types of crops (Figure 7-1). While, the optimum maximized individual farm net benefits using RW_B was $41,540 using 15.0 MCM of RW with an 85% IE while cultivating 1,784 ha with 12 different types of crops Figure 7-2). As illustrated in Figure 7-2, it is obvious that using RW_B results in a higher net benefit values in comparison to RW_A (Figure 7-1), due to the difference in the crops allowed to be cultivated using both RW types and due to the cost of RW_B being less than RW_A.

Using 6.0 MCM of RW_B with 45% IE has a computed net benefit of $\$0.645 \times 10^6$, cultivating 430.7 ha of 12 different crops, which is higher than the net benefit computed using RW_A, cultivating 314.5 ha of 13 crops. RW_B has shown a significant advantage over RW_A when both used the same quantity of water to cultivate different types of crops on different areas. The advantage of RW_B over RW_A is the cultivation cost and the selling price of the cultivated crops are the same except RW_B is less expensive than RW_A.

The higher quantities of reclaimed water in combination with higher irrigation efficiencies result in the cultivation of more land which produces a higher net benefit when crops with higher economic value are cultivated. In this optimization model, the maximized net benefit from using RW_A had a proportional increase reaching a value of \$3.41 × 10^6 when 15.0 MCM of RW_A was used with 85% IE. Optimizing the use of higher water availabilities with RW_B results in a commensurate increase in the net benefit with higher irrigation efficiencies satisfying higher net benefits in comparison to the use of the equivalent quantities with irrigation efficiencies of RW_A.

The cultivated areas predicted from optimizing the allocation of RW_A are presented in Figure 7-3. Increasing the quantities of RW_A used results in an oscillatory increase in the cultivated area. Using 6.0 MCM of RW_A with 45, 55, 65, 75, and 85% IEs results in irrigated areas of 430.7, 387.3, 489.1, 577.7, and 599.5 ha, respectively.

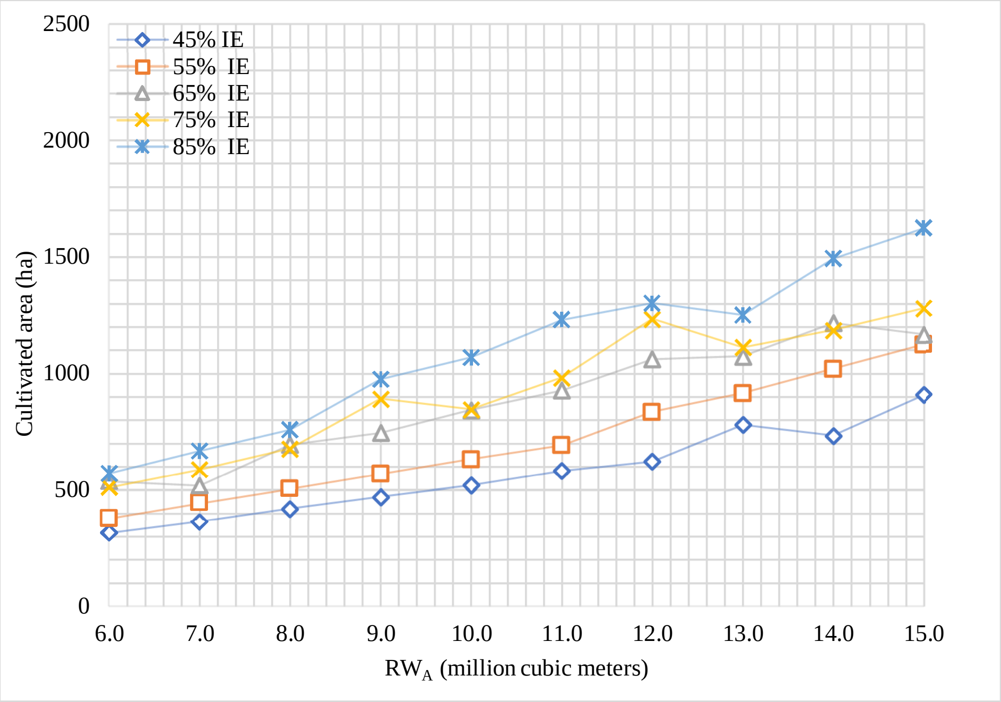


Figure 7-3. Total cultivated area (ha) predicted using reclaimed water type A (RW_A) with five different irrigation efficiencies (IEs).

The model satisfies the maximum individual farm net benefit by cultivating up to 4 crops at each farm. Therefore, tomatoes, potatoes, onion, eggplant, cucumber, and alfalfa were the most dominant crops selected by the model to be cultivated using RW_A. While, optimizing the model using 15.0 MCM of RW_A with 45, 55, 65, 75, and 85% IEs results in irrigated areas of 908.0, 1124.0, 1167.6, 1279.6, and 1624.0 ha, respectively. The cultivated area predicted by the model does not show a homogeneous pattern of increase because the model tends to satisfy the maximum net benefit regardless of how much area is to be cultivated since it has enough quantity of water. For example, using 10.0 MCM of RW_A with 65% and 75% irrigation efficiencies has predicted a total area of 843.3 and 845.2 ha respectively with a very small difference between the two water quantities. On the other hand, using 8.0 MCM of RW_A with 65% irrigation efficiency has predicted a total area of 694.2 ha which is higher than the predicted area of 676.0 ha using the same quantity of water with 75% irrigation efficiency. The model has provided a flexibility in crop selection considering the available amount of water in predicting the maximum individual farm net benefit.

The total cultivated areas using RW_B with different irrigation efficiencies are presented in Figure 7-4. The results show that the increase in the reclaimed water quantities used, the served area will increase accordingly depending on the evapotranspiration of the crops cultivated. The model predicts the individual farm maximum net benefit by cultivating certain areas using a variety of crops as a function of the available quantity of water. Maximizing the net benefit using RW_B has followed an unstable pattern in predicting the cultivated area. Using higher quantities of water should result in more cultivated areas to satisfy the maximum net benefit, but this optimization model does not follow this tactic as illustrated in Figure 7-4, where it predicts higher net benefits from the cultivation of less area. Using 9.0 MCM of RW_B with 55, 65, and 85% IEs results in the cultivation of 644.4, 737.3, and 833.2 ha which are lower than the 896.2 ha which was predicted using the same quantity of water with 45% IE. This is because the model has satisfied the individual maximum net benefit by considering crops with a higher economic value that consume less water, as with 9.0 MCM with 45% IE, where only 8 out of the 12 crops were irrigated using RW_B. Instead of cultivating all the 12 crops, the model has predicted to cultivate 8 of them to satisfy the maximum net benefit by including 1.5 ha of cotton, 276.0 ha of maize, 261.6 ha of tomatoes, 52.8 ha of clover, 108.3 ha of alfalfa, 49.0 ha of eggplant, 96.7 ha of sunflower, and 50.7 ha of okra. A similar pattern was followed by the model using 12.0 MCM and 13.0 MCM of RW_B with 45% IE. The flexibility of selecting more than one crop to be cultivated on each farm is one of the features of the model to satisfy the maximum net benefit. In addition, the minimum allowed area of crops to be cultivated may be adjusted based on specific conditions to provide constraints in the model consistent with supply and demand.

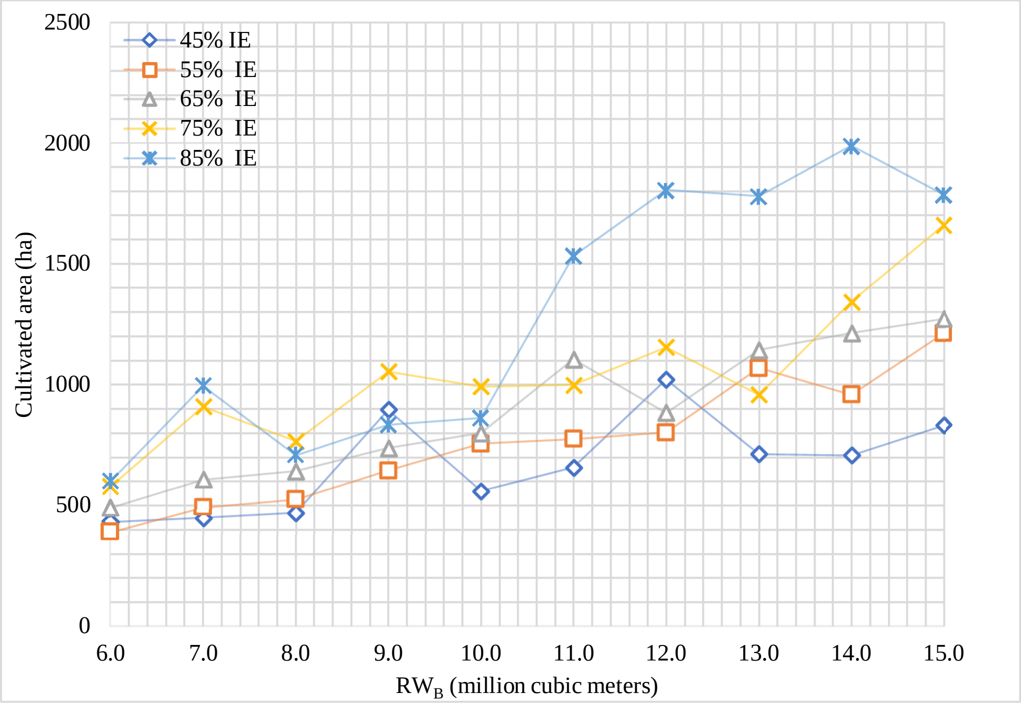


Figure 7-4. Total cultivated area (ha) predicted using reclaimed water type B (RW$_B$) with five different irrigation efficiencies (IEs).

The average net benefit per hectare ($/ha) predicted from optimizing the allocation of RW$_A$ and RW$_B$ is presented in Figures 7-5 and 7-6, respectively. The computed net benefit per cultivated hectares varied according to the cultivated area. The factors that limit the net benefit are the increase in the cultivated area along with the requirement to grow lower economic value crops. For example, using 6.0 MCM of RW$_A$ with 45% IE has predicted a net benefit per hectare of about 1,945 $/ha while the computed individual farm net benefit was about $7,241.8 with a total net benefit of $0.612 × 10^6 cultivating 13 different crops on 314.5 ha. While, the model predicted a net benefit of 2,388.9 $/ha, cultivating 570 ha of the same 13 crops using 6.0 MCM of RW$_A$ with 85% IE.

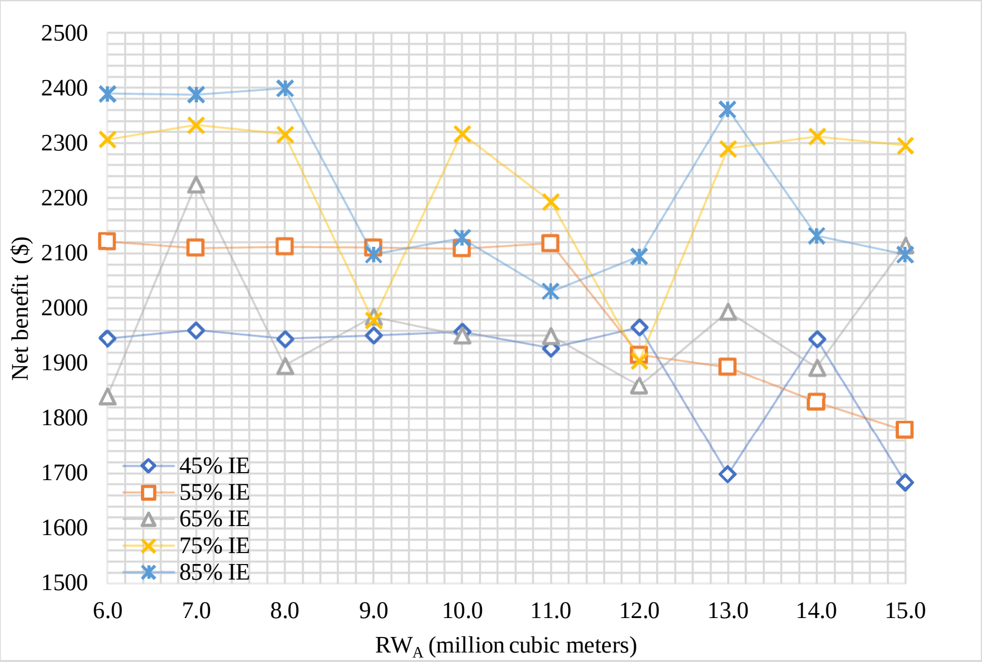


Figure 7-5. Net benefit per hectare ($/ha) predicted using reclaimed water type A (RW_A) with five different irrigation efficiencies (IEs).

In contrast, the model results experienced a significant fluctuation in the predicted net benefit per hectare with the increase in irrigation efficiencies using higher quantities of water while maintaining the homogeneous increase of the individual farm and the total maximized net benefit computed from the cultivation of up to 4 crops on each farm. Using 15.0 MCM of RW_A with 45% IE has predicted a net benefit of about 1,683.5 $/ha while cultivating 914.5 ha of the 14 crops allowed. A net benefit of 2,097.5 $/ha was predicted by cultivating 1,666 ha of all the 14 crops ranged from a 250 ha of sesame, 218.4 ha of tomatoes, 213.5 hectares of potatoes, 150 ha of eggplant, 150 ha of onion, 137.7 ha of cucumber, 100 ha of okra, reaching to 20.0 ha of maize using 15.0 MCM of RW_A with 85% IE (Figure 7-5). The net benefit per hectare using different availabilities of RW_B with different irrigation efficiencies, as illustrated in Figure 7-6, fluctuates with the increase in the quantities of RW_B with increase in IEs due to the same reasons mentioned under the use of RW_A.

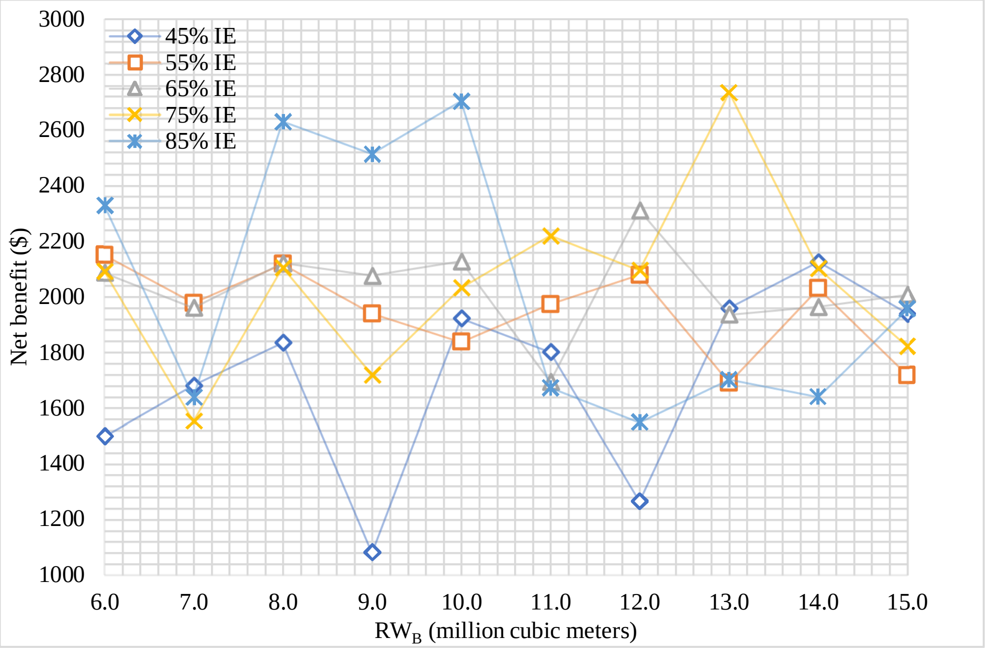


Figure 7-6. Net benefit per hectare ($/ha) predicted using reclaimed water type B (RW_B) with five different irrigation efficiencies (IEs).

The cultivated crops using different availabilities of RW_A with 45, 65, and 85% IEs are presented in Figures 7-7 to 7-9, respectively. There are 14 different types of crops available for cultivation using RW_A as listed in group A in Table 6-1. Each crop has its own evapotranspiration value, selling price, production cost, and yield per hectare. Starting with 6.0 MCM with 45% IE, the model predicted cultivation of 8.6 ha of cotton, 9.0 ha of wheat, 5.7 ha of maize, 64.6 ha of potatoes, 45.7 ha of tomatoes, 16.7 of clover, 31.6 ha of cucumber, 12.7 ha of alfalfa, 66.8 of onion, 33.7 ha of eggplant, 5.2 ha of sunflower, 8.1 ha of sesame, and 6.4 ha of okra. Except for tomatoes which satisfied the highest net benefit per hectare as compared to the other competitive crops in Table 6-1, the model has maintained cultivating as many crops as possible to satisfy the maximum individual farm net benefit while fulfilling the diversity in production (Table 7-2). All of the 84 cultivated farms of the system have the opportunity to cultivate 2-4 crops depending on the ratio of their areas to the total observed area of farms. Increasing the quantity of RW_A and/or increasing the irrigation efficiency, increases the quantity of water allocated on farms cultivating more crops except when the model used less crops to satisfy the maximum net benefit. With 45% IE using different RW_A availabilities, 13 crops have been cultivated, considering the economic value of each crop and its water consumption, as illustrated in Figure 7-7. Increasing the irrigation efficiencies using a certain quantity of reclaimed water provides the opportunity to cultivate more crops.

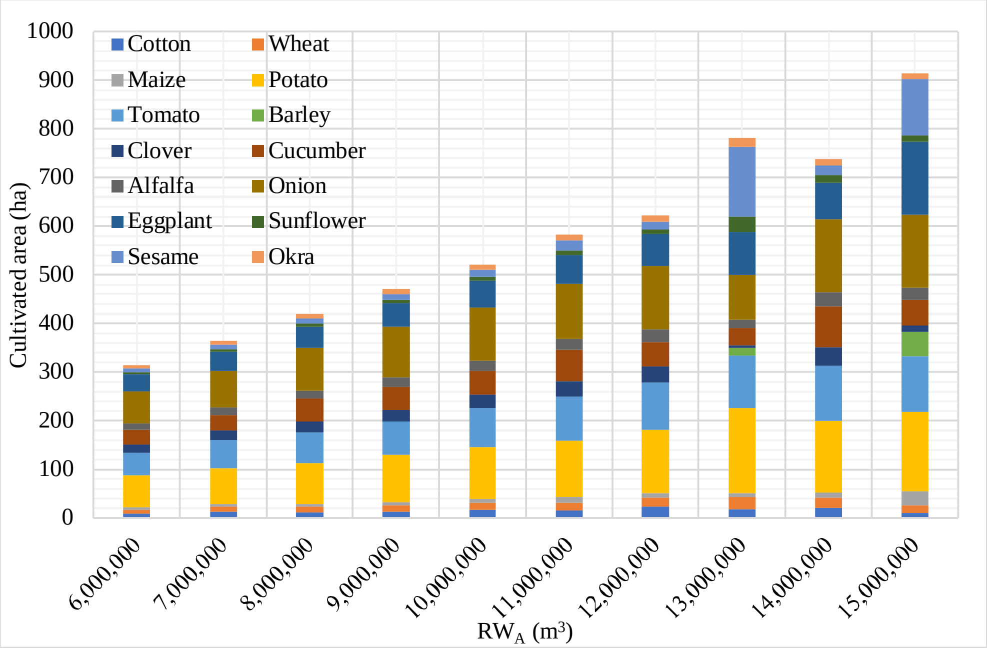


Figure 7-7. Predicted area (ha) of crops irrigated using reclaimed water type A (RW_A) with 45% irrigation efficiency.

For example, at 65% IE the model predicts the cultivation of all the 14 crops (Figure 7-8), with one exception when 7.0MCM of RW_A was used there was no barley. While, with 85% IE using certain availabilities of RW_A, barley was excluded from cultivating when 6.0, 7.0, 8.0 and 13.0 MCM was used (Figure 7-9). An example of how the model has predicted the areas for each crop is illustrated in Table 7-2 using 15.0 MCM of RW_A with 85% IE.

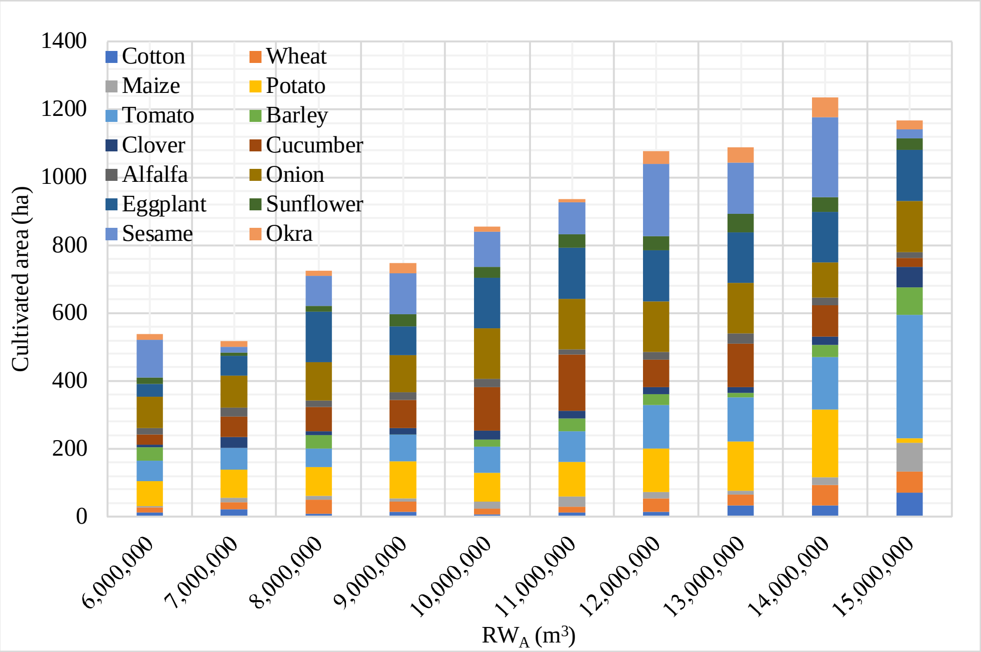


Figure 7-8. Predicted area (ha) of crops irrigated using reclaimed water type A (RW_A) with 65% irrigation efficiency.

The cultivated crops using different availabilities of RW_B with 45, 65, and 85% IEs are illustrated in Figures 7-10 to 7-12, respectively. The use of RW_B has followed the same patterns observed with RW_A by cultivating a variety of crops with the highest economic value crop then the next highest and so on while selecting from the 12 crops listed in group B in Table 6-1. Starting

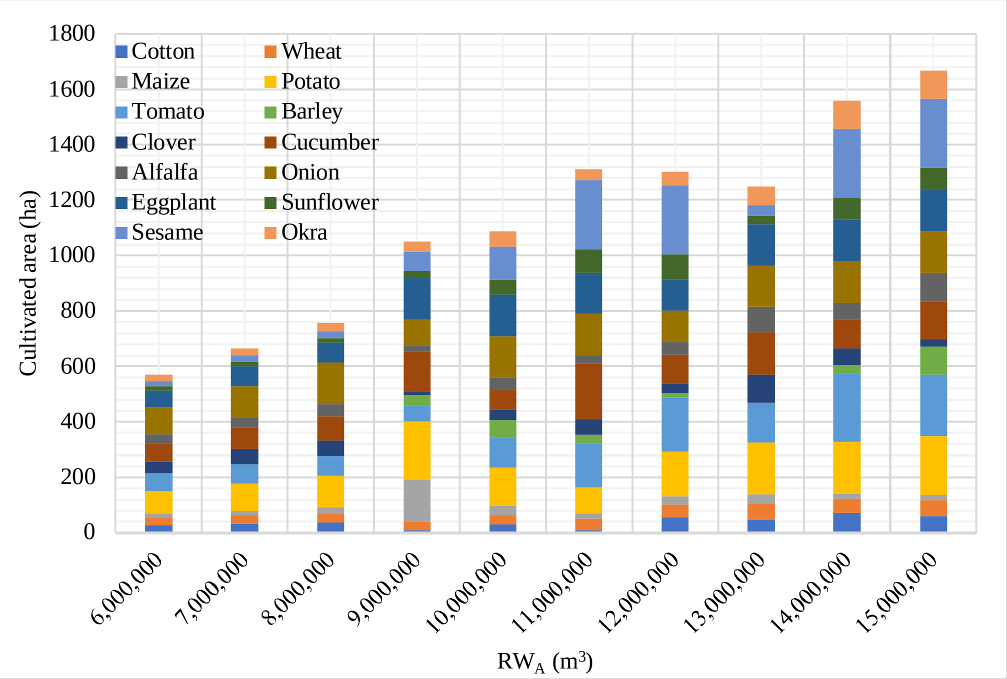


Figure 7-9. Predicted area (ha) of crops irrigated using reclaimed water type A (RW$_A$) with 85% irrigation efficiency.

from irrigating only 97.9 ha of tomatoes, 89.1 ha of eggplant, 71.5 ha of sesame, 69.2 ha of cucumber, and different areas of the other 8 crops using 6.0 MCM of RW$_B$ with 45% IE reaching to the irrigation of 301.9 ha of tomatoes, 150 ha of eggplant, 99.5 ha of cucumber, 75.4 ha of alfalfa, 50.1 ha of sunflower, and different areas of the other 7 crops by using 15.0 MCM of RW$_B$ (Figures 7-10). The cultivated crops using different RW$_B$ availabilities with 65% and 85% IEs are illustrated in Figures 17-11 and 7-12, respectively. Even though the optimization model allows up to 4 crops to be cultivated simultaneously on the same farm, results showed that most of the farms cultivated at least 2 crops depending on the RW availability and the IE implemented. An example of how the model has predicted the areas for each crop is illustrated in Table 7-3 using 15.0 MCM of RW$_B$ with 85% IE.

Table 7-2. Area (ha) of the cultivated crops in each farm (FA) using 15.0 million cubic meters of RW_A with 85% irrigation efficiency.

	Cotton	Wheat	Maize	Potato	Tomato	Barley	Clover	Cucumber	Alfalfa	Onion	Eggplant	Sunflower	Sesame	Okra
FA_{1}		17.61			10.29									
FA_{2}										7.93				23.42
FA_{3}					6.75				36.51	4.94				
FA_{4}				3.02							3.86			27.89
FA_{5}	6.56			9.48										
FA_{6}	12.83				10.16									
FA_{7}											19.76		47.42	
FA_{8}								23.14				4.28		
FA_{9}					6.07				3.50					
FA_{10}	7.41				8.40									
FA_{11}					7.80							9.30		
FA_{12}					0.02			20.26						
FA_{13}	4.85			8.83										
FA_{14}					6.18				8.68					
FA_{15}	5.11				7.66									
FA_{16}				7.73								3.26		
FA_{17}		4.85			7.18									
FA_{18}				7.09									15.16	
FA_{19}					6.11								19.42	
FA_{20}				7.07			4.66							
FA_{21}							0.59				18.97			
FA_{22}		7.89			7.92									
FA_{23}										10.73				4.65
FA_{24}						0.39					19.09			
FA_{25}										9.58	3.16		6.12	
FA_{26}		7.53			7.84									
FA_{27}					7.30							6.73		
FA_{28}								9.48		6.10				
FA_{29}			0.71					20.83						
FA_{30}				9.72		19.38								
FA_{31}	1.73									12.50				
FA_{32}		5.09			7.24									
FA_{33}			6.86	8.65										
FA_{34}	2.54			7.95										
FA_{35}					6.87							4.51		
FA_{36}	2.52			7.95										
FA_{37}								1.33		10.68				
FA_{38}					6.11				5.39					
FA_{39}	0.65				6.21									
FA_{40}				7.04			2.69							
FA_{41}					5.53									6.03
FA_{42}				7.44								1.98		

	Cotton	Wheat	Maize	Potato	Tomato	Barley	Clover	Cucumber	Alfalfa	Onion	Eggplant	Sunflower	Sesame	Okra
FA$_{43}$	2.44				6.79									
FA$_{44}$			3.38		6.70									
FA$_{45}$				6.78										2.38
FA$_{46}$					6.04				1.85					
FA$_{47}$	1.73				6.56									
FA$_{48}$				5.25							4.73			
FA$_{49}$										13.53		5.71		
FA$_{50}$	2.07										21.07			
FA$_{51}$					6.00									
FA$_{52}$				8.74								7.76		
FA$_{53}$			9.04	9.17										
FA$_{54}$				7.15			9.26							
FA$_{55}$								12.30		4.52				
FA$_{56}$									3.19	11.55				
FA$_{57}$	4.57				7.48									
FA$_{58}$				10.60		25.69								
FA$_{59}$							7.00			11.61				
FA$_{60}$					1.62			14.85						
FA$_{61}$					6.13				6.12					
FA$_{62}$											17.29			6.69
FA$_{63}$		4.40						23.98						
FA$_{64}$					4.54									18.67
FA$_{65}$				7.31									49.67	
FA$_{66}$		9.72		9.76										
FA$_{67}$				7.28					12.00					
FA$_{68}$				7.43					17.93					
FA$_{69}$					10.08	33.85								
FA$_{70}$						2.89					20.04			
FA$_{71}$				7.20					8.60					
FA$_{72}$					0.15						18.48			
FA$_{73}$										10.89				3.61
FA$_{74}$										12.16			71.04	
FA$_{75}$	0.56									11.77				
FA$_{76}$	3.97			8.50							3.54			
FA$_{77}$										11.51			7.67	
FA$_{78}$				8.44								6.41		
FA$_{79}$					8.57							13.32		
FA$_{80}$				8.51								6.74		
FA$_{81}$					7.38							7.15		
FA$_{82}$					8.70	22.39								
FA$_{83}$				3.02				11.57						
FA$_{84}$				6.39									33.49	6.67
Total	59.52	57.09	19.99	213.49	218.38	104.58	24.20	137.73	103.77	150.00	150.00	77.14	250.00	100.00

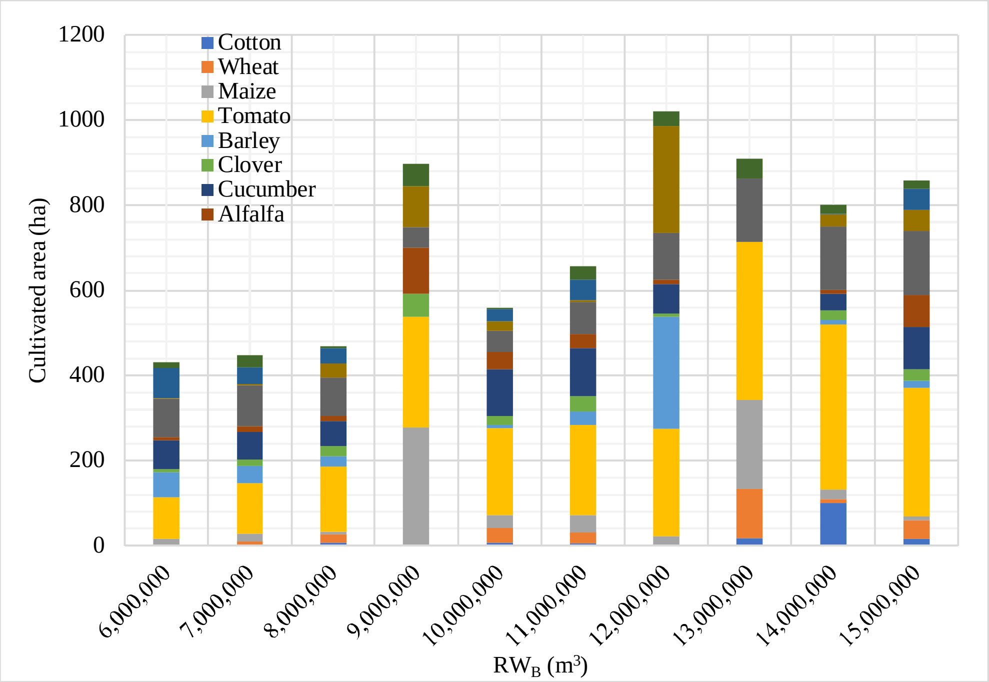


Figure 7-10. Predicted area (ha) of crops irrigated using reclaimed water type B (RW$_B$) with 45% irrigation efficiency.

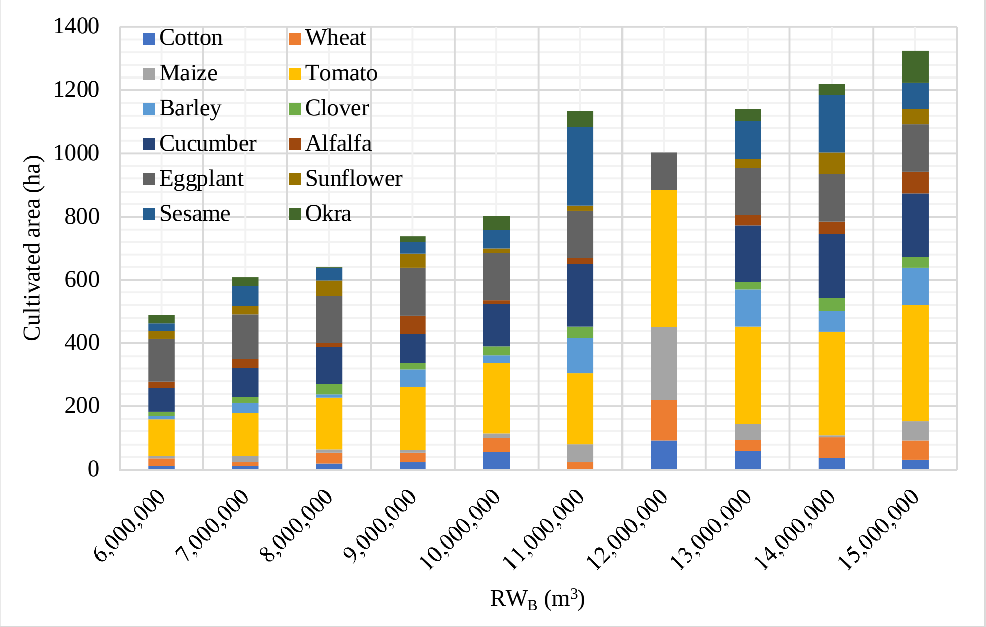


Figure 7-11. Predicted area (ha) of crops irrigated using reclaimed water type B (RW$_B$) with 65% irrigation efficiency.

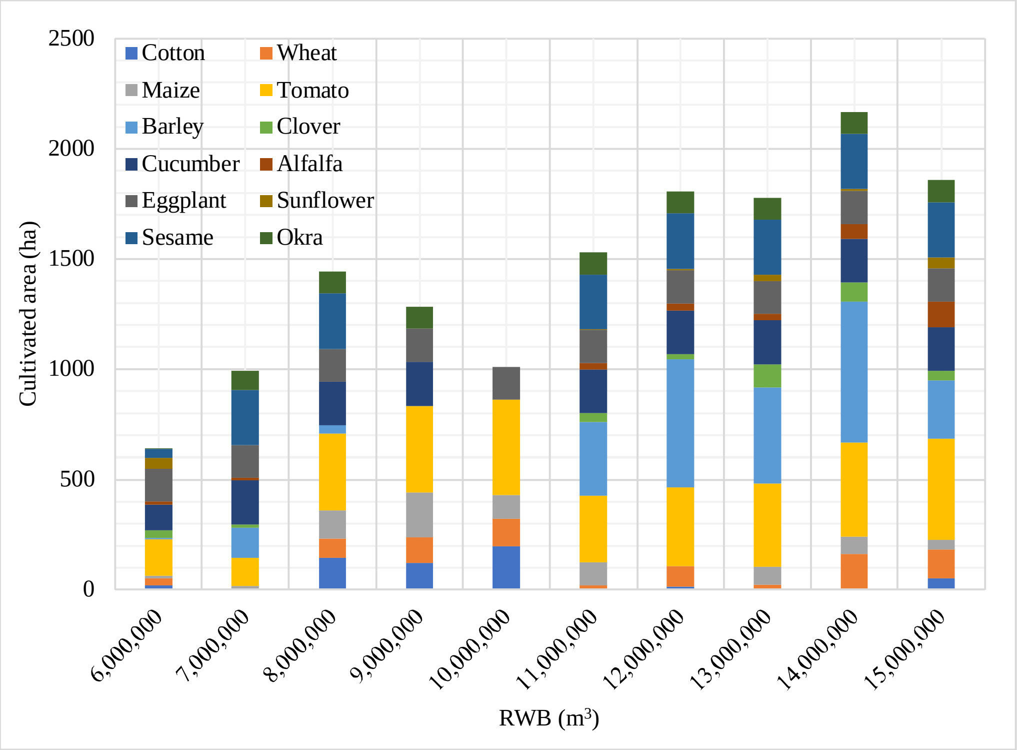


Figure 7-12. Predicted area (ha) of crops irrigated using reclaimed water type B (RW_B) with 85% irrigation efficiency.

Table 7-3. Area (ha) of the cultivated crops in each farm (FA) using 15.0 million cubic meters of RW_B with 85% irrigation efficiency.

	Cotton	Wheat	Maize	Tomato	Barley	Clover	Cucumber	Alfalfa	Eggplant	Sunflower	Sesame	Okra
FA_1		7.69					24.02					
FA_2			27.00	10.71			31.24		2.93			
FA_3							17.33				106.79	
FA_4				5.56				23.67				
FA_5				9.91	36.56							
FA_6		18.99		9.80								
FA_7	3.26								16.35			12.93
FA_8				5.68							60.24	
FA_9			4.41	6.77								
FA_{10}	7.59			7.98								
FA_{11}				9.42	31.98							
FA_{12}				5.75		10.43						
FA_{13}				5.82				9.49				
FA_{14}			10.94	7.91								
FA_{15}		7.57		7.51								
FA_{16}	3.17			6.83								
FA_{17}	3.44			6.90								
FA_{18}				5.87		5.66						
FA_{19}				5.22								7.23
FA_{20}				5.86		6.02						
FA_{21}	0.63								18.45			
FA_{22}							16.44		2.51			
FA_{23}	5.54			7.45								
FA_{24}				5.83							32.35	
FA_{25}				8.50	23.33							
FA_{26}		7.72		7.54								
FA_{27}				5.85				7.87				
FA_{28}				7.00						6.76		
FA_{29}				7.41						9.51		
FA_{30}		0.30							18.14			
FA_{31}				5.83				9.10				
FA_{32}				6.76						5.10		
FA_{33}				1.32			14.90					
FA_{34}				5.86		5.77						
FA_{35}				5.90				5.27				
FA_{36}		4.93		6.99								
FA_{37}				7.89	17.62							
FA_{38}				5.90				5.52				
FA_{39}		0.96		6.19								
FA_{40}				5.45								5.09
FA_{41}		4.15		6.83								
FA_{42}				7.12	10.47							
FA_{43}	2.50			6.65								

	Cotton	Wheat	Maize	Tomato	Barley	Clover	Cucumber	Alfalfa	Eggplant	Sunflower	Sesame	Okra
FA_{44}				5.93		2.94						
FA_{45}				6.93	8.72							
FA_{46}				5.96				1.90				
FA_{47}		2.56		6.51								
FA_{48}	1.88			6.49								
FA_{49}		12.04		8.41								
FA_{50}				5.68		13.57						
FA_{51}				6.00								
FA_{52}							19.03				5.08	
FA_{53}	0.56								18.40			
FA_{54}									18.73	1.73		
FA_{55}								0.36	17.94			
FA_{56}		0.78							18.43			
FA_{57}		6.76		7.35								
FA_{58}							19.02				5.81	
FA_{59}				5.76				12.67				
FA_{60}				5.86				7.31				
FA_{61}				5.88				6.27				
FA_{62}				10.09	38.19							
FA_{63}				8.19						14.76		
FA_{64}	8.88			8.32								
FA_{65}							15.66					10.07
FA_{66}				10.01	37.50							
FA_{67}							20.61			3.16		
FA_{68}				12.18	57.69							
FA_{69}				7.53						10.33		
FA_{70}				5.81				10.11				
FA_{71}	6.21			7.62								
FA_{72}				4.79								11.20
FA_{73}	5.09			7.33								
FA_{74}				2.28								34.55
FA_{75}		6.09		7.22								
FA_{76}		33.91		4.85							5.53	10.66
FA_{77}				5.85				7.89				
FA_{78}		7.99		7.60								
FA_{79}	3.17						21.75					
FA_{80}				5.82							34.20	
FA_{81}		0.28							18.13			
FA_{82}		6.99		7.40								
FA_{83}				5.11								8.28
FA_{84}				5.88				6.19				
Total	51.91	129.70	42.35	462.43	262.05	44.39	200.00	113.61	150.00	51.37	250.00	100.00

7.6. Summary and Conclusions

The MINLP reclaimed water allocation optimization model was completed using two different reclaimed water qualities with varying reclaimed water availabilities and irrigation efficiencies. The analysis predicted the maximum individual farm net benefit, total net benefit, individual farm cultivated area, total cultivated area, net benefit per hectare, and the area dedicated to each crop. Results showed that the net benefit of using RW_A and RW_B increases with the increase of the amount of reclaimed water used. For instance, using 6.0 MCM of RW_A with a 45% IE resulted in an individual farm net benefit of \$7282 cultivating up to 4 crops on each farm. While the total net benefit using the same quantity of RW_A with 45% IE is $\$0.612 \times 10^6$ including the cultivation of all 14 crops, except for barley. Small increases in irrigation efficiency are clearly beneficial which increase the individual farm net benefit as well as the total farms net benefit while maintaining greater crop diversity.

Using RW_B results in a higher net benefit values in comparison to RW_A due to the difference in the crops allowed to be cultivated using both RW types and due to the cost of RW_B being less than RW_A. The optimum maximized individual farm net benefits using RW_A was \$40,550 using 15.0 MCM of RW with an 85% IE while cultivating 1,624 ha with 14 types of crops. While, the optimum maximized individual farm net benefits using RW_B was \$41,540 using 15.0 MCM of RW with an 85% IE while cultivating 1,784 ha with 12 different types of crops. Increasing the quantities of RW used resulted in an oscillatory increase in the cultivated area as different crops were determined to be optimal for different quantities of RW. The model provided flexibility in crop selection considering the available amount of water while predicting the maximum individual farm net benefit. The maximum individual farm net benefit was satisfied by cultivating up to 4 crops at each farm. Tomatoes, potatoes, onion, eggplant, cucumber, and alfalfa were the most dominant crops selected by the model to be cultivated using RW_A.

The cultivated area predicted by the model does not show a homogeneous pattern of increase because the model tends to reach the maximum net benefit regardless of how much area is to be cultivated since it has enough quantity of water. The flexibility in crops selected is one of the features of the model to satisfy the maximum net benefit. In addition, the minimum allowed area of crops to be cultivated may be adjusted based on specific conditions to provide constraints in the model to respond to changing supply and demand.

CHAPTER 8 REGIONAL WATER ALLOCATION OPTIMIZATION MODEL USING THREE DIFFERENT WATER RESOURCES FOR FIVE DIFFERENT USES

8.1. Introduction

The goal of chapter 8 of this dissertation is the development of a regional water allocation optimization model that maximizes reclaimed water use from the allocation of surface water, groundwater, and reclaimed water for domestic, industrial, agricultural, commercial, and recreational uses, considering Baghdad as a case study. Over the last several years, Iraq has been experiencing serious water shortages due to the decline in transboundary water supplies, droughts, pollution, conflicts, political instability, water resources mismanagement, and an increasing population. The continuing threat to the future of water resources in Iraq has resulted in the World Bank identify Iraq as the most threatened Middle East country in terms of water shortages for the coming decades. Therefore, the implementation of sustainable water resources management systems to accommodate future water demand needs to take into consideration alternative and sustainable water resources.

The importance of water along with the potential shortage of renewable supplies have pushed many counties to consider reclaimed water (RW) as an alternative source of supply. It has been used widely in irrigation for decades ago, even with low qualities. Recently, RW plays an important role as an alternative and reliable source of water as it receives increased attention and acceptance among people. The economic viability and public acceptance for RW enhances the saving of available freshwater by substituting it with the RW for irrigation, industry, and/or recreation. RW has been widely used for the irrigation of parks, school grounds, landscapes, golf courses, construction, and industrial sites. Environmentally, RW use is desirable in reducing the negative impacts on the environment resulting from the discharge of pollutants.

The nomenclature of reclaimed water varies depending on which country or region it is used. Some countries call reclaimed water as reused wastewater while others call it as used water. In Singapore, the RW is known as the new water (NEWATER) to give it more acceptance among people. Many of the Middle East countries, such as in UAE, Jordan, Kuwait, Turkey, and others, have invested in the field of treated wastewater reuse as an alternative source of water to satisfy part of the essential demands for irrigation, recreation and industry.

The tertiary and/or secondary treated wastewaters are used to irrigate different types of crops and for industrial, domestic, commercial, groundwater recharge, and recreational uses, as done in many regions such as in the United States, as in California, Florida, Arizona, and Texas. Advanced wastewater treatment technologies have been introduced and practiced in the United States to facilitate and guarantee quality standards for direct potable reuse, as in El-Paso, Texas. On the other hand, the long-term conflicts and the financial shortage in Iraq has disturbed the investment in the field of reclaimed water use while only in Baghdad there is a daily disposal of more than 1.0 million cubic meters (MCM) of secondary treated wastewater to the environment. This quantity of treated wastewater is expected to be doubled shortly if the planned sewerage projects are being constructed. Recently, there is growing attention, at the governmental level, to use RW as an alternative source of water, due to the current impacts of inappropriate treatment and discharge with the generated wastewater which have caused the contamination of the environment, and to mitigate water shortage impacts.

Due to the increase in urbanization along with the rapid increase in population, RW deserves greater attention to be converted into an alternative and reliable resource of water, at least, for limited uses in Iraq. The inclusion of RW use is essential in the implementation of future water resource projects, to mitigate the pressure on built ones, and to reduce the recent and potential water shortage consequences.

8.2. Fresh Water Problems and Reclaimed Water Availability in Iraq

In Iraq, the recurrence of water shortages along with sequential droughts have exhausted significant quantities of water stored in reservoirs, such as the drought which occurred between 2007 and 2009, that strongly affected the agricultural sector. In summer 2018, Iraq was subjected to the worst modern water shortage due to the filling of the reservoir of Ilisu dam in Turkey. The filling process of the reservoir was stopped due to the agreement between the two countries, which will allow the filling of the reservoir to be resumed later while still allowing fair water supplies to Iraq. Mesopotamia is suffering real water shortage which needs to be realized by the Iraqis who keep practicing inefficient and traditional habits of water use, such as the flood irrigation. Furthermore, they should recognize that water must be conserved judiciously and used sustainably to satisfy both recent and future demands. One of the most practical and applicable techniques to develop alternative water sources is to invest in water reclamation by considering reclaimed water as a sustainable source to satisfy agricultural irrigation requirements along with other potential uses to relieve pressure on the available water resources.

Each one of the Iraqi nineteen provinces contains several administrative units, which directly or indirectly dispose their treated and/or untreated wastewater to the environment. The projected daily treated, untreated, or partially treated wastewater is more than 6.0 MCM. The quality of the disposed treated wastewater influences the quality of freshwater and groundwater resources as it is discharged in large quantities. Very little investment has been made in wastewater treatment facilities, due to the lack of finance, which in most cases is not appropriately treated leading to environmental and health hazards. Therefore, wastewater treatment deserves greater emphasis and investment to satisfy quality standards.

Iraq has experienced several periods of water shortage, which needed urgent management accompanied with practicality to allocate existing water resources to satisfy water demands. It is a common practice for arid and semiarid regions (Metcalf et al. 2007), such as in Iraq, to use RW for agricultural irrigation and thereby create an alternative water resource without importing water. In Baghdad, there is a large quantity of treated wastewater which contributes to the pollution of the receiving waters that could be a useful source of water for a variety of applications.

The goal of chapter 8 of this dissertation is the development of a regional water allocation optimization model that maximizes reclaimed water use from the allocation of surface water, groundwater, and reclaimed water for domestic, industrial, agricultural, commercial, and recreational uses, considering Baghdad as a case study.

8.3. The Regional Water Allocation Optimization Model

Reclaimed water is an alternative resource that has the potential to help resolve the water crisis and it has not been used in Iraq yet. A water allocation optimization model was developed by considering the available and the expected water resources including reclaimed water. Mays, et al. (1983) prepared a report entitled “Development and Application of Models for Planning Optimal Water Reuse” for the Center for Research in Water Resources Bureau of Engineering Research, the University of Texas. The report includes several water reuse allocation optimization models, which enhanced and supported the idea of the current project. Essential changes were made to the mathematical equations used in the previously mentioned report to match the idea of this regional water allocation optimization model and to satisfy its objective subjecting to different types of constraints.

The developed optimization model assures fair allocation of water among all users, as other models have been applied in many other regions around the world. This optimization model maximizes reclaimed water use through the allocation of surface water (SW), groundwater (GW), and reclaimed water (RW) for five different types of uses; industrial, domestic, agricultural, commercial, and recreational use. Surface water and groundwater are the main sources of fresh water, while the reclaimed water is the alternative source. All the wastewater generated from the domestic and the commercial demand nodes is diverted to the main wastewater treatment plant (WWTP). While, the wastewater generated from the industrial demand nodes is either diverted to the main WWTP or to the private wastewater treatment plant (PWWTP), depending on the availability of the PWWTP to the industrial demand node. The treated wastewater is assumed either to be reused as reclaimed water, or it will be discharged to the downstream sink. The schematic diagram of the developed water allocation optimization model system is illustrated in Figure 8-1.

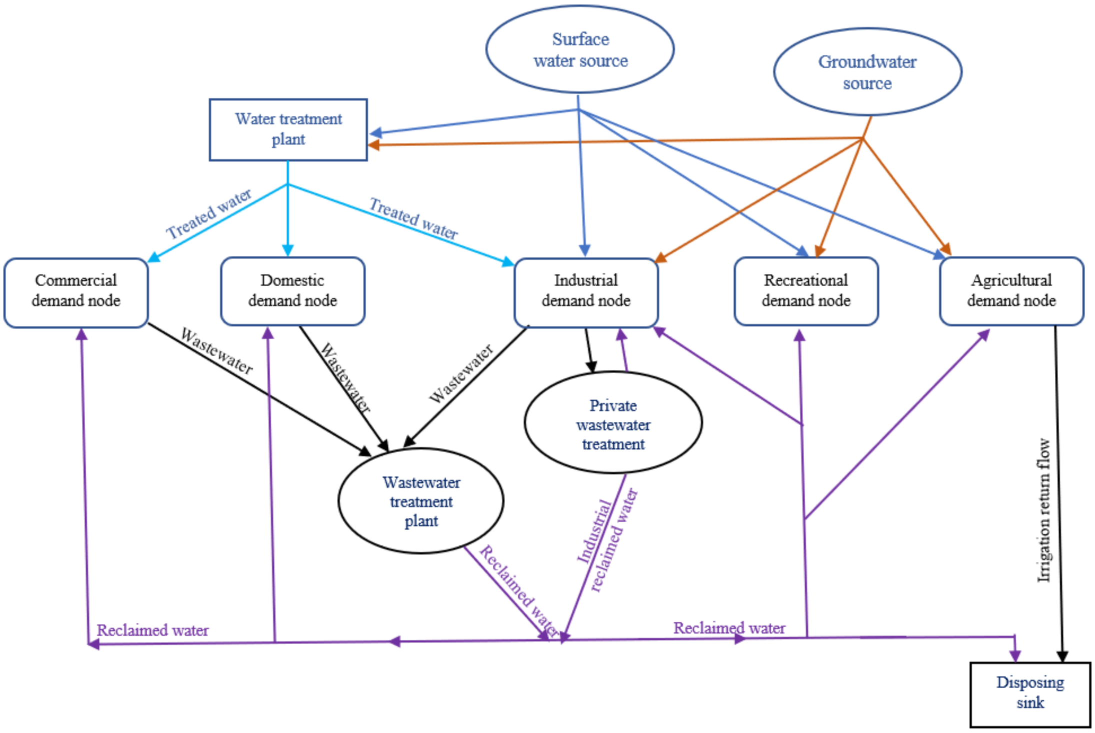


Figure 8-1. The schematic diagram of the developed regional water allocation optimization model system

The model was formulated using linear programming (LP) solved in the general algebraic mathematical solver (GAMS). The optimization model has been applied to Baghdad, with surface water supplies from the Tigris and the Euphrates Rivers, while the treated or partially treated wastewater is disposed to the Tigris River and to the Main Drain. In this dissertation, this model is expanding upon the previously developed models which have focused on agricultural use of surface and reclaimed water, respectively.

The mentioned three water resources supply water to the potential downstream users. Each type of use has a specific number of demand nodes. Surface water and groundwater are the fresh water resources which supply the domestic, industrial, and commercial demand nodes (municipal uses) through water treatment plants. While, fresh water resources supply untreated water to agricultural, and recreational demand nodes along with the large other industrial users, as illustrated in Figure 8-2. It should be mentioned that large industries, oil refineries and electrical power plant usually get their untreated water needs directly from water resources.

Each type of use satisfies its treated and/or untreated water demands from surface water, and groundwater resources as follows:

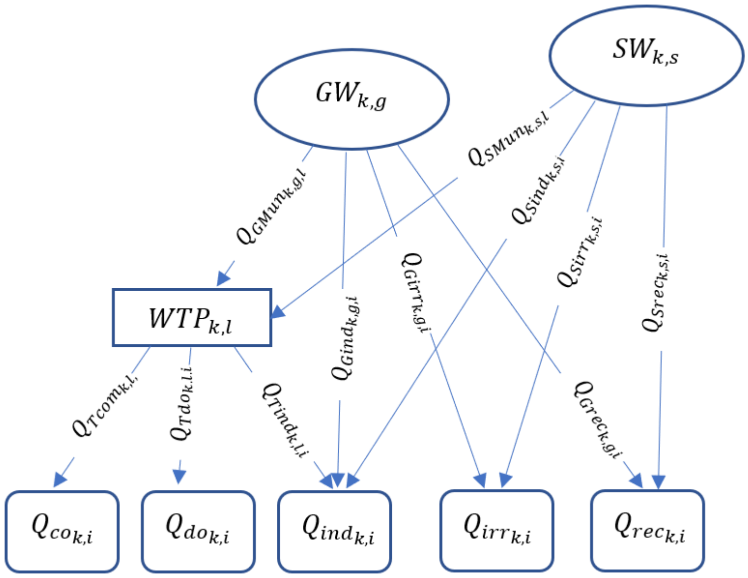


Figure 8-2. Schematic diagram of the assumed fresh water resources and types of use

8.3.1. *Industrial Water Demand* $Q_{ind_{k,i}}$

The industrial demand nodes are divided into two groups. The group of nodes which satisfy their treated water needs from the municipal water system, where it is treated in a water treatment plant (WTP). The second group of industrial demand nodes get their untreated fresh water needs directly from surface water and groundwater resources. This type of demand is possible to get reclaimed water either from its own private wastewater treatment plant (PWWTP), and/or from the main wastewater treatment plant (WWTP). The total diverted water from the mentioned three resources of water should meet or the water demand for each node. The potential water inflows for the industrial demand nodes are illustrated in Figure 8-3, which are:

a. Treated freshwater flow rate $\mathrm{Q_{Tind_{k,l,i}}}$ discharged from water treatment plant (WTP) l to industrial demand node i at reach k.

b. Surface water flow rate $\mathrm{Q_{Sind_{k,s,i}}}$ diverted from source (s) to industrial demand node i at reach k.

c. Groundwater flow rate $\mathrm{Q_{Gind_{k,g,i}}}$ pumped from source (g) to industrial demand node i at reach k.

d. Reclaimed wastewater rate $\mathrm{Q_{recind_{k,p,i}}}$ discharged from the private wastewater treatment plant (PWWTP) p at industrial demand node i to be used by the same node.

e. Reclaimed water rate $\mathrm{Q_{reind_{k,f,i}}}$ discharged from wastewater treatment plant (WWTP) (f) to industrial demand node i at reach k.

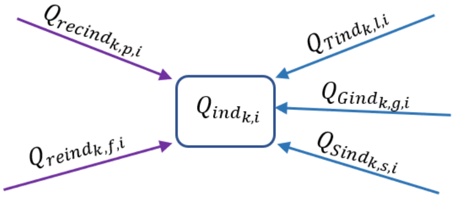


Figure 8-3. The potential water sources for industrial demand nodes

8.3.2. *Domestic Water Demand* $Q_{do_{k,i}}$

The potential water resources for the domestic demand nodes are illustrated in Figure 8-4. It is mandatory for domestic nodes to get their fresh water needs only from the WTP, for drinking water purposes. Furthermore, it is possible for this type of demand to get reclaimed water to satisfy part of their non-potable requirements and the maximum percentage of reclaimed water is specified in the model. The potential water resources for domestic demand are:

a. Treated freshwater rate $Q_{Tdo_{k,l,i}}$ discharged from WTP l to domestic demand node i at reach k.

b. Reclaimed water rate $Q_{Redo_{k,f,i}}$ discharged from WWTP f to domestic demand node i at reach k for gardens irrigation, toilet flushing and other non-potable uses.

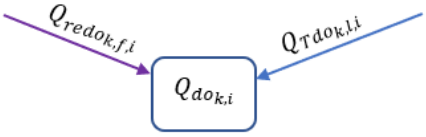


Figure 8-4. The potential water resources for domestic demand nodes

8.3.3. *Commercial Water Demand* $Q_{co_{k,i}}$

The potential water resources used to cover the commercial water needs can be satisfied from the same sources used for domestic uses, which are; treated fresh water and reclaimed water. The potential water sources for the commercial demand nodes are illustrated in Figure 8-5, which are:

a. Treated freshwater rate $\mathrm{Q_{Tco_{k,l,i}}}$ discharged from WTP l to commercial demand node i at reach k.

b. Reclaimed water rate $\mathrm{Q_{reco_{k,f,i}}}$ discharged from WWTP f to demand node i at reach k for landscape irrigation, toilet flushing and other non-potable uses.

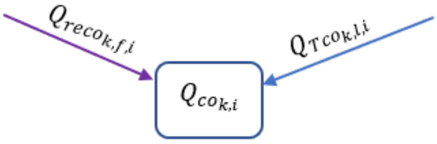


Figure 8-5. The potential water resources for commercial demand nodes

8.3.4. *Agricultural Irrigation Water Demand* $Q_{irr_{k,i}}$

The agricultural water demand nodes are assumed to satisfy their water demands from all the assumed untreated fresh and reclaimed water resources, as illustrated in Figure 8-6. The potential water sources for the agricultural irrigation demand nodes are:

a. Surface water flow rate $\mathrm{Q_{Sirr_{k,s,i}}}$ diverted from source s to irrigation demand node i at reach k.

b. Groundwater flow rate $\mathrm{Q_{Girr_{k,g,i}}}$ pumped from source g to irrigation demand node i at reach k.

c. Reclaimed water flow rate $\mathrm{Q_{reirr_{k,f,i}}}$ discharged from WWTP (f) for agricultural irrigation at demand node i at reach k.

d. Reclaimed water flow rate $\mathrm{Q_{reinirr_{k,p,i}}}$ discharged from PWWTP p to irrigation demand node i at reach k.

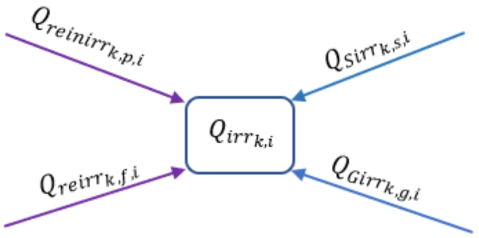


Figure 8-6. The potential water resources for agricultural demand nodes

8.3.5. *Recreational Water Demand* $Q_{rec_{k,i}}$

Recreational nodes are possible to satisfy their water needs from the untreated fresh water sources and/or reclaimed water resources, similar to agricultural demand nodes. The potential water sources for the recreational demand nodes (Figure 8-7) are:

a. Surface water rate $\mathrm{Q_{Srec_{k,s,i}}}$ diverted from source s to recreational demand node i at reach k.

b. Groundwater rate $\mathrm{Q_{Grec_{k,g,i}}}$ pumped from source g to recreational demand node i at reach k.

c. Reclaimed water rate $\mathrm{Q_{rerec_{k,f,i}}}$ discharged from WWTP (f) at node i at reach k for recreational use.

d. Reclaimed water rate $\mathrm{Q_{reinrec_{k,p,i}}}$ discharged from PWWTP p to recreational node i at reach k.

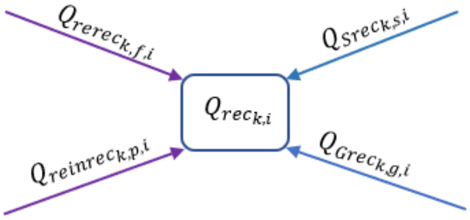


Figure 8-7. The potential water sources for recreational demand nodes

8.4. Objective and Constraints Definitions

The objective function of this regional water allocation optimization model is the maximization of reclaimed water use from the allocation of surface water, groundwater, and reclaimed water on domestic, industrial, irrigation, commercial, and recreational uses. The objective function of this model is subjected to continuity and mass balance constraints considering water demand and the generated wastewater at each demand node, available water resources, and WTPs, WWTPs, and PWWTPs treatment capacities, which are:

8.4.1. *Demand Node Constraints*

The sum of the total water diverted from each of surface water, groundwater, and/or reclaimed water resources to demand node i must be greater than or equal to its water demand. So, the total water consumed by each demand nodes is:

$$QN_{k,i} = \sum_{s}^{S} QS_{k,i,s}\, CSW_{s,i} + \sum_{g}^{G} QG_{k,i,g}\, CGW_{g,i} + \sum_{l}^{L} QT_{k,i,l}\, CWTP_{l,i} + \sum_{f}^{F} QRW_{k,i,f}\, CRW_{f,i} + \sum_{p}^{P} QRWPU_{k,i,p}\, CPRW_{p,i} \qquad i = 1, \ldots.., I \qquad (8\text{-}1)$$

Where

$QN_{k,i}$ is the total consumed water (m^3/day) at node i

$QS_{k,i,s}$ is the untreated SW rate (m^3/day) diverted from source s to node i

$CSW_{s,i}$ (0/1) coefficient defines the connectivity of node i to surface water source s

$QG_{k,i,g}$ is the untreated GW rate (m^3/day) pumped from source g to node i

$CGW_{g,i}$ (0/1) coefficient defines the connectivity of node i to groundwater source g

$QT_{k,i,l}$ is the treated water rate (m^3/day) discharged from water treatment plant l to user i

$CWTP_{l,i}$ (0/1) coefficient defines the connectivity of node i to water treatment plant l

$QRW_{k,i,f}$ is the RW rate (m^3/day) diverted from WWTP f to node i

$CRW_{f,i}$ (0/1) coefficient defines the connectivity of node i to RW source f

$QRWPU_{k,i,p}$ is the RW rate (m^3/day) diverted from PWWTP p to node i

$CPRW_{p,i}$ (0/1) coefficient defines the connectivity of node i to private RW source (PWWTP) p

To satisfy the continuity equation, the total consumed water $QN_{k,i}$ (m^3/day) at demand node i must be equal or greater than the total water demand $Q_{k,i}$, as follows:

$$QN_{k,i} \geq Q_{k,i} \qquad i = 1, \ldots, I \tag{8-2}$$

8.4.2. *Mass Balance Constraints*

This type of constraints is mandatory to be applied for users, WTPs, WWTP, and PWWTP to assure that the total quantity of water (m^3/day) entered to any element in the system must be equal to the disposed amount.

a. For users: The quantity of water (m^3/day) entered to demand node i subtract the total amount of wastewater (m^3/day) disposed and the total water losses at the same node i must be equal zero, as follows:

$$\sum_s^S QS_{k,i,s}\, CSW_{s,i} + \sum_g^G QG_{k,i,g}\, CGW_{g,i} + \sum_l^L QT_{k,i,l}\, CWTP_{l,i} + \sum_f^F QRW_{k,i,f}\, CRW_{f,i} + \sum_p^P QRWPU_{k,i,p}\, CPRW_{p,i} - \sum_s^S QWS_{k,i,s}\, CNSW_{s,i} - \sum_g^G QWG_{k,i,g}\, CNGW_{g,i} - \sum_f^F QWT_{k,i,f}\, CNWWTP_{f,i} - \sum_p^P QWPT_{k,i,p}\, CNPWWTP_{p,i} - QLUSR_{k,i} = 0.00 \qquad i = 1, \ldots.., I \qquad (8\text{-}3)$$

Where

$QWS_{k,i,s}$ is the wastewater rate (m^3/day) disposed from node i to SW source s

$CNSW_{s,i}$ (0/1) coefficient defines the connectivity of node i to SW source s (nodes as suppliers)

$QWG_{k,i,g}$ is the wastewater rate (m^3/day) disposed from node i to GW source g

$CNGW_{g,i}$ (0/1) coefficient defines the connectivity of node i to GW source g (nodes as suppliers)

$QWT_{k,i,f}$ is the wastewater rate (m^3/day) disposed from node i to WWTP f

$CNWWTP_{f,i}$ (0/1) coefficient defines the connectivity of node i to WWTP f (nodes as suppliers)

$QWPT_{k,i,p}$ is the wastewater rate (m^3/day) disposed from node i to PWWTP p

$\mathsf{CNPWWTP}_{p,i}$ (0/1) coefficient defines the connectivity of node i to PWWTP p (nodes as suppliers)

$\mathsf{QLUSR}_{k,i}$ is the water losses rate (m^3/day) at user i

b. For water treatment plants: The total untreated fresh water diverted from SW and GW resources to the water treatment plant l subtract the discharged treated outflow subtract the permissible water losses $\mathsf{QLWTP}_{k,l}$ (m^3/day) at WTP l must be equal to zero, as follows:

$$\sum_{s}^{S} \mathsf{QST}_{k,s,l}\,\mathsf{CWTPSW}_{s,l} + \sum_{g}^{G} \mathsf{QGT}_{k,g,l}\,\mathsf{CWTPGW}_{g,l} - \sum_{i}^{I} \mathsf{QT}_{k,i,l}\,\mathsf{CWTP}_{l,i} - \mathsf{QLWTP}_{k,l} = 0.00 \qquad l = 1, \ldots.., L \qquad (8\text{-}4)$$

Where,

$\mathsf{QST}_{k,s,l}$ is the SW rate (m^3/day) diverted from surface source s to WTP l

$\mathsf{CWTPSW}_{s,l}$ (0/1) coefficient defines the connectivity of WTP l to SW sources s

$\mathsf{QGT}_{k,g,l}$ is the GW rate (m^3/day) pumped from GW source g to WTP l

$\mathsf{CWTPGW}_{g,l}$ (0/1) coefficient defines then connectivity of WTP l to GW sources g

$\mathsf{QLWTP}_{k,l}$ is the permissible water losses rate (m^3/day) at WTP l

c. For wastewater treatment plants: The total wastewater inflow (m^3/day) entering WWTP f subtract the sum of the total reclaimed water (treated wastewater) discharged and the total water losses at the WWTP f must be equal to zero, as follows:

$$\sum_{i}^{I} QWT_{k,i,f}\, CNWWTP_{f,i} - \sum_{i}^{I} QRW_{k,f,i}\, CRW_{f,i} - \sum_{s}^{S} QRWS_{k,f,s}\, CWWTPSW_{s,f} - \sum_{g}^{G} QRWG_{k,f,g}\, CWWTPGW_{g,f} - QLWWTP_{k,f} = 0.00 \qquad f = 1, \ldots, F \qquad (8\text{-}5)$$

Where,

$QRWS_{k,f,s}$ is the RW rate (m^3/day) disposed from WWTP f to SW source s

$CWWTPSW_{s,f}$ (0/1) coefficient defines the connectivity of WWTP f to SW sources s (WWTP as a supplier)

$QRWG_{k,f,g}$ is the RW rate (m^3/day) disposed from WWTP f to GW source g

$CWWTPGW_{g,f}$ (0/1) coefficient defines the connectivity of WWTP f to GW sources g (WWTP as a supplier)

$QLWWTP_{k,f}$ is the permissible water losses rate (m^3/day) at WWTP f

d. For the private wastewater treatment plants: The total wastewater inflow (m^3/day) entering PWWTP p subtract the sum of the total RW released p and the total water losses at PWWTP p must be equal to zero, as follows:

$$\sum_{i}^{I} QWPT_{k,i,p}\, CNPWWTP_{p,i} - \sum_{i}^{I} QRWPU_{k,p,i}\, CPRW_{p,i} - \sum_{s}^{S} QRWPS_{k,p,s}\, CNPWWTSW_{s,p} - \sum_{g}^{G} QRWPG_{k,p,g}\, CNPWWTGW_{g,p} - QLPWWTP_{k,p} = 0.00 \qquad p = 1, \ldots, P \qquad (8\text{-}6)$$

Where,

$QRWPS_{k,p,s}$ is the RW rate (m^3/day) sent from PWWTP p to SW source s

$\mathsf{CNPWWTSW}_{s,p}$ (0/1) coefficient defines the connectivity of PWWTP p to SW source s (PWWTP as supplier)

$\mathsf{QRWPG}_{k,p,g}$ is the RW rate (m^3/day) sent from PWWTP p to GW source g

$\mathsf{CNPWWTGW}_{g,p}$ (0/1) coefficient defines the connectivity of PWWTP p to GW source g (PWWTP as supplier)

$\mathsf{QLPWWTP}_{k,p}$ is the permissible water losses rate (m^3/day) at PWWTP p

8.4.3. *Capacity Constraints*

This type of linear constraints has been applied to water and wastewater treatment plants as the water entering a treatment plant must be less than or equal to its treatment capacity.

a. WTP capacity constraint

$$\sum_{s}^{S} \mathsf{QST}_{k,s,l}\, \mathsf{CWTPSW}_{s,l} + \sum_{g}^{G} \mathsf{QGT}_{k,g,l}\, \mathsf{CWTPGW}_{g,l} \leq \mathsf{TCWTP}_{k,l} \qquad l = 1, \ldots, L \qquad (8\text{-}7)$$

Where,

$\mathsf{TCWTP}_{k,l}$ is the treatment capacity (m^3/day) of WTP l

b. WWTP capacity constraint

$$\sum_{i}^{I} \mathsf{QWT}_{k,i,f}\, \mathsf{CNWWTP}_{f,i} \leq \mathsf{TCWWTP}_{k,f} \qquad f = 1, \ldots, F \qquad (8\text{-}8)$$

Where,

$\mathsf{TCWWTP}_{k,f}$ is the treatment capacity (m^3/day) of WWTP f

c. PWWTP capacity constraint

$$\sum_{i}^{I} \mathrm{QWPT}_{k,i,p}\,\mathrm{CNPWWTP}_{p,i} \leq \mathrm{TCPWWTP}_{k,p} \qquad p = 1, \ldots.., P \qquad (8\text{-}9)$$

Where,

$\mathrm{TCPWWTP}_{k,p}$ is the treatment capacity (m^3/day) of the private wastewater treatment plant p

8.4.4. *Water Availability Constraints*

This type of linear constraints allows the allocated water from SW, GW and RW sources into demand nodes and WTPs not to exceed the total available quantities at each resource individually.

a. SW availability constraint

$$\sum_{i}^{I} \mathrm{QS}_{k,i,s}\,\mathrm{CSW}_{s,i} + \sum_{l}^{L} \mathrm{QST}_{k,s,l}\,\mathrm{CWTPSW}_{s,l} - \sum_{i}^{I} \mathrm{QWS}_{k,i,s}\,\mathrm{CNSW}_{s,i} - \sum_{f}^{F} \mathrm{QRWS}_{k,f,s}\,\mathrm{CWWTPSW}_{s,f} - \sum_{p}^{P} \mathrm{QRWPS}_{k,p,s}\,\mathrm{CNPWWTSW}_{s,p} \leq \mathrm{QSWav}_{k,s} \qquad s = 1, \ldots.., S \qquad (8\text{-}10)$$

Where,

$\mathrm{QSWav}_{k,s}$ is the available flow rate (m^3/day) from SW source s

b. Groundwater availability constraint

$$\sum_{i}^{I} \mathrm{QG}_{k,i,g}\,\mathrm{CNGW}_{g,i} + \sum_{l}^{L} \mathrm{QGT}_{k,g,l}\,\mathrm{CWTPGW}_{g,l} - \sum_{i}^{I} \mathrm{QWG}_{k,i,g}\,\mathrm{CNGW}_{g,i} - \sum_{f}^{F} \mathrm{QRWG}_{k,f,g}\,\mathrm{CWWTPGW}_{g,f} - \sum_{p}^{P} \mathrm{QRWPG}_{k,p,g}\,\mathrm{CNPWWTGW}_{g,p} \leq \mathrm{QGWav}_{k,g} \qquad g = 1, \ldots.., G \qquad (8\text{-}11)$$

Where,

$\mathrm{QGWav}_{k,g}$ is the available pumping rate (m^3/day) from GW source g

c. RW from WWTP availability constraint

$$\sum_i^I QRW_{k,f,i}\, CRW_{f,i} + \sum_s^S QRWS_{k,f,s}\, CWWTPSW_{s,f} + \sum_g^G QRWG_{k,f,g}\, CWWTPGW_{g,f} \leq TCWWTP_{k,f} \qquad f = 1, \ldots, F \tag{8-12}$$

d. RW from PWWTP availability constraint

$$\sum_i^I QRWPU_{k,p,i}\, CPRW_{p,i} + \sum_s^S QRWPS_{k,p,s}\, CNPWWTSW_{s,p} + \sum_g^G QRWPG_{k,p,g}\, CNPWWTGW_{g,p} \leq TCPWWTP_{k,p} \qquad p = 1, \ldots, P \tag{8-13}$$

8.4.5. *Percentage of RW Share Constraint*

In order to allocated RW, treated at WWTPs, for users taking into consideration the type of use u, a maximum percentage of RW share was specified for each type of use to prevent the domination of one use on the others. The RW share constraint is written as:

$$\sum_i^I \sum_f^F (QRW_{k,f,i}\, CRW_{f,i} TDN_{u,i}) \leq PRIRW_{k,u} \sum_i^I \sum_f^F QRW_{k,f,i} CRW_{f,i} \qquad u = 1, \ldots, U \tag{8-14}$$

Where,

$TDN_{u,i}$ is (0/1) coefficient defines the type u of demand node i

$PRIRW_{k,u}$ is the maximum permissible percentage of RW to be allocated defined by type of use u

8.5. Objective Function

The objective function of this optimization model is the maximization of the predicted quantities of reclaimed water $RWUSE_k$ discharged from WWTPs and PWWTPs to be allocated on for demand nodes. The maximization equation is:

$$\text{Max. } \mathrm{RWUSE}_k = \sum_i^I \left(\sum_f^F \mathrm{QRW}_{k,f,i}\, \mathrm{CRW}_{f,i} + \sum_p^P \mathrm{QRWPU}_{k,p,i}\, \mathrm{CPRW}_{p,i} \right) \qquad k = 1, \ldots\ldots, K \qquad (8\text{-}15)$$

The GAMS code used to solve this linear regional water allocation optimization model is described in Appendix E of this dissertation.

8.6. Data Input for the Model

The data used in this regional water allocation optimization model of chapter 8 partially collected from the most recent study performed for the Ministry of Water Resources, entitled “Strategy for Water and Land Resources in Iraq”. Water demand, water and wastewater treatment capacities, surface and groundwater availabilities, for Baghdad and other Iraqi provinces were provided by the previously mentioned study. The study included intensive and detailed information, which is considered as a valuable source for data related to Iraq. Other water and wastewater availabilities and treatment capacities were secured from either published and unpublished reports and studies, such as the Water Demand Management of Iraq (UNICEF/Iraq 2014), or governmental personnel. The researcher has had a good experience in water resources due to his background, which enhanced the accuracy of the collected data. Data which were unknown or inaccurate was estimated by the researcher considering his practical knowledge with Iraqi water resources.

The model included 50 different demand nodes. Twenty of them are domestic, twelve are agricultural, nine are industrial, four are commercial, and the last five are recreational demand nodes. In this optimization model, each demand node was defined in accordance to its type of demand, location in the system, water demand, water losses, generated wastewater, and source of water supply. Table 8-1illustrates all the required data regarding the demand nodes. Some data inputs were unable to be secured. Thus, they were estimated in order to test the validity of the model, such as the data related to commercial and recreational demand nodes. The connectivity of each demand node to surface water, groundwater, reclaimed water, WTP, WWTP, and PWWTP was defined using a 0/1 binary parameter. The status of the demand node of either being a wastewater source or not was defined as well using the 0/1 binary parameter.

Table 8-1. Demand nodes definitions, demand rates, water sources, water losses rates, wastewater discharges rates used in the optimization model

Used ID	User Definition	Type of use	Demand m^3/day	Water supply source	Water Losses (m^3/day)	Wastewater disposal (m^3/day)
D1	Karkh	Domestic	900	Tigris River	331.5	568.5
D2	Rasafa	Domestic	975	Tigris River	232.1	742.9
D3	Khadumyia	Domestic	95.2	Tigris River	28.6	66.6
D4	Al-Rasheed	Domestic	76.5	Tigris River	23.0	53.6
D5	Al-Qadisyia	Domestic	76.5	Tigris River	23.0	53.6
D6	Al-Baldyiat	Domestic	191.25	Tigris River	57.4	133.9
D7	Al-Maden	Domestic	18.7	Tigris River	5.6	13.1
D8	Al-Maden 2	Domestic	57.8	Tigris River	17.3	40.5
D9	Wahda	Domestic	32.3	Tigris River	9.7	22.6
D10	Wathbah	Domestic	57.8	Tigris River	17.3	40.5
D11	Sadder	Domestic	76.5	Tigris River	23.0	53.6
D12	Shek Hamad	Domestic	18.7	Tigris River	5.6	13.1
D13	Al-Tarmyia	Domestic	51	Tigris River	15.3	35.7
D14	Al-Abayji	Domestic	11.22	Tigris River	3.4	7.9
D15	Compact Units (Group 1)	Domestic	107.1	Tigris River	32.1	75.0
D16	Zidan	Domestic	17	Euphrates River	5.1	11.9
D17	Al-Mahmoudyia	Domestic	45.1	Euphrates River	13.53	31.57

Used ID	User Definition	Type of use	Demand m^3/day	Water supply source	Water Losses (m^3/day)	Wastewater disposal (m^3/day)
D18	Al-Yousfyia	Domestic	17.85	Euphrates River	5.4	12.45
D19	Al-Yousfyia Village	Domestic	9.35	Euphrates River	2.8	6.55
D20	Compact Units (Group 2)	Domestic	107.1	Euphrates River	32.1	75.0
D21	Karkh Farms	Agriculture	1000	Tigris River	1000.0	0.0
D22	Rasafa Farms	Agriculture	1000	Tigris River	1000.0	0.0
D23	Al-Maden Farms 1	Agriculture	800	Tigris River	800.0	0.0
D24	Al-Maden Farms 2	Agriculture	500	Tigris River	500.0	0.0
D25	Wahda Agr. 5	Agriculture	800	Tigris River	800.0	0.0
D26	Al-Tarmyia Farms	Agriculture	500	Tigris River	500.0	0.0
D27	Farms irrigated by Compact Units (Group 1)	Agriculture	500	Tigris River	500.0	0.0
D28	Zidan Farms	Agriculture	770	Euphrates River	769.0	0.0
D29	Al-Mahmoudyia Farms	Agriculture	815	Euphrates River	812.2	0.0
D30	Al-Yousfyia Farms	Agriculture	1660	Euphrates River	1658.9	0.0
D31	Al-Yousfyia Village Farms	Agriculture	695	Euphrates River	691.2	0.0
D32	Farms Irrigated by Compact Units (Group 2)	Agriculture	150	Euphrates River	150.0	0.0
D33	Aldowra Oil Refinery	Industry	28.8	Tigris River	11.5	17.3
D34	South of Baghdad/1 Steam Power Plant	Industry	9.86	Tigris River	8.0	1.9
D35	South of Baghdad/2 Steam Power Plant	Industry	16.5	Tigris River	13.2	3.3
D36	Aldowra Gas Power Plant	Industry	6.3	Tigris River	5.2	1.1
D37	Rasheed Gas Power Plant	Industry	3.56	Tigris River	2.7	0.8
D38	South of Baghdad Gas Power Plant	Industry	1.92	Tigris River	1.6	0.3
D39	Al quds Gas Power Plant	Industry	37.26	Tigris River	29.9	7.4
D40	Taji/1 Gas Power Plant	Industry	6.3	Tigris River	5.2	1.1
D41	Taji/2 Gas Power Plant	Industry	6.58	Tigris River	5.2	1.4
D42	Commercial Zone 1	Commercial	10	Tigris River	4.0	6.0

Used ID	User Definition	Type of use	Demand m^3/day	Water supply source	Water Losses (m^3/day)	Wastewater disposal (m^3/day)
D43	Commercial Zone 2	Commercial	10	Tigris River	4.0	6.0
D44	Commercial Zone 3	Commercial	10	Tigris River	4.0	6.0
D45	Commercial Zone 4	Commercial	10	Tigris River	4.0	6.0
D46	Recreational Park 1	Recreation	10	Tigris River	10.0	0.0
D47	Recreational Park 2	Recreation	10	Tigris River	10.0	0.0
D48	Recreational Park 3	Recreation	10	Tigris River	10.0	0.0
D49	Recreational Park 4	Recreation	10	Tigris River	10.0	0.0
D50	Recreational Park 5	Recreation	10	Tigris River	10.0	0.0

The optimized regional water allocation model included 11 water treatment plants with different treatment capacities located in Baghdad's districts (Table 8-2). The only source of water for these WTPs is the surface water from the Tigris River and the Irrigation canals which flow from the Euphrates River to satisfy part of the water requirements of the area between the two rivers to the west and south of Baghdad. Water treatment capacities of these WTPs were retrieved mainly from the Strategy for Water and Land Resources in Iraq (Iraqi Ministry of Water Resources 2014). The unknown treatment capacities were estimated, as for WTP15 and WTP20.

Table 8-2. Existing water treatment plants (WTPs) in Baghdad and its districts

WTP ID	Project Name	Water Source	Treatment Capacity (1000 m^3/day)
WTP1	Karkh Water Project	Tigris River	1300
WTP2	Rasafa Water Project	Tigris River	910
WTP3	Khadumyia Water Project	Tigris River	112
WTP4	Al-Rasheed Water Project	Tigris River	90
WTP5	Al-Qadisyia Water Project	Tigris River	90
WTP6	Al-Baldyiat Water Project	Tigris River	225
WTP7	Al-Maden Old Water Project	Tigris River	22

WTP ID	Project Name	Water Source	Treatment Capacity (1000 m^3/day)
WTP8	Al-Maden New Water Project	Tigris River	68
WTP9	Wahda Water Project	Tigris River	38
WTP10	Wathbah Water Project	Tigris River	68
WTP11	Sadder Water Project	Tigris River	90
WTP12	Shek Hamad Water Project	Tigris River	22
WTP13	Al-Tarmyia Water Project	Tigris River	60
WTP14	Al-Abayji Water Project	Tigris River	13.2
WTP15	Compact Units (Group1)	Tigris River	126
WTP16	Zidan Water Project	Euphrates River	20
WTP17	Al-Mahmoudyia Water Project	Euphrates River	53
WTP18	Al-Yousfyia Central Water Project	Euphrates River	21
WTP19	Al-Yousfyia Village Water Project	Euphrates River	11
WTP20	Compact Units (Group 2)	Euphrates River	126

Table 8-3. Existing and projected wastewater treatment plants treatment capacities in Baghdad and its districts

WWTP ID	Location	Treatment capacity (1000 m^3/day)	Disposal point
WWTP1	Karkh	200^{*}, 405^{**}	Tigris River
WWTP2	Rustumia	475^{*}, 600^{**}	Tigris River
WWTP3	Mahmudia	40^{*}	Tigris River
WWTP4	Madaen	20^{*}, 40^{**}	Tigris River
WWTP5	Khadumiya	60^{**}	Tigris River
WWTP6	Wahda	20^{**}	Tigris River
WWTP7	Shek Hamad	15^{**}	Tigris River
WWTP8	Al-Tarmyia	40^{**}	Tigris River
WWTP9	Al_Abayji	15^{**}	Tigris River
WWTP10	Zidan	15^{**}	Main Fall
WWTP11	Al_Yousfyia	40^{**}	Main Fall

*Current wastewater treatment capacity
**Projected wastewater treatment capacity

8.7. Optimization Model Run Scenarios

Twelve different scenarios using different assumptions were implemented to test the sensitivity of the computed results and how the model interacts accordingly. The assumed scenarios are presented in Table 8-4, and concisely described in the following:

Scenario 1-1: There are 4 WWTPs with a total treatment capacity of 7.35×10^5 m^3/day), which already exist. In addition to one PWWTP with a treatment capacity of 18×10^3 m^3/day that is located at demand node 33. There is no reclaimed water use. The only source of supply is the surface water with a daily flow of 7.8×10^6 and 4.35×10^6 m^3 from SW1 and SW2, respectively.

Scenario 1-2: The same assumptions as in scenario 1-1 with the inclusion of RW use for agricultural irrigation. The available RW quantities were allocated on agricultural demand nodes depending on their connectivity to RW sources.

Scenario 1-3: The same assumptions as in scenario 1-1 with taking into consideration RW allocation for all types of use depending on the connectivity of demand nodes to RW resources.

Scenario 1-4: This scenario is like scenario 1-3 with the assumption of less surface water availability to test the applicability of the model under shortage conditions. The available surface water flows upstream the system were assumed as 4.703×10^6 and 4.065×10^6 m^3 for SW1 and SW2, respectively.

Scenario 1-5: This scenario is similar to scenario 1-3 with the inclusion of groundwater from two sources, GW1 and GW2, as the third type of water sources. The available GW daily pumping rate was assumed as 2.2×10^5 m^3 and 1.7×10^5 m^3 for GW1 and GW2, respectively. This assumption was built to test the applicability of the model allocating water from three different sources on the five different uses.

Scenario 1-6: This scenario is like scenario 1-5 with the assumption of less surface water availability to test the applicability of the model under shortage conditions. And how the groundwater helps to mitigate the burden on surface water resources. The available surface water flows upstream the system were assumed as 4.333×10^6 and 4.065×10^6 m^3 for SW1 and SW2, respectively.

Scenario 2-1: In this scenario, 11 WWTPs were assumed in the system with a total treatment capacity of 1.29×10^6 m^3/day, considering future expansion. In addition to one PWWTP with a treatment capacity of 18×10^3 m^3/day that is located at demand node 33. There is no reclaimed water use. The only source of supply is the surface water with a daily flow of 7.8×10^6 and 4.35×10^6 m^3 from SW1 and SW2, respectively.

Scenario 2-2: The same assumptions as in scenario 2-1 with the inclusion of RW use for agricultural irrigation. Reclaimed water was allocated on agricultural nodes considering their connectivity to RW sources.

Scenario 2-3: The same assumptions as in scenario 2-1 with taking into consideration RW allocation for all types of use depending on the connectivity of demand nodes to RW resources.

Scenario 2-4: This scenario is similar to scenario 2-3 with the assumption of less surface water availability to test the applicability of the model under shortage conditions. The available surface water flows upstream the system were assumed as 4.333×10^6 and 4.052×10^6 m^3 for SW1 and SW2, respectively.

Scenario 2-5: This scenario is similar to scenario 2-3 with the inclusion of groundwater from two sources, GW1 and GW2, as the third type of water sources. The daily available GW pumping rate was assumed as 2.2×10^5 m^3 and 1.7×10^5 m^3 for GW1 and GW2, respectively.

Scenario 2-6: This scenario is similar to scenario 2-5 with the assumption of less surface water availability to test the applicability of the model under shortage conditions. The available surface water flows upstream the system were assumed as 3.901×10^6 and 4.052×10^6 m^3 for SW1 and SW2, respectively.

Table 8-4. The description of the assumed scenarios

	Surface water flow rate (1000 m^3/day)			Generated wastewater (1000 m^3/day)					Groundwater pumping rate (1000 m^3/day)		
	SW1	SW2	Type of use	WWTPs	Number of WWTPs	Type of use	PWWTP	Type of use	GW1	GW2	Type of use
Scenario 1-1	7800	4350	All uses	735	4	No use	18	No use	0	0	
Scenario 1-2	7800	4350	All uses	735	4	Agriculture use	18	Agriculture use	0	0	
Scenario 1-3	7800	4350	All uses	735	4	All uses	18	Industrial use	0	0	
Scenario 1-4	4703	4065	All uses	735	4	All uses	18	Industrial use			
Scenario 1-5	7800	4350	All uses	735	4	All uses	18	Industrial use	220	170	Agricultural, Industrial, and Recreational uses
Scenario 1-6	4333	4065	All uses	735	4	All uses	18	Industrial use	220	170	Agricultural, Industrial, and Recreational uses
Scenario 2-1	7800	4350	All uses	1290	11	No use	18	No use	0	0	
Scenario 2-2	7800	4350	All uses	1290	11	Agriculture use	18	Agriculture use	0	0	
Scenario 2-3	7800	4350	All uses	1290	11	All uses	18	Industrial use	0	0	
Scenario 2-4	4333	4052	All uses	1290	11	All uses	18	Industrial use	0	0	
Scenario 2-5	7800	4350	All uses	1290	11	All uses	18	Industrial use	220	170	Agricultural, Industrial, and Recreational uses
Scenario 2-6	3901	4052	All uses	1290	11	All uses	18	Industrial use	220	170	Agricultural, Industrial, and Recreational uses

8.8. Results and Discussion

The linear programming regional water allocation optimization model was solved using GAMS. The analysis was completed using three different sources of water; surface water, groundwater, and reclaimed water, to be allocated on five different uses; domestic, industrial, irrigation, commercial and recreational uses. Baghdad was considered as the case study to test the validity of the model. Surface water and groundwater availability depends on current conditions, while the availability of reclaimed water depends upon the diverted treated wastewater from WWTP(s) to the users. Each user has the possibility to get its water share from all the mentioned resources depending on its connectivity to a resource.

In this regional water allocation optimization model, the allocated reclaimed water was maximized to relieve the pressure on fresh water resources and to reduce the potential environmental pollution and the related economical and health concerns. Twelve different scenarios have been compared. The compared scenarios have taken into consideration either using RW or not. If RW is used, will it be allocated only for irrigation or for all five uses. Scenarios assumed using only SW, as is currently the case in Baghdad. While, other scenarios assumed SW, and RW as the only resources of supply. Two scenarios have used SW, GW, and RW to test the validity of the model. SW1 and SW2 used in the optimization model refer to the Tigris River and the Euphrates River, respectively.

The computed results proved that the developed model can allocate the three water resources efficiently on the 50 demand nodes considering the type of demand nodes along with the connectivity of water resources to the other components in the system. Regarding the location of the demand node in the system, the observed total daily water demand for the 50 demand nodes is 12.34×10^6 m^3. Of the 50 demand nodes, 40 nodes demand up to 8.05×10^6 m^3 which must be supplied from the Tigris River basin in Baghdad, while the other 10 demand nodes have to be supplied from the Euphrates River basin with a total demand of 4.29×10^6 m^3. The size of the generated wastewater from all demand nodes is assumed to be the same taking into consideration that the water demand was maintained equal for all the simulated scenarios. Figures 8-8 to 8-13 illustrate the computed results from the twelve different scenario runs.

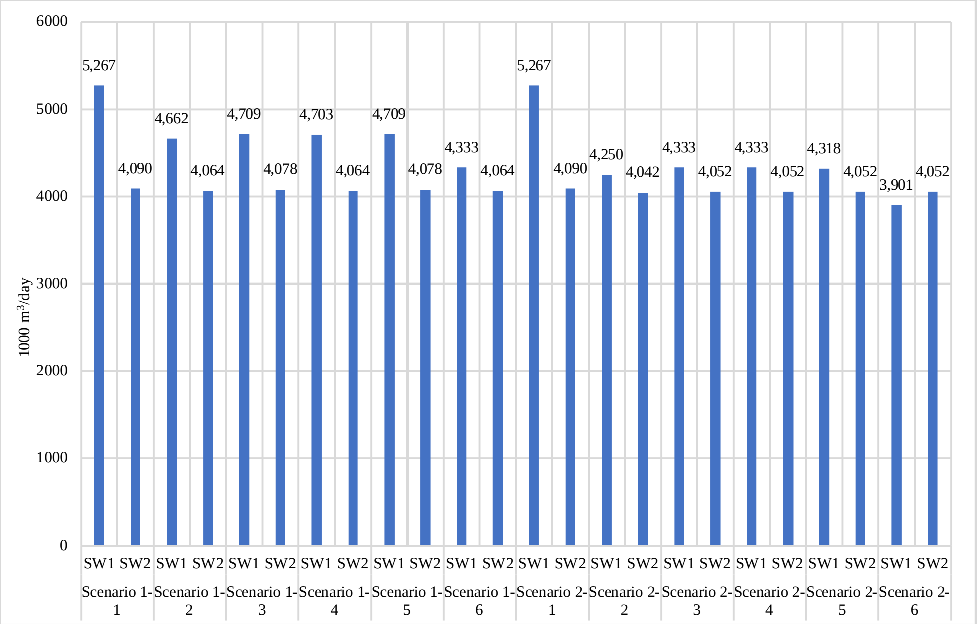


Figure 8-8. The predicted untreated surface water rate (1000 m^3/day) sent from sources SW1 and SW2 under different scenarios

Scenarios 1-1 and 2-1 considered there is no groundwater resource and no reclaimed water use where the discharge from 4 WWTPs and 11 WWTPs in the system, respectively, is discharged to the environment. The 4 WWTPs already exist with a daily treatment capacity of 1.085×10^6 m^3. The quantity of the diverted surface water was assigned as 9.36×10^6 m^3/day and 3.16×10^6 from SW1 and SW2, respectively, with a total of 12.51×10^6 m^3/day with the accounting of water losses in the system. Scenario 1-1 and 2-1 predict identical trends in the allocation of fresh water to all users since surface water is the only available option in both scenarios. The surface water sent to demand nodes without treatment was as 5.27×10^6 m^3/day and 4.9×10^6 m^3/day from SW1 and SW2, respectively (Figure 8-8). By considering municipal water demand, which needs water treatment, the total diverted water from SWs to WTPs was about 3.16×10^6 m^3/day with 2.95×10^6 m^3/day from SW1 and 0.21 $\times 10^6$ m^3/day from SW2 (Figures 8-9, and 8-10). By subtracting 15% as a total loss in the WTPs and the related water supply system, the discharged treated water from all WTPs was as 2.98×10^6 m^3/day, as illustrated in Figure 8-11. So, in scenarios 1-1 and 2-1, the water diverted from surface sources demand nodes without treatment was 9.36×10^6 m^3/day, while the quantity which was diverted to WTPs was as 3.16×10^6 m^3/day, as a total of 12.52×10^6 m^3/day (Figure 8-12).

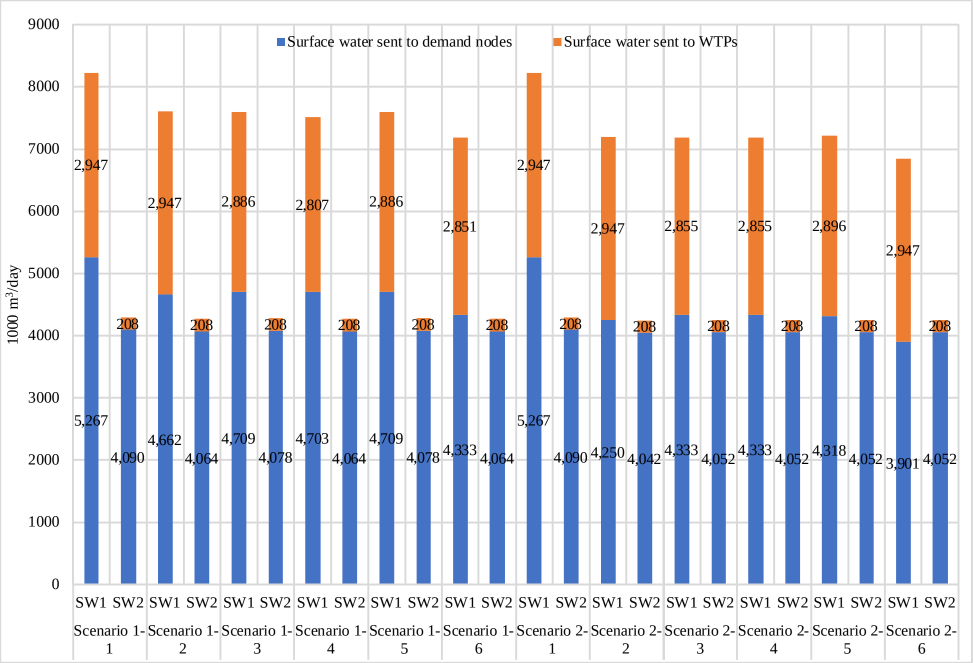


Figure 8-9. The predicted untreated surface water rate (1000 m^3/day) diverted from source SW1 and SW2 to water treatment plants (WTPs) and demand nodes

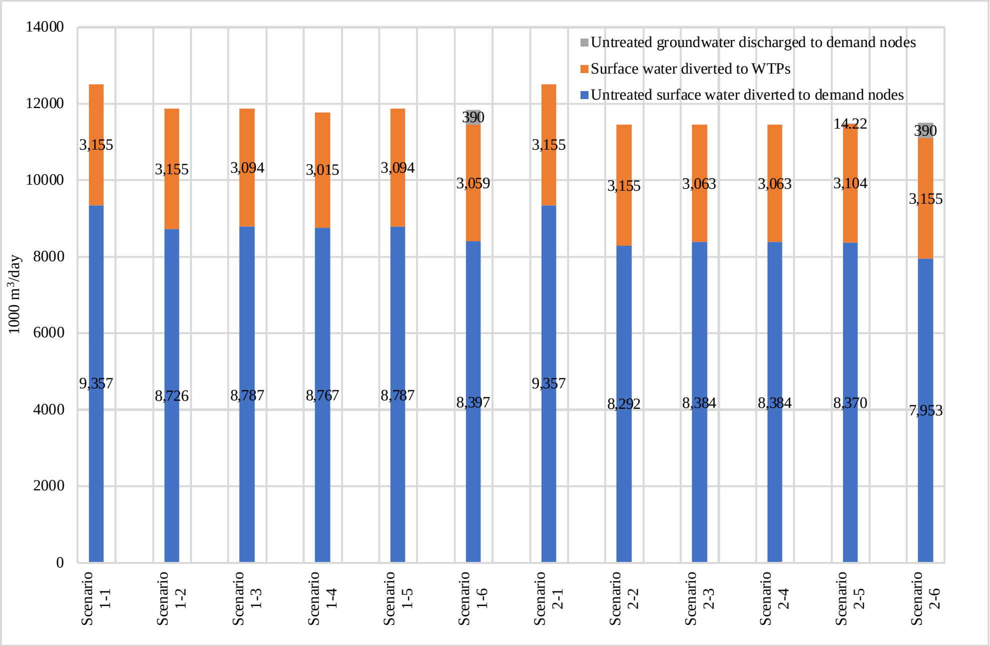


Figure 8-10. Untreated surface water and groundwater sent to demand nodes and the untreated surface water diverted to water treatment plants (WTPs) (1000 m^3/day)

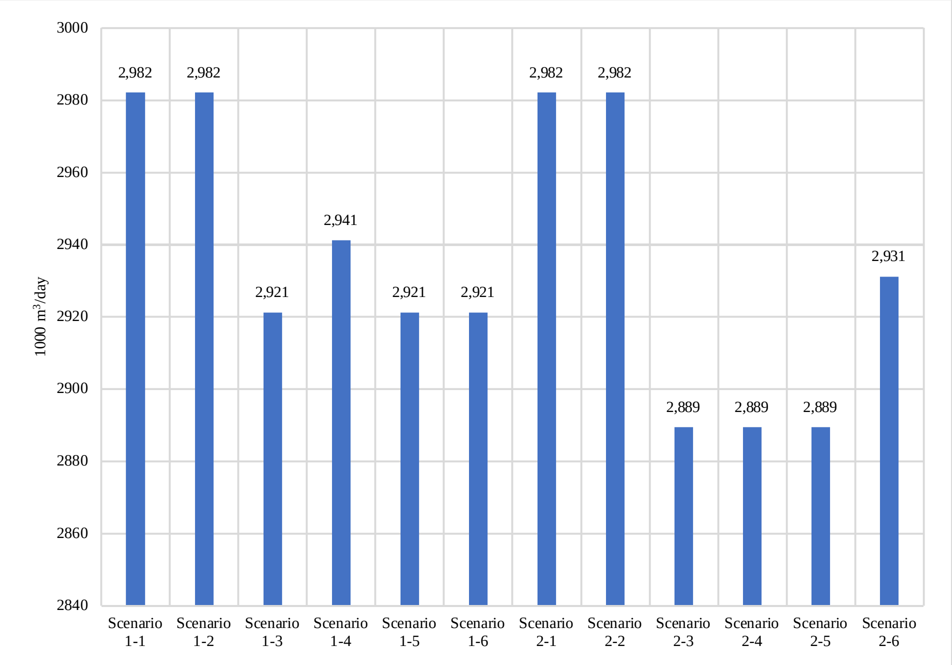


Figure 8-11. Treated water rate (1000 m^3/day) sent from WTPs to demand nodes

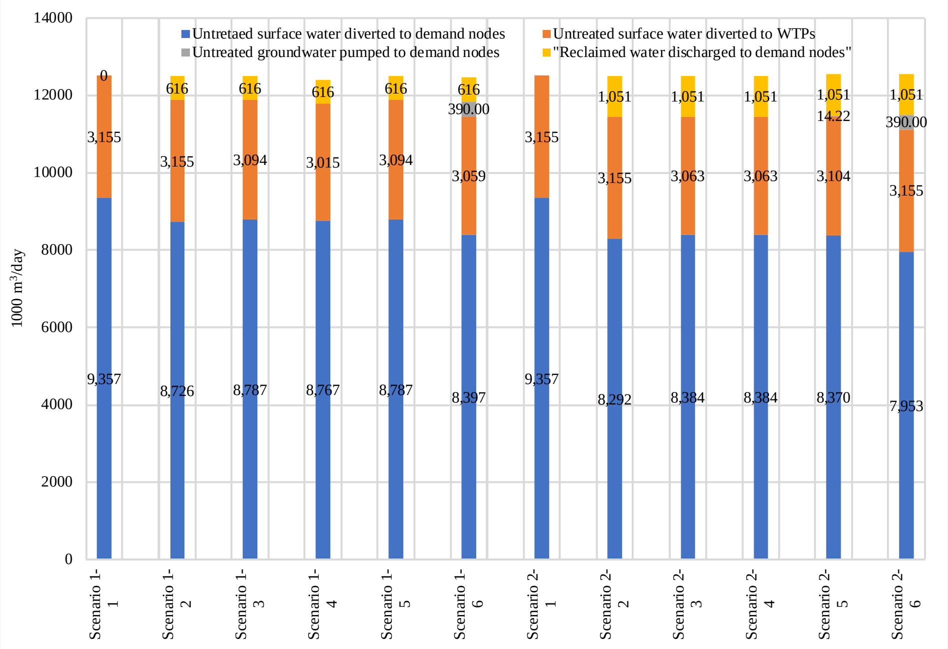


Figure 8-12. Untreated surface water (1000 m^3/day) diverted to demand nodes and water treatment plants (WTPs), untreated groundwater pumped to demand nodes, and reclaimed water discharged to demand nodes

Maximizing reclaimed water allocation for agricultural irrigation and/or other uses was applied using scenarios 1-2 to 1-6, and scenarios 2-2 to 2-6 under different assumptions. In scenarios 1-1 to 1-6, the available 4 WWTPs have a daily treatment capacity of 7.35×10^5 m^3 in addition to 18×10^3 m^3 which is treated at the PWWTP located in demand node D33. Scenario 1-2 maximizes the allocation of RW only for agricultural irrigation. Taking into consideration the losses at the wastewater treatment plants, the predicted total daily reclaimed water rate for agricultural use was about 6.163 ×10^5 m^3 diverted from WWTPs (Figure 8-13), and 14.58×10^3 m^3 diverted from PWWTP. The use of reclaimed water as an alternative source of water has reduced the burden on the consumed surface water (Table 8-8), which reduced the amount of contamination from

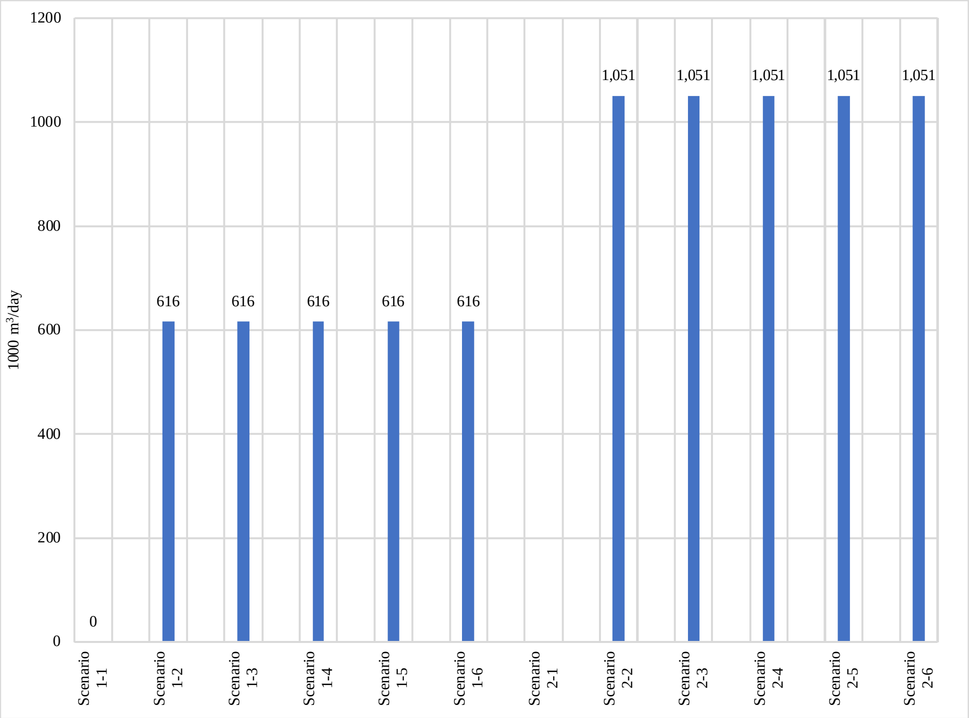


Figure 8-13. Reclaimed water rate (1000 m^3/day) discharged from wastewater treatment plants to demand nodes

discharges, and allowed more water to flow downstream. The untreated surface water diverted from SW1 and SW2 to demand nodes has decreased from 5.267×10^6 and 4.09×10^6 m^3/day to 4.662×10^6 and 4.064×10^6 m^3/day, respectively. The optimization model showed that SW1 has saved more water than SW2 due to most of the agricultural demand nodes which are connected to WWTPs are located at the SW1 basin. As a result of using reclaimed water in scenario 1-2, surface water resources have saved as much as 5% of its daily flow within the city, which consequently increased water flow rate downstream in the rivers.

Scenarios 1-3 and 1-4 were applied allowing reclaimed water to be allocated for all uses depending on the connectivity of demand nodes to WWTPs and PWWTPs in the system, in addition to the surface water. Two different surface water availabilities were considered. Under scenario 1-3, daily flows of 7.8×10^6 and 4.35×10^6 m^3 were assumed considering normal flow conditions of SW1 and SW2, respectively. While, scenario 1-4 tested the model using the minimum possible daily surface water flows of 4.703×10^6 and 4.065×10^6 m^3 for SW1 and SW2, respectively, to meet the demand of the system in cooperation with reclaimed water. Results showed that SW2 is more sensitive to water shortage than SW1 due to its lower quantities of water supply. Under these two scenarios, 1-3 and 1-4, the reclaimed water was allocated on demand nodes by allowing maximum percentage of RW to be used by each type of use. Taking into account the type of use, the assumed maximum allowed percentage of reclaimed water was as 100%, 20%, 5%, 5%, and 10% for agricultural, industrial, domestic, commercial, and recreational uses, respectively. The quantities of surface water diverted to demand nodes and to WTPs have been varied depending on the available quantity of reclaimed water which was allocated simultaneously to users, as illustrated in Figures 8-8, 8-9, and 8-10. Scenarios 2-3 and 2-4 are similar to scenarios 1-3 and 1-4 with the exception of including all the projected 11 WWTPs (Table 8-3) with a total treatment capacity of 1.29×10^6 m^3/day. The daily predicted reclaimed water allocated for demand nodes was 1.05×10^6 m^3, which means a saving in surface water flows of the same quantity. The untreated surface water diverted from SW1 to demand nodes has dropped from 5.267×10^6 m^3 under scenario 2-1 to 4.25×10^6 and 4.33×10^6 m^3 under scenarios 2-3 and 2-4, respectively. While, the quantity of water diverted from SW1 has decrease from 4.09×10^6 m^3 using scenario 2-1 to 4.052×10^6 m^3 for both of scenarios 2-3 and 2-4 (Figure 8-8). The reduction in the diverted surface water quantities to demand nodes was substituted by reclaimed water considering the assumed percentages of RW that must be allocated to nodes depending on the type of use. Furthermore, the quantities of water diverted to WTPs varies (Figures 8-9 and 8-10) as reclaimed water was allowed to cover no more than 5% of domestic and commercial use, and 20% for industrial use. This regional water allocation optimization model has maintained the satisfaction of water demand for all nodes by allocating surface water and reclaimed water concurrently with the allowance of supplying water a little more than the demand (Figure 8-12) by maximizing RW use subjected to the previously listed constraints.

To test the accuracy of the model using all the potential water resources, groundwater was considered in scenarios 1-5, 1-6, 2-5, and 2-6. Two sources of groundwater, GW1 and GW2, were assumed with a maximum daily withdrawal rate of 2.2×10^5 and 1.7×10^5 m^3, respectively. The GW sources are capable to supply untreated water for industrial, agricultural and recreational demand nodes to mitigate the pressure on surface water resources. Domestic and commercial demand nodes were excluded from getting GW because of salinity concerns. In scenarios 1-5 and 1-6, the allocation of the available quantities of SW, GW, and RW considering only 4 WWTPs, was tested. While, scenarios 2-5 and 2-6 were applied by allocating three types of water for the 50 demand nodes of different uses considering 11 WWTPs. Figure 8-10 shows how the presence of GW has decreased SW consumption, especially in scenarios 1-6 and 2-6. A total of 3.9×10^5 m^3 of GW was allocated for 5 different demand nodes, D21, D22, D33, D49, and D50, with different quantities for three uses under the canopy of scenario 1-6. On the other hand, scenario 2-6 considered the allocation of GW for only three demand nodes, D21, D22, and D33, with different quantities for agricultural and industrial uses.

Considering the downstream SW flow remaining, as the used RW increases, the system downstream of the city maintains a suitable quantity if compared to no RW use. The computed downstream SW flow was 2.79×10^6 m^3/day with no RW use, as in scenarios 1-1 and 2-1. While, the use of RW has increased the remaining surface water flow in the downstream to be as 3.42×10^6, 3.36×10^6, 2.79×10^6, 3.86×10^6 m^3/day for scenarios 1-2, 1-3, 2-2, and 2-3, respectively (Table 8-5). The potentiality of increasing RW use in Baghdad consequently decreases the discharge of pollutant to the environment and allows more safe surface water flow downstream of the city. Enhancing the aquatic system downstream of big cities is a consequence of the increase in RW use while decreasing wastewater discharges. Furthermore, considering GW use in Baghdad for irrigation, industry, and recreation has the same effects as RW use by mitigating the burden at SW resources. Table

8-5 illustrates SW remainder flow rates downstream the city under the assumed twelve scenarios.

Table 8-5. Upstream and downstream surface water (SW) flow rates (1000 m^3/day) considering different allocation scenarios.

Scenario	Upstream flow rate (1000 m^3/day)			Water demand (1000 m^3/day)			Downstream flow (1000 m^3/day)		
	SW1	SW2	Total	SW1	SW2	Total	SW1	SW2	Total
Scenario 1-1	7800	4350	12150	8052.65	4286.4	12339	2532.92	260.00	2792.92
Scenario 1-2	7800	4350	12150	8052.65	4286.4	12339	3138.25	285.57	3423.82
Scenario 1-3	7800	4350	12150	8052.65	4286.4	12339	3091.25	271.75	3363.00
Scenario 1-4	4703	4065	8768	8052.65	4286.4	12339	0.43	0.57	1.00
Scenario 1-5	7800	4350	12150	8052.65	4286.4	12339	3091.25	271.75	3363.00
Scenario 1-6	4333	4065	8398	8052.65	4286.4	12339	0.03	0.07	0.10
Scenario 2-1	7800	4350	12150	8052.65	4286.4	12339	2532.92	260.00	2792.92
Scenario 2-2	7800	4350	12150	8052.65	4286.4	12339	3549.89	308.22	3858.11
Scenario 2-3	7800	4350	12150	8052.65	4286.4	12339	3467.36	298.22	3765.58
Scenario 2-4	4333	4052	8385	8052.65	4286.4	12339	0.36	0.22	0.58
Scenario 2-5	7800	4350	12150	8052.65	4286.4	12339	3481.58	298.22	3779.80
Scenario 2-6	3901	4052	7953	8052.65	4286.4	12339	0.05	0.22	0.27

The summary of the allocated water quantities from surface water (SW), groundwater (GW), and reclaimed water (RW) resources from the run off the twelve scenarios separately is presented in Table 8-6.

Table 8-6. Summary of scenarios describes the allocated water quantities (1000 m^3/day) from the three sources of water

Scenario	Untreated surface water (SW) diverted to demand nodes (1000 m^3/day)			Untreated surface water diverted to water treatment plants (1000 m^3/day)			Total consumed surface water (1000 m^3/day)		Allocated reclaimed water (RW) (1000 m^3/day)			Allocated groundwater (GW) (1000 m^3/day)			Total Allocated water (1000 m^3/day) 15=7+8+11+14
	SW1 1	SW2 2	Total 3=1+2	SW1 4	SW2 5	Total 6=4+5	SW1 7=1+4	SW2 8=2+5	WWTPs 9	PWWTPs 10	Total 11=9+10	GW1 12	GW2 13	Total 14=12+13	
Scenario 1-1	5267.1	4090.0	9357.1	2947.3	208.0	3155.2	8214.4	4298.0	0.0	0.0	0.0	0	0	0	12512.3
Scenario 1-2	4661.8	4064.4	8726.2	2947.3	208.0	3155.2	7609.0	4272.4	616.3	14.6	630.9	0	0	0	12512.3
Scenario 1-3	4708.8	4078.2	8787.0	2886.5	208.0	3094.4	7595.2	4286.2	616.3	14.6	630.9	0	0	0	12512.3
Scenario 1-4	4702.6	4064.4	8767.0	2806.8	208.0	3014.7	7509.3	4272.4	616.3	14.6	630.9	0	0	0	12412.6
Scenario 1-5	4708.8	4078.2	8787.0	2886.5	208.0	3094.4	7595.2	4286.2	616.3	14.6	630.9	0	0	0	12512.3
Scenario 1-6	4332.6	4064.4	8397.0	2850.7	208.0	3058.6	7183.2	4272.4	616.3	14.6	630.9	220	170	390	12476.5
Scenario 2-1	5267.1	4090.0	9357.1	2947.3	208.0	3155.2	8214.4	4298.0	0.0	0.0	0.0	0	0	0	12512.3
Scenario 2-2	4250.1	4041.8	8291.9	2947.3	208.0	3155.2	7197.4	4249.7	1050.6	14.6	1065.2	0	0	0	12512.3
Scenario 2-3	4332.6	4051.8	8384.4	2854.7	208.0	3062.7	7187.4	4259.7	1050.6	14.6	1065.2	0	0	0	12512.3
Scenario 2-4	4332.6	4051.8	8384.4	2854.7	208.0	3062.7	7187.4	4259.7	1050.6	14.6	1065.2	0	0	0	12512.3
Scenario 2-5	4318.4	4051.8	8370.2	2896.4	208.0	3104.4	7214.9	4259.7	1050.6	14.6	1065.2	14.2	0	14.2	12554.0
Scenario 2-6	3900.9	4051.8	7952.7	2947.3	208.0	3155.2	6848.2	4259.7	1050.6	14.6	1065.2	220	170	390	12563.2

8.9. Summary and Conclusions

In this chapter, twelve different scenarios were evaluated using a developed regional water allocation optimization model which maximize reclaimed water use. The model considers the allocation of surface water, groundwater, and reclaimed water for domestic, industrial, agricultural, commercial, and recreational uses, in Baghdad, using as much reclaimed water as possible which will minimum wastewater discharges to the environment.

Considering the SW flow downstream of Baghdad, as the use of RW increases, the SW flow downstream of the city maintains a suitable quantity as compared to the scenario without RW. The computed downstream SW flow was 2.79×10^6 m^3/day with no RW, as in scenarios 1-1 and 2-1. While, the use of RW has increased the remaining surface water flow in the downstream to be as 3.42×10^6, 3.36×10^6, 2.79×10^6, 3.86×10^6 m^3/day for scenarios 1-2, 1-3, 2-2, and 2-3, respectively. The potential for increasing RW use in Baghdad consequently decreases the discharge of pollutants to the environment and allows more high-quality surface water flow downstream of the city which enhances the aquatic system downstream while decreasing wastewater discharges. Even though groundwater is not used widely in Baghdad, it was considered in the model as another alternative source of poor quality for irrigation, industry, and recreation which has the same effects as RW use by mitigating the pressure on SW resources.

Using a practical and sustainable water management system in Iraq conserves the available fresh water resources and minimizes the discharge of pollution. Therefore, the adoption of a similar regional water allocation optimization model for Baghdad is important due to the very large volume of treated and/or partially treated wastewaters which have been discharged directly to the Tigris River. Public perception about the imminent threat to available water resources and their acceptance to the idea of including reclaimed water as an alternative source, absolutely will help reduce the impacts of potential water shortages. Furthermore, such an optimization modelling approach can assist decision makers by taking advantage of other global experiences to control water allocations in Iraq with special concern to potential water shortages.

CHAPTER 9 CONCLUSIONS AND PERSPECTIVES

9.1. Conclusions and Recommendations

9.1.1. The Projected Impacts of Using the Tigris And Euphrates Rivers Basins Water Allocation Optimization Model

Due to the importance of agriculture in Iraq, a basins management model was developed, which measures the net economic benefits by optimizing the system in terms of the most sustainable net economic benefit. The Tigris and the Euphrates Rivers have been considered as part of a case study by investigating the ongoing challenges of water resources in Iraq and evaluating the profitability for a variety of scenarios.

A. Conclusions

- Considering the Tigris River, the proportional sharing rule (PSR) provided a 32% increase in total farm income under dry supply conditions as compared to the upstream water sharing rule (UPR). While, under drought supply conditions, the PSR provided a 75% increase in total farm income as compared to the UPR. The PSR showed a similar performance over the downstream water sharing rule (DPR) under water scarcity conditions. Thus, the PSR clearly performed better than the UPR and DPR for the Tigris River under water shortage conditions.
- Considering the Euphrates River under dry water supply conditions, the PSR provided a 47% increase in total farm income as compared to the downstream water sharing rule (DPR). While under drought water supply conditions, the PSR provided an 83.5% increase in total farm income as compared to the DPR. On the other hand, the PSR provided a similar superiority over the UPR under water

shortage as it provided some water for all provinces rather than some provinces getting nothing for the others as under other sharing rules.

- Under water shortage conditions using the UPR, the common water right system typically used in Iraq, water is used primarily by the upstream provinces and lower value crops continue to be grown in the upstream provinces while downstream provinces receive lower amounts of water or no water at all. Therefore, the downstream provinces suffer the most during water shortages.
- Using DPR under shortage conditions, the downstream provinces receive most of the water and lower value crops continue to be grown in the downstream provinces. So, the upstream provinces suffer the most during water shortages.
- The net income losses under PSR during shortages have less economic damage caused by drought if compared to UPR and DPR due to the fact that PSR provides the opportunity for all provinces, under dry and drought conditions, to cultivate part of their farmland with higher economical crops.
- Considering the PSR, all provinces receive water under drought conditions, where the water provides a positive impact on the maximized net benefit in comparison to the UPR and DPR under the same water availability conditions enabling the achievement of economic and food security.
- The PSR clearly performs with the highest level of flexibility for adapting to water shortages because the PSR provides the opportunity for all provinces, under dry and drought conditions, to cultivate part of their farmland with higher economical crops.

- The flexibility in the use of the PSR grants the incentive to all provinces to eliminate their lowest value crops from production in drought seasons, while continuing to cultivate the highest valued crops that require specialized soils, management, and market access.

B. Recommendations

- The adoption of PSR is essential to be in Iraq using advanced control technology to estimate water demand and to control water release to consumers to ensure water sharing for each one of the partnered provinces.
- The developed model is a hypothetical guidance for decision makers in Iraq for potential future water shortages while it demonstrated how it is feasible to adopt the PSR as an alternative and efficient water allocation rule due to its flexibility of providing fair water resource allocation in drought seasons.
- The development of the water management system on both the administrative and technical aspects is necessary to satisfy the optimum distribution to maximize the potential benefits and to minimize water losses.
- Adopting such an optimization modelling approach can be supportive to decision makers by ensuring that water related decisions will benefit the economy. Furthermore, the model assists in enhancing decision-making by taking advantage of other global experiences to control water allocations in Iraq especially with concern to diminished water supplies.

9.1.2. The Projected Impacts of Using the Reclaimed Wastewater Allocation Optimization Model for Agricultural Irrigation

Dealing with water shortages and to mitigate the burden on renewable water resources, a mixed-integer nonlinear programming (MINLP) water allocation optimization model was developed to optimally allocate crops with reclaimed water (RW) on farmlands while maximizing the net benefit. Different qualities of RW were considered for agricultural irrigation cultivating a variety of crops. The municipal treated wastewater from Baghdad's wastewater treatment plans was used as the only source of reclaimed water.

A. Conclusions

- Under most scenarios evaluated, the use of tertiary treated wastewater (RW_A) provided the greatest net benefit over the secondary treated wastewater (RW_B), and the primary treated wastewater (RW_C). While, RW_C provided the lowest net benefit as only low value crops could be cultivated.
- Using RW_A, the computed results show a consistent net benefit increase with the increase of irrigation efficiencies because the crops, which were selected by the model, are close to each other in their net benefit.
- The computed results of using RW_B show a slightly different behavior than RW_A because it has a lower range of crops to be cultivated which reduces the maximum net benefit.
- The computed results using RW_C maintained the same trend of increase with the maximized net benefit because it can only irrigate a limited selection of crops due to

quality standards, and the low marginal benefit of those crops in comparison to RW_A and RW_B.

- The increase of irrigation efficiency reflects positively on the net income due to the decrease in the RW requirement which gives the opportunity to cultivate larger areas selecting the highest value crops.
- The total cultivated area has been varied according to the type of irrigated crops, crop's water requirement, water availability and the irrigation efficiency. Using a higher water availability does not always mean cultivating larger areas because each crop has its own evapotranspiration value, which is different than the others, that causes the variation in the predicted cultivated areas.
- The capability of RW_A to irrigate all the suggested crops, due its high quality, provides the model the flexibility to select the most economic crops to satisfy the maximum limit of the allowable cultivated area for each crop. A similar phenomenon is observed under the use of RW_B where it has fewer options for crops to be cultivated as compared to RW_A.
- Under low water quantity availabilities, RW_B performs better than RW_A because the model selected the same type of crop to be cultivated on the same areas using RW_A and RW_B, but the difference occurred because the cost of RW_B is less. That domination of RW_B over RW_A decreases with the increase in RW volumes, as the model allocates water on farmlands to cultivate the most economic crop.

B. Recommendations

- In the evaluation of the WWTPs in Iraq based on the computed results comparing the use of different RW qualities under different irrigation efficiencies is important to demonstrate the need to invest in wastewater treatment for agricultural irrigation instead of disposing it to the environment.
- The developed model is a good tool to be used by decision makers to take advantage of the recently rebuilt WWTPs by considering tertiary treatment for the existing and potential new WWTPs to employ their RW for agricultural irrigation or other practices.
- Considering RW_A with a wide range of selected crops is important to provide flexibility in selecting the highest economic crops while satisfying the maximum limit of the allowable cultivated area by each crop.

9.1.3. The Projected Impacts of Using the Optimization Model for Agricultural Reclaimed Water Allocation Using Mixed-Integer Nonlinear Programming

A mixed-integer nonlinear programming reclaimed water allocation optimization model was developed to maximize the net benefit generated from the cultivation of different types of crops, comparing the use of RW_A and RW_B. The analysis generated the maximum net benefit, total cultivated area, net benefit per hectare, and the area dedicated to each crop.

A. Conclusions

- The model demonstrated that RW_A generally results in a higher net benefit as compared to RW_B. With lower quantities of available water, only the most economic crops are grown with both RW_A and RW_B while the cost of RW_B is less than RW_A.

- The net benefit of using RW_A and RW_B increases with the increase in the amount of reclaimed water used until certain limits where the increase in net benefit will decrease as higher irrigation efficiencies (IEs) are achieved. This decrease of the net benefit increase is because the model tends to allocate the available quantities of RW by selecting lower economic value crops after satisfying the maximum allowed area of the most economic value crops.
- Small increases in IEs are clearly beneficial as the model demonstrates that the use of higher IEs, which means more water availability due to advanced irrigation techniques, can produce a higher net benefit and greater crop diversity. Even small increases in irrigation efficiency are clearly beneficial as increasing the irrigation efficiency from 45% to 55% can result in a net benefit increase of 30.7%.
- The maximization of the net benefit from the use of RW_B followed a different trend than that observed with RW_A as the increase in net benefit decreases as the quantity of RW_B used increases and the same is true for increases in IEs. The decreases in the ratio of the net benefit with higher irrigation efficiencies is due to the increase in the practically employed amount of water which tends to irrigate the maximum allowed area of the most economic crops first and later to find crops of lower economic values.
- The higher quantities of reclaimed water in combination with higher irrigation efficiencies result in the cultivation of more land which produces a higher net benefit when crops with higher economic value are cultivated.
- The net benefits from using lower quantities of reclaimed water were similar for both types of reclaimed water as the highest net benefit crop was cultivated on 384 ha.

- The model satisfies the maximum allowed area of the most economic crop then it starts cultivating the crop with the next higher economic value and so on. Therefore, tomatoes were selected first by the model to be cultivated using RW_A followed by potatoes, onion, eggplant, cucumber, and okra.
- With an increase in irrigation efficiency using a specific quantity of RW, the computed net benefit per cultivated hectare of crops increased until a limit was reached as the model results experienced a significant decline in the predicted net benefit per hectare due to the increase in the cultivated area, and the decrease of the total maximized net benefit computed from the cultivation of crops with a lower economic value.
- Increasing the quantity of RW and/or increasing the irrigation efficiency, increases the quantity of water which is allocated on farms cultivating more crops. Using different RW_A availabilities, tomatoes, potatoes, onion, eggplant, cucumber, okra and clover have been cultivated, respectively, starting from the highest economic value crop then next highest and so on. While, the most economic crops identified by using RW_B are tomatoes, eggplant, cucumber, okra, clover, sesame, alfalfa, sunflower, cotton, and wheat. Therefore, increasing the irrigation efficiencies using a certain quantity of reclaimed water provides the opportunity to cultivate more crops after cultivating the maximum allowed area for each crop.

B. Recommendations

- It is more efficient to upgrade the Iraqi WWTPs to tertiary treatment to produce RW_A, which will help in reducing the potential negative environmental impacts of wastewater discharges while increasing the potential uses of RW for agriculture.

- Since most of Iraq's built or under construction WWTPs are located in or adjacent to agricultural lands, it is logical and efficient to invest in using their secondary or tertiary treated wastewater for agricultural irrigation to enhance the economy of farmers and the environment while providing a diversity of crops.
- Considering RW_A with a wide range of selected crops is important to provide flexibility in selecting the highest economic crops while satisfying the maximum limit of the allowable cultivated area by each crop.
- Improve the irrigation techniques in Iraq to increase the irrigation efficiencies is essential to produce a higher net benefit and greater crop diversity.

9.1.4. The Projected Impacts of Using the Agricultural Reclaimed Water Allocation Optimization Model to Maximize the Individual Farm's Net Benefit

A mixed integer nonlinear programming (MINLP) optimization model for agricultural water allocation was developed to maximize the net benefit, taking into consideration individual farms, generated from the cultivation of different types of crops comparing the use of RW_A and RW_B. The model predicts the individual farm maximum net benefit, total net benefit, individual farm cultivated area, total cultivated area, net benefit per hectare, and the area dedicated to each crop.

A. Conclusions

- The model demonstrates that the use of higher irrigation efficiencies, which means more water availability due to advanced irrigation techniques, can produce a higher net benefit and greater crop diversity. Therefore, small increases in irrigation efficiency are clearly beneficial which increase the individual farm net benefit as well as the total farms net benefit.

- The model resulted in a significant fluctuation in the predicted net benefit per hectare with the increase in irrigation efficiencies using higher quantities of water, but it maintained a homogeneous increase for the individual farm with the total maximized net benefit from the cultivation of up to 4 crops on each farm.
- Increasing the quantities of RW used resulted in an oscillatory increase in the cultivated area as different crops were determined to be optimal for different quantities of RW because the model tends to reach the maximum net benefit regardless of how much area is to be cultivated since it has a sufficient quantity of water.
- Optimizing the use of higher water availabilities with RW_B results in a commensurate increase in the net benefit with higher irrigation efficiencies satisfying higher net benefits in comparison to the use of the equivalent quantities with irrigation efficiencies of RW_A. The advantage of RW_B over RW_A is the cultivation cost and the selling price of the cultivated crops are the same except RW_B is less expensive than RW_A.
- The model provided flexibility in crop selection considering the available amount of water while predicting the maximum individual farm net benefit. The maximum individual farm net benefit was satisfied by cultivating up to 4 crops at each farm. Tomatoes, potatoes, onion, eggplant, cucumber, and alfalfa were the most dominant crops selected by the model to be cultivated using RW_A.

- The higher quantities of reclaimed water in combination with higher irrigation efficiencies result in the cultivation of more land which produces a higher net benefit when crops with higher economic value are cultivated.
- Maximizing the net benefit using RW_B followed an unstable pattern in predicting the cultivated area to satisfy the maximum net benefit as it predicted higher net benefits from the cultivation of less area. This is because the model has satisfied the individual maximum net benefit by considering crops with a higher economic value that consume less water.
- The average net benefit per hectare ($/ha) predicted from optimizing the allocation of RW_A and RW_B varied according to the cultivated area. The factors that limit the net benefit are the increase in the cultivated area along with the requirement to grow lower economic value crops.
- The model results experienced a significant fluctuation in the predicted net benefit per hectare with the increase in irrigation efficiencies using higher quantities of water while maintaining an homogeneous increase of the individual farm and the total maximized net benefit computed from the cultivation of up to 4 crops on each farm.
- Except for tomatoes, which satisfied the highest net benefit per hectare as compared to other competitive crops, the model-maintained cultivating as many crops as possible to satisfy the maximum individual farm net benefit while fulfilling the diversity in production.

- Even though the optimization model allows up to 4 crops to be cultivated simultaneously on the same farm, results showed that most of the farms cultivated at least 2 crops depending on the RW availability and the IE implemented.

B. Recommendations

- The adoption of water allocation optimization models is helpful to provide the diversity of cultivated crops which enhances the possibility of covering the local market demand while reducing the quantity of imports.
- Since the model maintained an homogeneous increase for the individual farm total maximized net benefit, the model is recommended to satisfy the highest net benefit along with the diversity in crops production.
- It is logical and efficient to invest in using secondary or tertiary treated wastewater for agricultural irrigation to enhance the economy of farmers and benefit the environment while providing a diversity of crops by using the developed model which maximize the individual farm net benefits.
- This model is applicable in Iraq since most of the treated wastewater is secondary treated, which is easier to be used, and because the model provides flexibility in selecting the highest economic crops while satisfying the maximum limit of the allowable cultivated area by each crop. In addition, the minimum allowed area of crops to be cultivated may be adjusted based on specific conditions through constraints in the model consistent with supply and demand.
- Improving the treated wastewater quality along with irrigation techniques in Iraq is important to produce a higher net benefit and greater crop diversity.

9.1.5. The Projected Impacts of Using the Regional Water Allocation Optimization Model Using Three Different Water Resources for Five Different Uses

The goal of chapter 8 of this dissertation was the development of a regional water allocation optimization model that maximizes reclaimed water use from the allocation of surface water, groundwater, and reclaimed water for domestic, industrial, agricultural, commercial, and recreational uses, considering Baghdad as a case study.

A. Conclusions

- The computed results proved that the model can allocate the three water resources efficiently on the 50 demand nodes considering the type of demand nodes along with the connectivity of water resources to the other components in the system.
- The optimization model showed that in Baghdad, the Tigris River has saved more water than the Euphrates River due to most of the agricultural demand nodes which are connected to WWTPs are located on the Tigris River basin.
- As a result of using reclaimed water in scenario 1-2, surface water resources were saved by as much as 5% of the daily flow within the city, which consequently increased the water flow rate downstream in the rivers.
- Results showed that the Euphrates River is more sensitive to water shortage than the Tigris River due to its lower quantities of water supply. Under scenarios 1-3 and 1-4, the reclaimed water was allocated on demand nodes by allowing the maximum percentage of RW to be used by each type of use.
- The quantities of surface water diverted to demand nodes and to water treatment plants (WTPs) was varied depending on the available quantity of reclaimed water which was

allocated simultaneously to users, as a maximum of 100%, 20%, 5%, 5%, and 10% for agricultural, industrial, domestic, commercial, and recreational uses, respectively.

- The reduction in the diverted surface water quantities to demand nodes was substituted by reclaimed water considering the assumed percentages of RW that must be allocated to nodes depending on the type of use. Furthermore, the quantities of water diverted to WTPs varies as reclaimed water was allowed to cover no more than 5% of domestic and commercial use, and 20% for industrial use.
- This regional water allocation optimization model satisfied the water demand for all nodes by allocating surface water and reclaimed water concurrently with the allowance of supplying a little more than the demand by maximizing RW use subjected to the previously listed constraints.
- Under the allocation of the three types of water for the 50 demand nodes of different uses considering 11 WWTPs, the presence of the groundwater (GW) decreased surface water (SW) consumption.
- Considering the downstream SW flow remaining, as the RW increases, the system downstream of the city maintains a suitable quantity as compared to no RW use.
- The water allocation model determines how the available quantities of water are allocated fairly to satisfy the demand of each demand node using as much reclaimed water as possible which will minimum wastewater discharge to the environment.
- The different water allocation schemes which were developed were assumed to find practical and applicable water allocation scenarios that can help relieve the impact of

potential droughts and water shortages in Iraq along with environmentally affirmative outcomes.

- All wastewater generated from the domestic and commercial demand nodes is diverted to the main wastewater treatment plant (WWTP), while the wastewater generated at industrial nodes is either recycled by its own private wastewater treatment plant (PWWTP) or diverted to the main WWTP, depending on the availability of the PWWTP at the industrial demand node.

B. Recommendations

- The adoption of a similar regional water allocation optimization model for Baghdad is important due to the very large volume of treated and/or partially treated wastewaters which have been discharged directly to the Tigris River. Even though groundwater is not used widely in Baghdad, it is important to be considered as another alternative source of poor-quality water.
- As many water management models were developed and applied in many regions, this optimization model assures fair allocation of water among all users.
- Using the regional water allocation optimization model considering RW is necessary to relieve the pressure on fresh water resources and to reduce the potential environmental pollution and the related economical and health concerns.
- It is recommended to use a practical and sustainable water management system in Iraq to conserves available fresh water resources and minimize the discharge of pollution.

- Enhancing the public perception about the imminent threat to available water resources and their acceptance of the idea of including reclaimed water as an alternative source, absolutely will help reduce the impacts of potential water shortages.
- Increasing RW use in Baghdad consequently decreases the discharge of pollutants to the environment and allows more high-quality surface water flow downstream of the city which enhances the aquatic system downstream while decreasing wastewater discharges.
- Groundwater use in Baghdad as another alternative source of poor-quality water for irrigation, industry, and recreation, will have the same effects as RW use by mitigating the pressure on SW resources.
- The adoption of a practical and sustainable water management system in Iraq conserves the available fresh water resources and minimizes the discharge of pollution. Using this regional water allocation optimization model for Baghdad is important due to the very large volume of treated and/or partially treated wastewaters which have been discharged directly to the Tigris River.

This study provides guidance for decision makers in Iraq for potential future conditions where water supplies are reduced and demonstrate how it is feasible to adopt an efficient water allocation strategy with flexibility in providing equitable water resource allocation considering alternative resources. Using reclaimed water for irrigation will help in reducing the potential negative environmental impacts of wastewater discharges while increasing the potential uses of RW for agriculture and other applications. It is logical to invest in reclaimed water use by increasing wastewater treatment efficiencies to be used for irrigation, especially since most of Iraq's built or under construction WWTPs are located in or adjacent to agricultural lands. Using reclaimed water for irrigation is a logical and efficient method to enhance the economy of farmers and benefit the environment while providing a diversity of crops. Adopting such an optimization modelling approach can assist decision makers, ensuring their decisions will benefit the economy by taking the advantage of other global experiences to control water allocations in Iraq especially with concern to diminished water supplies.

9.2. Future Work

Future work to expand upon the water allocation models developed in this dissertation include, but are not limited the following approaches:

9.2.1. Water Sustainability Index

The river basin management model which measures the net economic benefits should be expanded to include a sustainability index such that different management scenarios for case studies can be optimized in terms of the most sustainable net economic benefit. The sustainability index should be quantified considering the uncertainty of the transboundary water supply and the equitable distribution of water to downstream provinces along with the negative consequences from low supplies and deteriorating water quality. The transboundary water supply uncertainty along with the climate change impacts on the environmental, economic, social, and/or politics are important to be considered in potential future models with different sustainability indexes.

9.2.2. *Effects of Reclaimed Water Salinity*

In regarding to the agricultural water allocation optimization models, the effects of reclaimed water salinity on both crop yield and farm productivity should be included to distinguish between alternatives with different reclaimed water qualities and the related consequences of using saline waters. The influence of salinity considering the assumption of mixing freshwater with reclaimed water is recommended to compute the potential net benefit generated from blending different sources of water. As Iraq relies on importing large quantities of crops due to water issues, different crop cultivation costs and selling prices should be combined considering the river basin use of freshwater in combination with reclaimed water resources. The precise adoption of water-crop-cost scenarios may promote the decision to invest in fresh and reclaimed water resources to satisfy economic and social improvement along with the protection of surface water quality.

9.2.3. *Water Quality Considerations*

Water quality constraints should be included in further applications of the developed regional water allocation optimization model. A penalty system may be applied on the disposal of treated wastewater and from industrial users, which do not meet water quality standards. The sustainability of different scenarios should be evaluated to identify the most sustainable and applicable scenarios.

The regional water allocation optimization model could consider water quality changes produced by water treatment plants, consumers, and wastewater treatment plants, as it was assumed by Mays et al. (1983). Taking into consideration multi-period water allocation scenarios should be done by considering the future expansion of water and wastewater treatment plants capacities, increasing demands, sanitary infrastructure, and/or generated wastewater flow increases. For any future expansion, a cost function can be included to minimize the cost of reclaimed water use as it was done by Mays et al. (1983) considering Iraqi cities as different case studies.

9.2.4. Water-Energy-Food-Climate Nexus

Since Iraq has been suffering from the negative consequences of water shortages and mismanagement of the essential sectors, water, energy, and food along with climatic change have to be evaluated. The impacts on these sectors must be evaluated considering the Tigris and the Euphrates Rivers basins. In Iraq, the oil industry, agriculture, and power generation all rely on water. A quadrant hybrid water-energy-food-climate optimization model to maximize the net benefit from the allocation of the available sources of freshwater in addition to reclaimed water should be developed. The model could also minimize the potential damage from the generated pollutant gases and their impacts on the environment and the potential climate changes. The model should take into account the economic, social, health, environmental, and climate related consequences from the allocation of the available resources of water considering various availability scenarios. To continue the efforts completed in this study, the combination of water, energy, food, and climate in one quadrant hybrid system can be a good tool for decision makers in Iraq to highlight not only the advantages of the current and potential water allocation scenarios, but it should also consider the disadvantages, recognize the vulnerabilities, and assess the resilience of the potential outcomes. The proposed study will include climate trends and impacts, which have been affected due to water shortages in the last three decades as the number and size of the dust storms has increase dramatically in Iraq. Al-Riffai et al. (2017) developed a water-energy-food nexus modeling approach which considered the Nile River basin countries. The study used three models which work together to recognize the biophysical, energy, and economic impacts considering the Eastern Nile Basin. So, it is logical to propose similar approaches applied in Iraq considering the Tigris and The Euphrates Rivers, especially since the hybrid modeling approaches are recognized as more comprehensive models to generate policy information that enhances decision making. The main sectors which should be included in the potential hybrid model are; water, energy, and food, as illustrated in Figure 9-1 (Al-Riffai et al. 2017). The climate change effects are to be included and analyzed as the fourth element in the framework of the potential models. The importance of water has promoted it to play the central role in the nexus where water is the main source for domestic, energy, and food supplies, in addition to its role in enhancing and maintaining an adequate climate. In Iraq, energy production, including power plants and the oil industry, mainly depend on water. Consequently, the generated pollution has a large impact on big cities and rivers and streams. Different sources of water with different qualities should be considered to reduce the pressure on surface water resources and to minimize the effects of the generated pollution, and dust storms.

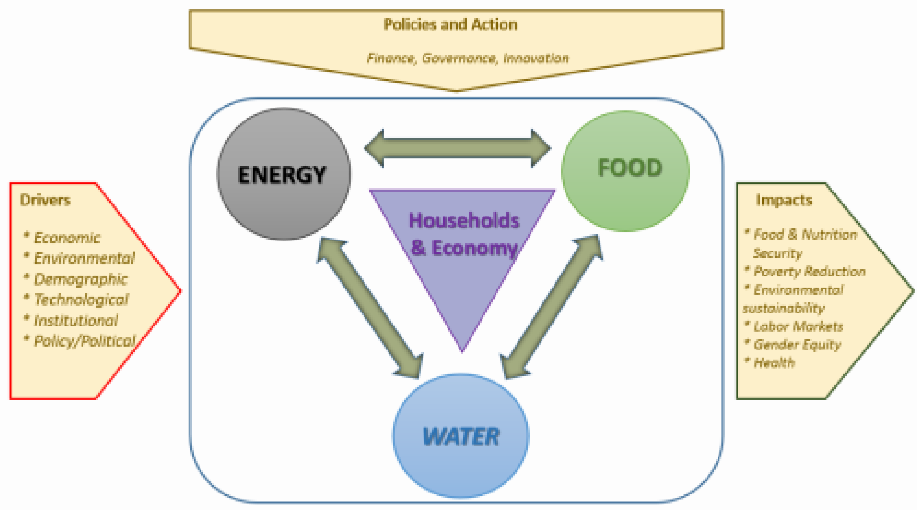


Figure 9-1. The Water, Energy, and Food Nexus Perspective

Source: Al-Riffai et al. (2017) adaptation of Hoff (2011) and von Braun (2015)

Since agricultural irrigation is the main consumer of water in Iraq, where it demands more than 70% of the renewable water supply, it plays an important role in Iraq's economy and social security. Therefore, the economy and society in general will be affected by water availability. Furthermore, the inclusion of green belts around big cities, mainly in the western region of Iraq, is relying on RW and GW as the main sources for irrigation due to the limited SW supplies. The potential water demand for both energy production and agricultural irrigation along with domestic demand play mutual roles in Iraq's economic, social, and political stability. The quadrant may have negative impacts on the environment regarding released pollutant gases, discharge of treated and untreated wastewaters, and dust storms because of desertification.

The potential framework of the quadrant hybrid water-energy-food-climate optimization study, should include biophysical, energy, and economic models, Figure 9-2 (Al-Riffai et al. 2017), in addition to include a climatic changes forecasting model to predict any climatic change impacts generated from the allocation of water and related energy-food production consequences, which are defined as:

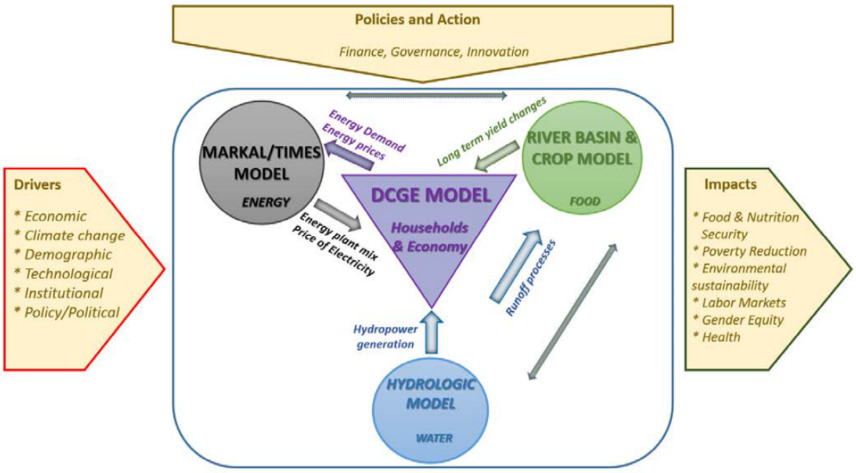


Figure 9-2. The nexus modeling framework presented by Al-Riffai et al. (2017)

- The biophysical model should include the river basin management model, which is an extension of the model developed in Chapter 4. The model optimizing crop production, should be interfaced with a hydrological model used, such as HEC-HMS. Metrological data will be included in the model to simulate the projected impacts, by adopting different climate scenarios, on temperature and precipitation along with the evapotranspiration and rainfall runoff to the river basin. Furthermore, the RW discharged will be considered in the model to evaluate permanent and sustainable water releases to the environment. The generated agricultural net benefit will be maximized considering the water availability and quality, soil type, farm productivity, management techniques, irrigation efficiency, irrigation policy, and technology constraints. Figure 9-2, adapted from (Al-Riffai et al. 2017), represents part of the potential constraints which will be adopted to optimize the potential quadrant hybrid water-energy-food-climate nexus. An extended time period water allocation optimization model should be developed by improving the model in Chapter 4 to include multi-year periods to cover different hydrological scenarios by including the stochastic nature of the Tigris and Euphrates Rivers flows and the expected performance and potential risks.

- In order to cover the energy part of the nexus, an energy-flow optimization model should be developed by including national and international energy sources. Renewable energy resources, such as solar and wind energy, will be considered as an alternative local resource of energy, which mitigates the pressure on the traditional energy resources, reduces fossil fuel power generating water demand, and to reduce the generated emissions to the environment. Cost analysis along with the generated damages of the included energy sources should be considered in this part of the nexus. Al-Riffai et al. (2017) used the MARKAL optimizer, (MARKet Allocation)/TIMES (The Integrated MARKAL-EFOM (Energy Flow Optimization Model) System, a successor of MARKAL), to cover the energy section, Figure 9-3. A similar energy flow optimizer should be used, to optimize energy production and use, considering the previously mentioned sources of power taking into account socioeconomic constraints. The long-term analysis of energy systems should be considered at the national level with different energy production and demand scenarios. The inclusion of private solar power production for certain types of consumers can be included in the potential scenarios. The privatization of part of the power production sector must be included in the proposed scenarios to analyze the socio-economic impacts along with the potential new policies to promote privatization. Furthermore, including various renewable energy sources in the proposed system will have certain socio-economic impacts, which must be investigated in the model.

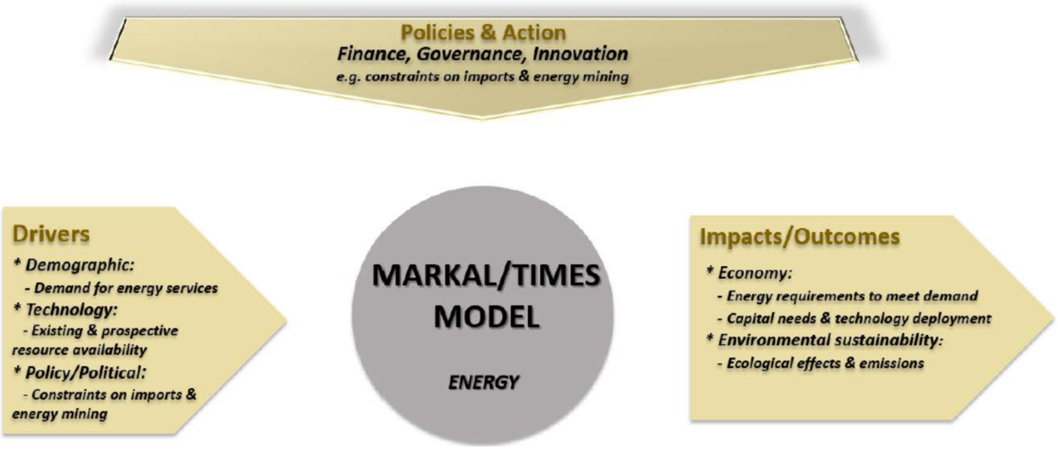


Figure 9-3. A typical structure of the MARKAL/TIMES model presented by Al-Riffai et al. (2017)

Different types of constrains can be included to get more reasonable and applicable results. The projected energy demands, the limits of emissions, the energy balance, the limits of energy production, population growth, energy consumption and cost per household, the quality standards of the treated wastewater discharged to the environment, and the technology used are the main constraints which are usually adopted in such energy flow optimization modelling (Al-Riffai et al. 2017). A multi-period approach should be included covering different seasons during each period, to optimize the energy flow taking into consideration the projected change in demand per season, demand per period, energy production, and energy generation efficiency along with the potential future costs and the generated emissions and pollutants.

- Climatic change will be considered using one of the specialized metrological forecasting models, such as the weather research and forecasting (WRF) model or others. The potential impacts from the allocation of the available resources of water for agricultural and green belt irrigation will be considered in this model. More water quantities, more irrigated areas, more RW use, and fewer dust storms are potential benefits. The environmental impacts along with the social and health impacts will be analyzed considering the potential climatic improvement. The model will consider water availability and quality, land in production, types of crops and bushes to be cultivated, the ownership of lands, irrigation technology and efficiency, type of soil (source of dust), and economic constraints (cost of cultivation and irrigation). Different scenarios are to be considered including different water quantity and quality, priority levels of irrigation over other uses, public perception levels, economic prosperity, and the potential weather changes taking into account multi-period analysis to test the flexibility of the developed model.
- A socio- economic section should be included in the water-energy-food-climate nexus model, considering at the national level, to analyze the potential impacts from connecting the biophysical, energy, and climate models. It is possible to build a new optimization model, by considering all the mentioned objectives and constraints in one multi-objective optimization model, to maximize the socio-

economic impacts of using the water-energy-food-climate nexus by considering the dollar value for the potential social impacts generated from the proposed scenarios considering the Iraqi provinces. It is possible to use a province-specific dynamic recursive computable equilibrium (DCGE) model, which was developed by the International Food Policy Research Institute, with limited constraints. It should be mentioned that the DCGE was used by Al-Riffai, et al. (2017) considered at the international level. The agricultural production strategies, income distribution, investment, consumption, and household net income can be included under the socio-economic section taking into consideration taxes, subsidies, product markets, savings, investment, quantity, and other constraints.

It is necessary to complete the water-energy-food-climate nexus framework to provide policy perspectives for the Iraqi decision makers regarding further investment in the power sector with less water consumption and lower emissions to better the environment.

The inclusion of all the four previously mentioned components of the water, energy, climate and food nexus framework in Iraq, will be an essential work to build a hybrid water management system and to evaluate the potential water-energy-food-climate policy scenarios.

9.2.5. Multi-objective Approach

The improvement of the developed models of this study considering multi-objective optimization modelling is one of the aspects to be considered in the future. Using multi-objective optimization modelling is important to optimize the allocation of the available sources of water; SW, GW and RW, for agricultural irrigation considering different crop growth stages in Iraq.

There are several potential objectives to be optimized using a multi-objective optimization modelling approach to continue the efforts completed in this study with better data. Some of the potential objectives are to maximize the net benefits, maximize the use of RW, minimize the use of SW, maximize water allocation efficiency, maximize crop allocation efficiency on farms. Different soil qualities, damage from the deposition of salts and pollutants in soil need also be assessed assuming different water qualities. This can be implemented, for instance, by considering different water availabilities with different allocation scenarios and irrigation schedules. Two or more objectives can be optimized simultaneously depending on the required outcomes subject to certain types of constraints.

Solving a multi-objective optimization model is different than solving a single objective optimization model, because the different objectives are non-commensurable. Therefore, the formulation of models for multi-objective analysis is implemented to find the most preferred solution by finding the efficient or Pareto optimal (nondominated or non-inferior) solutions (Mavrotas 2007). Converting the existing models to multi-objective optimization models along with the availability of additional preference inputs will provide good guidance for water resources related decision makers in Iraq. The multi-objective optimization problems can be tackled, for instance, by using the weighting method and ε-constraint method (Mavrotas 2007), as they are widely used to solve large problems.

- A multi-objective optimization model can be developed using three objective functions. The first function maximizes the generated net benefit from the allocation of RW, SW, and/or GW for agricultural irrigation by optimizing the cultivated areas along with the selection of the highest economic value crops. This objective function assures the maximum net benefit to be satisfied by cultivating more than one crop on each individual farm to satisfy the demand for a variety in produce. The second function maximizes RW use generated from the allocation of the available resources of water considering that each individual farm has to satisfy its water demand from the available resources. The third function is to minimize soil damage from the accumulation of salts and other pollutants. This function will consider mitigation of damage by mixing RW with SW and/or GW taking into consideration water quality parameters and constraints. Different scenarios considering various water quantities and qualities are to be compared to optimally specify the quantity and quality of RW discharges. The additive weighted method will be applied to integrate the results of the three objective functions by specifying a weight for each objective depending on the practical experience of related personnel. The results computed from the multi-objective optimization model developed from integrating the three objectives are necessary to be compared with the results computed from optimizing each objective independently. This model is necessary to decide the minimum allowable quality of RW which should be used depending on the type of soil and the cultivated crops.

- A multi-objective optimization model is necessary to optimize four objectives considering the socio-economic impacts of using RW. The first objective is to maximize the generated economic net benefit from allowing more than one crop to be cultivated on each farm using RW as the only available source of water. The number of crops to be cultivated on each farm, the amount of the allocated RW, and the area to be cultivated are the main decision variables of the first objective, which should be solved using a mixed-integer nonlinear programming (MINLP). The second objective is to maximize the social acceptance of using RW. This objective can be applied by using the dollar value to represent the social impacts to compute the net benefit generated from RW use considering several potential social impacts. The third objective is to minimize the generated damage from using RW by summing the values of the physical damages resulting from irrigation using RW, and the social damage generated due to the level acceptance of farmers and consumers regarding the use of RW for irrigation. The fourth objective minimizes the cost of RW production and conveyance by considering different wastewater treatment technologies along with water conveyance technologies, depending on the RW quality impact on environmental aspects. This multi-objective optimization model should include the decentralization approach for potential WWTP(s) expansion considering different candidate locations and RW allocation scenarios. The result of this multi-objective optimization model can be compared with the results of the four objectives individually to test the resilience of the developed models. Including the socio-economic impacts, the model will provide a clear vison for decision makers about the future of RW use in Iraq and the potential social and environmental consequences.

- A multi-objective optimization model considering four objectives to optimally allocate the potential RW, SW, and GW from the expansion of WWTP systems in Baghdad should be developed. The first objective minimizes the cost of RW production and allocation from the current and potential future WWTPs considering decentralization in wastewater collection and treatment. The potential decision variables of this objective are the quantity and the treatment level of the generated RW, the type of use along with the potential number of consumers of each quality level of the allocated RW. The third objective is to minimize the cost of the new potential WWTPs considering candidate locations using 0/1 binary variable approach. The third optimization model should be solved using a MINLP including the cost of construction, operation and maintenance of the potential WWTPs, taking into account the treatment level and the potential uses of RW. The fourth objective of the potential multi-objective optimization model is to maximize the quality of water allocated by mixing the available resources of water for certain types of use. The objective of this model will be subject to water quality constraints considering the blending of water from the available resources considering the type of use and conveyances. Minimizing the generated damage from the allocation of available RW is the fifth objective of this optimization system. By considering a blending approach of different qualities of RW with SW and/or GW for irrigation, industrial, and recreational uses, the model will predict the quantity and the quality of the allocated water, for each user, along with the accumulated quantity of salts and/or other pollutants. The results of the five optimization models will be integrated using the additive weighted method by specifying a weight for each objective depending on the experience of related personnel. The results computed from this multi-objective optimization model are necessary to be compared with the results computed from optimizing the developed models separately to provide significant guidance for decision makers regarding mixing RW with other freshwater resources. Also, it will provide an indication about the economic value of the generated damage by comparing different RW qualities and allocation scenarios.

- The consideration of economic, social impacts, and climate change is necessary to be included in the potential future water allocation optimization models, which will be a pioneering concept in Iraq. The development of a multi-objective optimization model which considers the effect of dust storms in Iraq and the related consequences is necessary. The first objective is to minimize the value of damage generated from dust storms considering social, economic, health, and environmental impacts. Different scenarios for climate change should be considered to optimize the first objective using one of the related applications, such as a weather research and forecasting (WRF) model. Each one of these aspects will be represented using dollar values through consulting specialists in each of the mentioned fields. The second objective is to minimize the quantities of water allocated, including RW as an alternative source, for agricultural and green belt irrigation in addition to municipal, recreational and industrial uses. This multi-objective optimization model is essential to be applied considering the western region of Iraq.

Multi-objective modelling can be used to specify the best or the most applicable and feasible alternative of water allocation schemes. The multi-objective optimization models can be solved using different approaches, such as; the non-dominated sorting genetic algorithm (NSGAII) (Lalehzari et al. 2015), particle swarm optimization (PSO) integrated with the addition of a weighting method (Yousefi et al. 2018), the minimum deviation method (MDM) (Özcan and Erol 2014), shuffled frog leaping algorithm (SFLA) (Fallah-Mehdipour et al. 2012), and many other algorithms, which are globally used to facilitate this type of optimization programming.

9.2.6. Other Refinements

1. With the availability of better data, which covers different water related sectors of Iraq, all of the developed models in this study will generate more reasonable and applicable results, that should be adopted by decision makers. More comprehensive and accurate data, which covers the Iraqi provinces, cities, districts, and towns, will enhance model accuracy for the efforts which completed in this study along with the potential new models.

   The application of the regional water allocation optimization model using comprehensive data, considered at the province level, will support decisions regarding water demand and consumption along with potential RW production and use. Furthermore, it can be used as a basis for negotiations among the consecutive provinces, which share the same sources of water, to avoid internal conflicts and to build robust water management strategies based on proportional water sharing among the Iraqi provinces.

The application of the regional water allocation optimization model for all of the Iraqi provinces considering water quality constraints is essential to reduce the damage due to low quality water downstream of big cities. By considering the Tigris and the Euphrates Rivers as two separate reaches, a clear vision regarding the damage generated due to low quality waters may be achieved, taking into account accurate and comprehensive data as provided from the Iraqi administrations. Furthermore, it will provide guidance for potential future strategies and alternatives which should be followed to mitigate the current damage resulting from the mismanagement of water resources. To accomplish this, different scenarios will be tested considering different water resource availabilities with different water qualities under various demand assumptions and multi-period optimization approaches.

2. Capacity expansion of the available sources of water, water demand, water and wastewater treatment capacities, changes in water quality, climatic change, and other system parameters, and increase population are essential to be considered in the future water allocation optimization models. The development of multi-period optimization problems will provide a clear vision for decision makers about the potential solutions by considering different water alternatives and allocation scenarios. Also, it will help in making the correct decisions regarding the required expansions of water and wastewater infrastructures and related construction and operation costs.

3. All of the completed optimization models may be applied assuming reclaimed water is free of charge and a system of incentives for agricultural and industrial users to mitigate the pressure on fresh water use and enhance the environment can be considered. Groundwater use can be considered as an alternative resource, together with surface water and reclaimed water, for many of the northern, eastern, and western Iraqi cities. Using the developed water allocation optimization models including groundwater withdrawal and recharge constraints is necessary to control groundwater levels and to avoid severe drops in water levels. It should be mentioned that the completed reclaimed water allocation optimization models, in Chapters 5-8 and their potential future work, may be applied to other Iraqi provinces by adjusting the models' inputs.
4. Considering the resilience of the developed models of this study, all of the five models are adjustable to adapt with the changing circumstances of water supplies and demands.
    - The water allocation optimization model, which was developed in Chapter 4, has considered different water allocation scenarios with different water availabilities, which provided clear results. Considering the uncertainty in water supply along with the increase in water demand, the model will appropriately and proportionally allocate the available resources of water to consumers depending upon the input data. There is no doubt that the proportional water sharing rule (PSR), which is used in this optimization model, has the flexibility to adapt to the shortages in water supplies. Using the PSR, the available quantity of water is allocated proportionally to consumers depending on the consumer's area-based demand in the system. In addition, with any change in water demand

due to a change in cultivated area, or the type of the cultivated crops, the model is capable of adapting to the expected changes. The model may be adjusted to allow water trading among users depending on water availability and consumer's priorities to overcome the potential uncertainty in water supplies. It assures that water will be allocated to where it is needed most considering accurate data inputs. Therefore, it is recommended to run the model considering different water shortages and different water demand scenarios taking into account the most economic crops to test the model's resilience to adapt to uncertain water supplies and demands.

- The agricultural reclaimed water allocation optimization models, which were developed in Chapters 5-7, are flexible to adapt to changes in the quantity and type of RW used, irrigation efficiency, crops irrigated, water demand by crops, and the cultivated area. In these models, the results of allocating different RW qualities using different irrigation efficiencies were compared. The developed models showed significant flexibility to adapt to the changes of RW quantities and qualities by selecting the most economic value crops to be cultivated and to satisfy the maximum net benefit. Improving the completed models to include different RW qualities to satisfy the maximum net benefit under water shortages with a minimum loss is necessary by considering different modelling scenarios. Furthermore, controlling the number of crops and the maximum area allowed for each crop is essential to test the flexibility of the models under various demand assumptions. Using updated data in the completed models further the accuracy of results by checking the capacity of the models to adapt to the changing circumstances of water supplies and demands while achieving the desired goals.

- Considering the resilience of the regional water allocation optimization model developed in Chapter 8, different water resource availabilities were implemented to test the flexibility of the model using different water supply conditions. The model maintained the allocation of the available water resources on demand nodes considering both type of water and type of use. To continue the efforts which have done in this model, it is recommended to include further application scenarios, including multi-period simulation, considering the uncertainty in water supplies to test how the resilience of the model while satisfying the demand. Furthermore, the model should be tested considering other Iraqi cities and provinces, considered at the national level, to check the adaptation of the model to include more cities under uncertain conditions to identify the optimal allocation scenario from a wide range of potential water resources availabilities and demands.

5. The feasibility of investing to improve the current wastewater collection system in Baghdad to minimize losses and increase flows to the WWTPs, will be tested in potential future optimization models. Different scenarios should be considered by comparing different WWTPs treatment efficiencies, capacities, and locations, along with different wastewater allocation scenarios. Rehabilitating the current wastewater collection system and adding new collection systems for the unserved regions will be

included in the proposed scenarios to cover the metropolitan region of Bagdad. Effective use of increased wastewater flows in the current sewerage system will be assessed with a variety of treatment and allocation scenarios considering decentralized wastewater collection and treatment. The model will maximize the RW use by allocating the available water resources in Baghdad to minimize the use of surface water and to maximize the remaining freshwater flow downstream of the city. Different fresh water availabilities under different demand scenarios with various wastewater treatment efficiencies will be compared using a multi-period optimization model. Both quantity and quality parameters will be considered in the potential water allocation model taking into account the tolerance of demand nodes to RW use. The quantity of pollutants discharged downstream of the city will be estimated for the current system and assessed with the feasibility of implementing each scenario separately.

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APPENDIX A

GAMS CODE USED TO SOLVE THE APPLICATION OF AN OPTIMIZATION MODEL FOR ASSESSING THE PERFORMANCE OF WATER APPROPRIATION IN IRAQ, DEVELOPED IN CHAPTER 4

```
$EOLCOM //
$TITLE APPLICATION OF AN OPTIMIZATION MODEL FOR ASSESSING THE PERFORMANCE OF WATER
APPROPRIATION IN IRAQ
$OFFSYMXREF OFFSYMLIST OffLISTING OFFUPPER
OPTION LIMROW=000, LIMCOL = 0;
$ONTEXT
******************************************************************************************
***
Set i     Iraqi provinces supplied by the Tigris River
/ 1-Mousil
  2-Kerkuk
  3-Salaheldeen
  4-Deyala
  5-Baghdad-A
  6-Wasit
  7-Meesan
  8-Basra-A /
Set  k    crops allowed to be cultivated
/ 1-Rice
  2-Wheat
  3-Cotton
  4-Sunflower
  5-Maize
  6-Barley
  7-Tomato
  8-Lettuce
  9-Onion/
Set S   Water availability conditions
/N     Normal water availability conditions
 D     Dry water availability conditions
 DD    Drought water availability conditions/
Set j   provinces i priority to get water in the Tigris River Basin
/  j1*j8 /
Parameter supply(s)  total Tigris River basin water supply in millions of cubic meters per year
/N  42000
  D   21000
  DD  8400/
Set r water allocation rule
/DS   downstream water allocation rule
 US   upstream water allocation rule
 PR   proportional sharing of shortages water allocation rule/
Set map(r, j, i) mapping set: assigns priorities of provinces to get water
/DS  . (j1.8-Basra-A,  j2. 7-Meesan,  j3.6-Wasit,  j4.5-Baghdad-A,  j5.4-Deyala,   j6.3-Salaheldeen, j7.2-
Kurkuk,  j8.1-Mousil)
```

```
 US  . (j1.1-Mousil,  j2.2-Kerkuk,    j3.3-Salaheldeen, j4.4-Deyala,   j5.5-Baghdad-A,  j6.6-Wasit,  j7.7-
Meesan, j8.8-Basra-A )
 PR  . (j1.1-Mousil, j2.2-Kerkuk, j3.3-Salaheldeen, j4.4-Deyala, j5.5-Baghdad-A, j6.6-Wasit,  j7.7-Meesan,
j8.8-Basra-A )/
Table land_p(i,  k)   observed land in production (1000 ha) in each province// source:  Iraqi Central
Statistical Organization
             1-rice       2-wheat     3-cotton   4-sunflower     5-maize    6-barley    7-tomato    8-lettuce     9-
onion
  1-Mousil         0.0          90.76        0.00        0.01          0.96        0.00        1.60        0.06          1.11
  2-Kurkuk         0.0          142.0        11.6        0.09          30.64       1.95        3.16        0.03          0.08
  3-Salaheldeen    0.0          191.6        1.06        0.05          12.56       3.54        14.1        0.21          2.50
  4-Deyala         0.0          143.3        0.03        0.01          2.03        24.3        3.30        0.16          1.31
  5-Baghdad-A      0.0          35.00        0.18        0.55          10.52       5.14        4.51        1.14          1.03
  6-Wasit          0.0          234.1        2.65        0.00          23.50       38.3        0.70        0.13          0.08
  7-Meesan         0.23         102.4        0.00        0.00          8.60        51.1        0.09        0.54          0.00
  8-Basra-A        0.0          17.51        0.00        0.00          0.67        1.45        11.85       0.00          0.00;
Parameter TLP(i);    //Total land in production in each province
TLP(i) = sum(k, land_p(i,k));

Table Bc(i, k)    Crop k water demand (1000 m^3/ ha)
            1-rice     2-wheat    3-cotton  4-sunflower  5-maize   6-barley     7-tomato      8-lettuce      9-onion
 1-Mousil          30.8       11.9        18.0       12.9        7.0       2.8        7.1           1.7        9.5
 2-Kerkuk          32.4       12.3        19.1       13.4        7.8       2.6        7.9           1.6        10.0
 3-Salaheldeen     28.4       9.9         16.6       10.9        6.8       2.5        6.9           1.6        9.4
 4-Deyala          29.6       10.8        17.3       11.8        6.6       3.1        6.7           2.4        10.1
 5-Baghdad-A       32.2       11.8        18.8       13.0        8.2       2.8        8.2           1.7        10.8
 6-Wasit           32.5       11.9        18.6       13.0        8.2       3.0        8.2           1.8        10.9
 7-Meesan          34.8       12.5        20.1       13.8        9.2       3.4        9.2           2.1        12.3
 8-Basra-A         37.2       13.4        21.4       14.9        9.7       3.4        9.8           2.1        12.7;
Scalar epsilon /0.00000001/;
Parameter supply(s)  water supply scenario;
supply('N') =  sum((i,k), Bc(i,k) * land_p(i,k));
supply('D')    =  0.5 * supply('N');
supply('DD')    =  0.2 * supply('N');
Parameter   TAS(r,s)  total amount of water assigned to province i;
  TAS(r,s)  = 0;
Parameter RP(i)  basin's water right by province (%);
  RP(i)  =  (sum(k, Bc(i,k) * land_p(i,k)));
Parameter
  TPR(r,j)        total paper rights by priority considering the allocation rule
  RSP(r,s,j)      remaining water in the system by jth priority after supplying province i considering the
allocation rule
  WWU(r,s,i)      amount of water use assigned to ith province, not exceed the total water supply by
scenario;
```

```
Loop(r,                                             // water sharing rule
Loop(j,                                             // priority
  TPR(r,j) = sum[i$map(r, j, i), RP(i)] ;          // total paper rights considering the priority j of province i
  RSP(r,s,j) =
  min[(supply(s) - TAS(r,s)), TPR(r,j)];    // remaining supply after supplying province i considering the
priority j with higher priorities
  Loop(i$map(r, j, i),
     WWU(r,s,i) = (RP(i)/TPR(r,j))
     * rsp(r,s,j);                          // Amount of water (1000 cubic meters) assigned to province i
   TAS(r,s) = TAS(r,s) + WWU(r,s,i) ;              // cumulative water assigned to last province getting water
  ); ); );
Table   Y(i,k)   Crop Yield (tons per Ha)
              1-rice     2-wheat   3-cotton   4-sunflower   5-maize    6-barley        7-tomato       8-lettuce
9-onion
 1-Mousil       2.89       3.05       2.40       1.33        4.40       0.90            17.9          19.97          5.89
 2-Kerkuk       2.89       3.35       2.05       2.86        5.63       2.76            5.86          15.2           4.80
 3-Salaheldeen   2.89       2.49       0.80       1.58        3.57       1.18            12.79         15.44          2.10
 4-Deyala       2.89       3.58       1.87       1.67        2.51       2.00            27.90         21.7           11.54
 5-Baghdad-A     2.89       2.61       0.58       1.45        2.26       1.21            14.59         26.18
20.13
 6-Wasit        2.89       2.81       0.50       1.33        2.58       1.28            7.12          11.91          4.40
 7-Meesan        2.20       2.17       2.42       1.33        3.40       1.41            14.44         11.45          0.01
 8-Basra-A       2.89       1.98       2.42       1.33        0.88       0.87            2.97          20.7           0.01;
Parameter P(k)     Selling price ($ US per ton) of crop k
/1-rice             623
 2-wheat              570
 3-cotton             1355
 4-sunflower            795
 5-maize              535
 6-barley             396
 7-tomato              485
 8-lettuce            435
 9-onion              717/;
Table  C(i,k)     Production cost ($ US per ha) of the cultivated crops, No water costs included
                  1-rice     2-wheat   3-cotton  4-sunflower   5-maize   6-barley  7-tomato         8-lettuce
9-onion
 1-Mousil         850       820          1300           655            900         720       1300                 850
580
 2-Kerkuk         850       820          1300           655            900         720       1300                 850
580
 3-Salaheldeen 850        820          1300           655            900        720        1300                 850
580
 4-Deyala         850       820          1300           655            900        720        1300                 850
580
```

```
 5-Baghdad-A   850      820         1300           655           900       720        1300                 850
580
 6-Wasit          850      820         1300          655           900       720        1300                 850
580
 7-Meesan       850      820         1300           655           900       720        1300                 850
580
 8-Basra-A        850      820         1300           655          900       720        1300                 850
580;
Parameter landrhs_p(i)      total land available per providence (1000 Ha)
/ 1-Mousil                    172.7
  2-Kerkuk                    38.7
  3-Salaheldeen          331.4
  4-Deyala                  178.7
  5-Baghdad-A            110.75
  6-Wasit                    210.0
  7-Meesan                212.7
  8-Basra-A                 26.6/
Parameter Nr(i,k);    // Net revenue (1000$/ha)
          Nr(i,k) = P(k) * Y(i,k) - C(i,k);
Parameter Inc_v(i,k)  income per 1000 m^3;
           Inc_v(i,k) =  Nr(i,k) / Bc(i,k) ;
Positive Variables
L (r,s,i,k)  land use by crop and province i
TL (r,s,i)   total land use by province i
Uses_v (r,s,i)  total water used by province i

Variables
Ag_Ben_j_v              (r,s,i,k)    Net  benefits by crop  k
Ag_Ben_v                (r,s,i)    Net benefits by province
T_Ag_Ben_v              (r,s,i)    Total net benefit
Nb  (r,s)    Total net benefit by allocation rule              ;

Equations
Land_e (r,s,i) land in production
Uses_crop_e (r,s,i,k) Crop's water consumption
Uses_e (r,s,i)  define water use
Ag_Ben_j_e (r,s,i,k)  benefits by crop
Ag_ben_e (r,s,i)   benefits by province
TNb (r,s)  total net benefit by rule and supply scenario  ;
Land_e (r,s,i)..   sum(k, hectares_v(r,s,i, k)) =E= T_hectares_v(r,s,i);
Uses_crop_e(r,s,i,k).. X_v(r,s,i,k) =E= Bc(i,k) * hectares_v(r,s,i,k) ;
Uses_e     (r,s,i)..  Uses_v(r,s,i) =E=  sum(k, X_v(r,s,i,k,t,p));
Ag_Ben_j_e(r,s,i,k).. Ag_Ben_j_v(r,s,i,k) =E=  Nr(i,k)  *   hectares_v(r,s,i,  k,t,p);
Ag_ben_e  (r,s,i).. Ag_Ben_v  (r,s,i) =E=  sum(k, Ag_Ben_j_v(r,s,i,  k,t,p));
```

```
TNb (r,s).. Tot_ben_v (r,s) =E=  sum((i), ag_ben_v(r,s,i));
Model Tigris_Basin_Allocation /ALL/;
hectares_v.lo  (r,s,i, k) = 0;
uses_v.up   (r,s, i) $ (wet_wat_use(r,s,i) > 0 ) = wet_wat_use(r,s,i) - 5;  // makes water the limiting
resource not land
uses_v.up   (r,s, i) $ (wet_wat_use(r,s,i) = 0 ) = 0;
hectares_v.up  (r,s,i, k) = land_p(i,k) ;  // upper bound on cropped land;
Solve Tigris_Basin_Allocation Using NLP Maximizing TNb;
```

APPENDIX B

GAMS CODE USED TO SOLVE THE RECLAIMED WASTEWATER ALLOCATION OPTIMIZATION MODEL FOR AGRICULTURAL IRRIGATION, DEVELOPED IN CHAPTER 5

```
$EOLCOM //
$TITLE A Reclaimed Wastewater Allocation Optimization Model for Agricultural Irrigation
$OFFSYMXREF OFFSYMLIST OffLISTING OFFUPPER
OPTION LIMROW=000, LIMCOL = 0;
$ONTEXT
* -----------------------------------------------------------------------------------------
$OFFTEXT
set i  RW type
/ 1-RWA
 2-RWB
 3-RWC/;

set x Farms
/FA1
FA2
  .
  .
  .
FA105
FA106/;

set C  Crop
/Cotton
Wheat
Maize
Potato
Tomato
Barley
Clover
Cucumber
Alfalfa
Onion
Eggplant
Sunflower
Sesame
Okra/;

Parameter  ETc (C)  Evapotranspiration requirements (mm per unit time) to cultivate crop C
/Cotton        1448
 Wheat         990
 Maize         703
 Potato        700
 Tomato        621
 Barley        273
```

```
 Clover       970
 Cucumber   675
 Alfalfa      1010
 Onion        825
 Eggplant    650
 Sunflower  1047
 Sesame      275
 Okra          815/;

Parameter  LR(C) Leaching requirements (mm per unit time) to cultivate crop C
/Cotton      13
Wheat        13
Maize         13
Potato       13
Tomato      13
Barley       13
Clover       13
Cucumber  13
Alfalfa       13
Onion         13
Eggplant    13
Sunflower  13
Sesame      13
Okra          13
/;
Parameter E(C) Irrigation efficiency to cultivate crop C
/
Cotton      0.65
Wheat       0.65
Maize       0.65
Potato      0.65
Tomato     0.65
Barley      0.65
Clover      0.65
Cucumber  0.65
Alfalfa      0.65
Onion        0.65
Eggplant   0.65
Sunflower  0.65
Sesame     0.65
Okra         0.65
/;
Parameter QRw(i) Released reclaimed water i  (m^3  per season)
/ 1-RWA          6000000.00
```

```
 2-RWB        6000000.00
 3-RWC        6000000.00/;

Table CRw(i,c) Connectivity map of crop c to RW type i
       Cotton   Wheat   Maize   Potato  Tomato   Barley  Clover  Cucumber  Alfalfa  Onion   Eggplant
Sunflower  Sesame   Okra
1-RWA     1     1     1     1     1      1     1     1     1     1     1     1     1     1
2-RWB     1     1     1     0     1      1     1     1     1     0     1     1     1     1
3-RWC     1     0     0     0     0      1     1     0     1     0     0     1     0     0;

Table FA_RW_Crop (i,c)  Maximum limit of cultivated Area of Crop C Using RW i
       Cotton   Wheat   Maize   Potato  Tomato  Barley  Clover  Cucumber  Alfalfa  Onion   Eggplant
Sunflower  Sesame   Okra
1-RWA    1500    1500    1500    1250    750    1500    1000    300    1000    300    250     1000
500     200
2-RWB    1500    2000    1500       0    750    1500    1000    300    1000      0    250     1000
500     200
3-RWC    1500      0        0        0      0    1500    2000      0    2000      0      0     1500
0       0;

parameter  NR(C)  net irrigation requirements (mm  per season)     ;
NR(C)= ETc(c) * (1+(LR(C)/100)) ;    // This equation from Water Reuse Book

parameter  Lw(C)  crop's hydraulic loading rate (m^3 per ha) ;
Lw(C)= ((NR(c)/E(c))*(10000/1000))  ;        // the (10000/1000) is to convert mm to m^3/ha

Parameter Y(C)  Crop Yield (tons per ha)
/Cotton       2.0
Wheat         2.6
Maize         2.26
Potato        15.7
Tomato        19.0
Barley        1.2
Clover        16.25
Cucumber   9.2
Alfalfa       22.4
Onion         7.9
Eggplant     23.0
Sunflower   1.5
Sesame       1.0
Okra          7.8/;

parameter   P(c)      Crop selling Prices ($ US per ton)
/Cotton       900
```

```
Wheat       390
Maize       360
Potato      500
Tomato      485
Barley      345
Clover      125
Cucumber    500
Alfalfa     100
Onion       717
Eggplant    200
Sunflower   795
Sesame      950
Okra        420/;

Parameter CCost(C)    Production cost of crop c excluding water cost ($US per Ha)
/Cotton     1300
Wheat        820
Maize       900
Potato      750
Tomato      1300
Barley      720
Clover      320
Cucumber    1350
Alfalfa     500
Onion       580
Eggplant    1250
Sunflower   550
Sesame       475
Okra         1230/;

Parameter RWc(i)  Reclaimed water  cost ($ per cubic meter)
 / 1-RWA    0.14
 2-RWB      0.12
 3-RWC      0.10/;

Parameter Ln(x)   Observed land in production (Ha)
/FA1      111.80
FA2       120.26
FA3       192.90
FA4       128.33
FA5       75.70
FA6       116.80
FA7       121.60
FA8       94.30
```

FA9	34.20
FA10	74.80
FA11	68.50
FA12	64.30
FA13	62.00
FA14	59.20
FA15	57.10
FA16	41.45
FA17	43.35
FA18	42.90
FA19	42.80
FA20	44.35
FA21	60.50
FA22	59.70
FA23	59.30
FA24	58.70
FA25	54.60
FA26	57.90
FA27	54.30
FA28	53.70
FA29	68.30
FA30	56.70
FA31	60.10
FA32	44.70
FA33	51.00
FA34	43.30
FA35	42.05
FA36	43.20
FA37	45.50
FA38	43.30
FA39	22.30
FA40	35.10
FA41	39.10
FA42	34.00
FA43	36.30
FA44	30.50
FA45	31.20
FA46	26.20
FA47	30.50
FA48	31.50
FA49	80.00
FA50	78.00
FA51	17.30
FA52	66.80

FA53	59.90
FA54	65.40
FA55	56.25
FA56	59.50
FA57	52.60
FA58	67.40
FA59	76.30
FA60	51.50
FA61	46.70
FA62	78.05
FA63	95.85
FA64	83.95
FA65	87.75
FA66	76.40
FA67	80.50
FA68	108.50
FA69	72.35
FA70	64.35
FA71	63.00
FA72	56.85
FA73	56.00
FA74	138.90
FA75	49.30
FA76	54.95
FA77	54.50
FA78	59.30
FA79	90.40
FA80	61.15
FA81	56.68
FA82	54.08
FA83	46.50
FA84	46.55
FA85	26.75
FA86	42.55
FA87	60.00
FA88	33.07
FA89	104.67
FA90	141.42
FA91	77.50
FA92	92.90
FA93	83.40
FA94	67.97
FA95	62.25
FA96	45.20

```
FA97      47.50
FA98      107.57
FA99      37.33
FA100       115.63
FA101       87.20
FA102       97.93
FA103       131.90
FA104       151.90
FA105       56.85
FA106       89.90/;

Parameter TLn(i)  Total Observed Farmlands Areas in the System (ha);
TLn(i)= sum(x,Ln(x));

Parameter RLn(i,x) The Ratio of observed Farmlnad x in the system ;
RLn(i,x)= Ln(x)/TLn(i);

Variables
     NRe (i,x)      Net revenue by RW type_farm  ($ US )
     NbRWA      Net benefit for RW type A ($ US)
     NbRWB      Net benefit for RW type B ($ US)
     NbRWC      Net benefit for RW type C ($ US)

Binary variable
     M(i,x,c) connectivity by RW type_farm_crop

positive variables
     RW (i,x,c)     Assigned RW from source i to farm x and crop c   (m^3)
     FA (i,x,c)      Assigned Area of Farm x using RW i cultivating crop c (Ha)

Equations
    Consumed_RW_source       Total consumed RW by farms  (m^3)
    RW_cons_by_farm         RW consumed by farm x (m^3)
    RW_by_source_farm_crop   Assigned RW from source i to farm x and crop c   (m^3)
    Irrigated_Area          Irrigated area of farm x to cultivate crop c  (ha)
    Tot_irr_farms          Total farms irrigated area (ha)
    Conn_source_farm        Connectivity by source_farm_crop
    TFA_RW_Crop (i,c)         Maximum limit of cultivated crop c Using RW i
    Net_Revenue            Net revenue by RW type_farm  ($ US )
    Net_Benefit_RWA        Net benefit for RW type A ($ US)
    Net_Benefit_RWB        Net benefit for RW type B ($ US)
    Net_Benefit_RWC        Net benefit for RW type C ($ US)
    RW_cons_by_farm        Consumed RW by type_farm (m^3)
    P_NbRWA              Positive Net benefit for RW type A ($ US)
```

```
    P_NbRWB              Positive Net benefit for RW type B ($ US)
    P_NbRWC              Positive Net benefit for RW type C ($ US)
    Min_benefit_by_farm      Minimum benefit allowed per farm which is a percent of the total cost;
********CONSTRAINTS**********
**1- Reclaimed Water Availability Constraints:
*    1) consumed RW from source i :
** The following equation is for the proportional sharing demonstration
   RW_by_source_farm_crop (i,x).. sum((c), RW(i,x,c)*M(i,x,c)*CRw(i,c))=E= RLn(i,x)*QRw(i);
   Consumed_RW_source (i)..   sum((x,c),RW (i,x,c)) =L=  QRw(i);
*   2) Consumed RW by farm x from type i:
  RW_cons_by_farm (i,x)..  sum (c,RW(i,x,c)*M(i,x,c)*CRw(i,c))=E=
sum(c,Lw(c)*FA(i,x,c)*M(i,x,c)*CRw(i,c));
*    Total consumed RW by farm_rule (m^3)
**2-  Irrigated Farmlands Constraints:
*   1) Irrigated area by farm x and surce i:
  Irrigated_Area(i,x)..    sum((c),FA(i,x,c)*CRw(i,c))=L= Ln(x);  // this was editited to consider the CRw(i,c)
** Here are other constraints limit the cultivated area of some crops
  TFA_RW_Crop (i,c).. sum ((x), FA(i,x,c))=L= FA_RW_Crop (i,c);
*  2) Total irrigated farmlands per source i:
   Tot_irr_farms (i)..  sum ((x,c),FA(i,x,c))=L=sum((x),Ln(x));
**3- Connectivity constraints:
*   1) Connectivity of source i to farm x and crop c constraint M(i,x,c):
  Conn_source_farm (i,x) .. sum ((c), M(i,x,c))=E=1;
***Net revenue by farm x and RW type i:
     Net_Revenue (i,x)  ..  NRe (i,x) =e=   sum [(c),( (P(c) * Y(c)* FA(i,x,c)* M(i,x,c)*CRw(i,c))-  // Crops' selling
price
                              (RW(i,x,c)*RWC(i)*M(i,x,c)*CRw(i,c))-     // Cost of RW
                                (FA(i,x,c)*CCost(c)*M(i,x,c)*CRw(i,c)))];     // Cost of crops' production
Min_benefit_by_farm (i,x)..  NRe (i,x) =G=10;
*The objective function is to maximize the net benefit for each RW type:
Net_Benefit_RWA ('1-RWA')..  NbRWA   =e=   sum((x), NRe ('1-RWA',x)) ;
Net_Benefit_RWB ('2-RWB')..  NbRWB   =e=   sum((x), NRe ('2-RWB',x)) ;
Net_Benefit_RWC ('3-RWC')..  NbRWC   =e=   sum((x), NRe ('3-RWC',x)) ;
P_NbRWA..  NbRWA   =G= 1000.00000;
P_NbRWB..  NbRWB   =G= 1000.00000;
P_NbRWC..  NBRWC   =G= 1000.00000;
option minlp=BARON;
model RW_Allocation /all/ ;
solve RW_Allocation using minlp maximizing NbRWA;
solve RW_Allocation using minlp maximizing NbRWB;
solve RW_Allocation using minlp maximizing NbRWC;
*THE END
```

APPENDIX C

GAMS CODE USED TO SOLVE THE OPTIMIZATION MODEL FOR AGRICULTURAL RECLAIMED WATER ALLOCATION USING MIXED-INTEGER NONLINEAR PROGRAMMING, DEVELOPED IN CHAPTER 6

```
$EOLCOM //
$TITLE Optimization Model for Agricultural Reclaimed Water Allocation Using Mixed-Integer Nonlinear
Programming
$OFFSYMXREF OFFSYMLIST OffLISTING OFFUPPER
OPTION LIMROW=000, LIMCOL = 0;
$ONTEXT
* --------------------------------------------------------------------------------------
$OFFTEXT
set i  RW type  // RWA is teriary treated wastewater, RWB is secondary treated wastewater
/
 1-RWA
 2-RWB
/;
set x Farms  // There are a total of 84 farms with different areas
/
FA1
FA2
  .
  .
  .
FA83
FA84/;

set C  Crop
/
Cotton
Wheat
Maize
Potato
Tomato
Barley
Clover
Cucumber
Alfalfa
Onion
Eggplant
Sunflower
Sesame
Okra/;

Parameter  ETc (C)  Evapotranspiration requirements (mm per unit time) to cultivate crop C
/
Cotton      1448
Wheat        990
```

```
Maize        703
Potato       700
Tomato        621
Barley       273
Clover       970
Cucumber     675
Alfalfa      1010
Onion        825
Eggplant     650
Sunflower    1047
Sesame       275
Okra         815
/;
Parameter  LR(C) Leaching requirements (mm per unit time) to cultivate crop C
/
Cotton       13
Wheat        13
Maize        13
Potato       13
Tomato        13
Barley       13
Clover       13
Cucumber     13
Alfalfa      13
Onion        13
Eggplant     13
Sunflower    13
Sesame       13
Okra         13/;

Parameter E(C) Irrigation efficiency to cultivate crop C // The value of E(c) depends on the irrigation
technology used
/
Cotton       0.75
Wheat        0.75
Maize        0.75
Potato       0.75
Tomato        0.75
Barley       0.75
Clover       0.75
Cucumber     0.75
Alfalfa      0.75
Onion        0.75
Eggplant     0.75
```

```
Sunflower    0.75
Sesame       0.75
Okra         0.75/;

Parameter QRw(i) Released reclaimed water i  (m^3  per season)// The value of QRw is the wastewater
treatment plants seasonal releases of reclaimed water
/
 1-RWA         6000000.00
 2-RWB         6000000.00/;

Table CRw(i,c) Connectivity map of crop c to RW type i

       Cotton   Wheat   Maize   Potato  Tomato   Barley  Clover   Cucumber  Alfalfa  Onion   Eggplant
Sunflower  Sesame   Okra
1-RWA      1      1      1       1     1       1      1      1      1      1      1      1      1      1
2-RWB      1      1      1      0      1       1      1      1      1      0      1      1      1      1;

Table FA_RW_Crop (i,c)  Maximum limit of cultivated Area of Crop C Using RW i
       Cotton   Wheat   Maize   Potato  Tomato  Barley  Clover  Cucumber  Alfalfa   Onion   Eggplant
Sunflower  Sesame   Okra
1-RWA    1000    1000    1000     500     500     1000    750     200     750     150     150     750     250
100
2-RWB    1000    1000    1000      0     500     1000    750     200     750      0     150     750     250
100;
Table Min_FA_RW_Crop (i,c) Minimum limit of cultivated Area of crop C using RW type i
       Cotton   Wheat   Maize   Potato  Tomato  Barley  Clover  Cucumber  Alfalfa  Onion   Eggplant
Sunflower  Sesame   Okra
1-RWA    0       0      0       0     0       0      0      0       0      0      0      0       0      0
2-RWB    0       0      0       0      0       0      0      0       0      0      0      0       0      0;

Parameter  NR(C)  net irrigation requirements (mm  per season)     ;
NR(C)= ETc(c) * (1+(LR(C)/100)) ;

Parameter Lw(C)  crop's hydraulic loading rate (m^3 per ha) ;
Lw(C)= ((NR(c)/E(c))*(10000/1000)) ;        // the (10000/1000) is to convert mm to m^3/ha

Parameter Y(C)  Crop Yield (tons per ha)
/
Cotton       2.0
Wheat        2.6
Maize       2.26
Potato       15.7
Tomato     19.0
Barley      1.2
```

```
Clover      16.25
Cucumber  9.2
Alfalfa     22.4
Onion       7.9
Eggplant   23.0
Sunflower 1.5
Sesame     1.0
Okra        7.8/;

parameter   P(c)       Crop selling Prices ($ US per ton)
/
Cotton        900
Wheat         390
Maize         360
Potato        500
Tomato       485
Barley        345
Clover        125
Cucumber   500
Alfalfa       100
Onion         717
Eggplant     200
Sunflower  795
Sesame      950
Okra          420/;

Parameter CCost(C)    Production cost of crop c excluding water cost ($US per Ha)
/
Cotton      1300
Wheat        820
Maize        900
Potato      750
Tomato     1300
Barley      720
Clover      320
Cucumber 1350
Alfalfa      500
Onion        580
Eggplant   1250
Sunflower 550
Sesame     475
Okra        1230/;

Parameter RWc(i)  Reclaimed water  cost ($ per cubic meter)
```

```
 /
 1-RWA     0.14
 2-RWB     0.12/;

Parameter Ln(x)   Observed land in production (Ha)
/
FA1       111.90
FA2       120.40
FA3       192.90
FA4       128.50
FA5       75.80
FA6       116.90
FA7       121.60
FA8        94.40
FA9        34.30
FA10        74.90
FA11        68.50
FA12        64.30
FA13        62.00
FA14        59.20
FA15        57.10
FA16        41.45
FA17        43.50
FA18        42.90
FA19        42.90
FA20        44.50
FA21        60.60
FA22        59.80
FA23        59.40
FA24        58.80
FA25        54.70
FA26        57.90
FA27        54.40
FA28        53.70
FA29        68.40
FA30        56.80
FA31        60.20
FA32        44.80
FA33        51.10
FA34        43.40
FA35        42.20
FA36        43.30
FA37        45.60
FA38        43.40
```

FA39	22.50
FA40	35.40
FA41	39.20
FA42	34.20
FA43	36.40
FA44	30.70
FA45	31.40
FA46	26.40
FA47	30.90
FA48	31.70
FA49	80.50
FA50	78.40
FA51	17.50
FA52	66.90
FA53	60.00
FA54	65.70
FA55	56.50
FA56	59.90
FA57	52.90
FA58	67.80
FA59	76.90
FA60	51.80
FA61	46.90
FA62	78.40
FA63	96.50
FA64	84.70
FA65	88.20
FA66	77.30
FA67	80.90
FA68	109.50
FA69	72.80
FA70	64.90
FA71	64.50
FA72	56.85
FA73	56.00
FA74	138.90
FA75	49.40
FA76	54.95
FA77	54.50
FA78	59.30
FA79	90.50
FA80	61.15
FA81	56.68
FA82	54.08

```
FA83       46.60
FA84       46.55/;
Parameter TLn(i)  Total Observed Farmlands Areas in the System (ha);
TLn(i)= sum(x,Ln(x));

Parameter RLn(i,x) The Ratio of observed Farmlnad x in the system ;
RLn(i,x)= Ln(x)/TLn(i);

Variables
    F_Y     Farm Yield $
    C_C     Crop cultivation cost $ per hectare
    RW_C    Reclaimed water cost $ per cubic meter
    Arcp    Irrigated area per crop per farm (ha)
    NRe     Net revenue by RW type_farm  ($ US )
    NbRWA   Net benefit for RW type A ($ US)
    NbRWB       Net benefit for RW type B ($ US)
    TIA     Total Irrigated Areas (ha) per RW type i

Binary variable
   N(x,i) connectivity by source_farm
   M(x,c) connectivity farm_crop

positive variables
    RW (i,x,c)     Assigned RW from source i to farm x and crop c   (m^3)
    FA (i,x,c)     Assigned Area of Farm x using RW i cultivating crop c (Ha)
    NRe

Equations
   Consumed_RW_source       Total consumed RW by farms  (m^3)
   RW_cons_by_farm            RW consumed by farm x (m^3)
   RW_by_source_farm_crop   Assigned RW from source i to farm x and crop c   (m^3)
   Irrigated_Area           Irrigated area of farm x to cultivate crop c  (ha)
   Tot_irr_farms            Total farms irrigated area (ha)
   Irr_Area_Crop            Total cultivated area by crop (ha)
   Conn_source_farm         Connectivity by source_farm
   Conn_farm_crop           Connectivity by farm_crop
   Min_Conn_farm_crop   Minimum number of crops allowed by each farm
   TFA_RW_Crop (i,c)       Maximum limit of cultivated crop c using RW i
   Farm_Yield (i,x)           Yield by farm ($ US )
   Crop_Cost  (i,x)           Cultivation cost by farm($ US )
   RW_Cost_Crop (i,x)       RW cost by farm ($ US )
   Net_Revenue               Net revenue by RW type_farm  ($ US )
   Net_Benefit_RWA          Net benefit for RW type A ($ US)
   Net_Benefit_RWB          Net benefit for RW type B ($ US)
```

```
    RW_cons_by_farm         Consumed RW by type_farm (m^3)
    P_NbRWA                Positive Net benefit for RW type A ($ US)
    P_NbRWB                Positive Net benefit for RW type B ($ US)
   Tot_Irr_Area            Total Irrigated Farm Lands (ha) Using RW type i;

********CONSTRAINTS**********
**1- Reclaimed Water Availability Constraints:
*    1) consumed RW from source i :
** The following equation is for the proportional sharing demonstration
   RW_by_source_farm_crop (i,x).. sum((c), RW(i,x,c)*N(x,i)*M(x,c)*CRw(i,c))=E= RLn(i,x)*QRw(i);
   Consumed_RW_source (i)..   sum((x,c),RW (i,x,c)*N(x,i)*M(x,c)) =L=  QRw(i);
*   2) Consumed RW by farm x from type i:
  RW_cons_by_farm (i,x)..  sum (c,RW(i,x,c)*M(x,c)*CRw(i,c))=E= sum(c,Lw(c)*FA(i,x,c)*M(x,c)*CRw(i,c));
*    Total consumed RW by farm_rule (m^3)
**2-  Irrigated Farmlands Constraints:
*   1) Irrigated area by farm x and surce i:
   Irrigated_Area(i,x)..    sum((c),FA(i,x,c)*M(x,c)*N(x,i)* CRw(i,c))=L= Ln(x);
** Here are other constraints limit the cultivated area of some crops
     TFA_RW_Crop (i,c).. sum ((x), FA(i,x,c))=L= FA_RW_Crop (i,c);
*  2) Total irrigated farmlands per source i:
   Tot_irr_farms (i)..  sum ((x,c),FA(i,x,c)*N(x,i)) =L= sum((x),Ln(x));
**3- Connectivity constraints:
*   1) Connectivity of source i to farm x and crop c constraint M(i,x,c):
    Conn_source_farm (i,x) .. N(x,i)=E=1;
    Min_Conn_farm_crop (i,x)  .. sum (c, M(x,c)) =G= 2;
    Conn_farm_crop (i,x)    .. sum (c, M(x,c)) =L= 4;
    Irr_Area_Crop (i,c).. Arcp(i,c) =e= sum(x, FA(i,x,c)*M(x,c)*N(x,i));
***Net revenue by farm x and RW type i:
    Farm_Yield (i,x)   ..  F_Y (i,x) =e= sum (c, P(c)* Y(c)* FA(i,x,c)* M(x,c)*CRw(i,c));
    Crop_Cost  (i,x)   ..  C_C (i,x) =e= sum(c,FA(i,x,c)*CCost(c)*M(x,c)*CRw(i,c));
    RW_Cost_Crop (i,x) ..  RW_C (i,x)=e= sum (c,RW(i,x,c)*RWC(i)*N(x,i)*CRw(i,c));
    Net_Revenue (i,x)  ..  NRe (i,x) =e= F_Y (i,x) - C_C(i,x) - RW_C(i,x);
** Net benefit per hectare
   NB_Hectare (i,x) .. Nbhe (i,x) =e= NRe(i,x)/sum(c, FA(i,x,c));
** Net benefit per crop
  NB_Cr (i).. NB_Crop=e=
** Net benefit per cubic meter of water
NB_Cu (i).. NB_Cubic =e= Net_Revenue (i,x)/(sum((x,c), RW(i,x,c));
*The objective function is to maximize the net benefit for each RW type:
Net_Benefit_RWA ('1-RWA')..  NbRWA   =e=   sum((x), NRe ('1-RWA',x)) ;
Net_Benefit_RWB ('2-RWB')..  NbRWB   =e=   sum((x), NRe ('2-RWB',x)) ;
P_NbRWA('1-RWA',x).. NbRWA =G= 1.2* sum [c,((RW('1-RWA',x,c)*RWC('1-RWA')*N(x,'1-RWA')*CRw('1-
RWA',c))+(FA('1-RWA',x,c)*CCost(c)*M(x,c)*CRw('1-RWA',c)))];
```

```
P_NbRWB('2-RWB',x)..  NbRWB   =G= 1.2* sum [c,((RW('2-RWB',x,c)*RWC('2-RWB')*N(x,'2-RWB')*CRw('2-RWB',c))+(FA('2-RWB',x,c)*CCost(c)*M(x,c)*CRw('2-RWB',c)))];;
Tot_Irr_Area (i) .. TIA =E= Sum((x,c), FA(i,x,c)*M(x,c));
option MINLP=ANTIGONE;
model RW_Allocation /all/ ;
solve RW_Allocation using MINLP maximizing NbRWA;
solve RW_Allocation using MINLP maximizing NbRWB;
*THE END
```

APPENDIX D

GAMS CODE USED TO SOLVE THE AGRICULTURAL RECLAIMED WATER ALLOCATION OPTIMIZATION MODEL MAXIMIZES INDIVIDUAL FARM'S NET BENEFIT, DEVELOPED IN CHAPTER 7

```
$EOLCOM //
$TITLE AGRICULTURAL RECLAIMED WATER ALLOCATION OPTIMIZATION MODEL MAXIMIZES INDIVIDUAL
FARM'S NET BENEFIT
$OFFSYMXREF OFFSYMLIST OffLISTING OFFUPPER
OPTION LIMROW=000, LIMCOL = 0;
$ONTEXT
* -------------------------------------------------------------------------------------
$OFFTEXT
set i  RW type
/
 1-RWA
 2-RWB
/;
set x Farms
/FA1
FA2
  .
  .
  .
FA83
FA84/;

Set C  Crop
/Cotton
Wheat
Maize
Potato
Tomato
Barley
Clover
Cucumber
Alfalfa
Onion
Eggplant
Sunflower
Sesame
Okra/;

Parameter  ETc (C)  Evapotranspiration requirements (mm per unit time) to cultivate crop C
/
Cotton       1448
Wheat         990
Maize        703
Potato       700
```

```
Tomato     621
Barley     273
Clover     970
Cucumber   675
Alfalfa   1010
Onion      825
Eggplant   650
Sunflower 1047
Sesame     275
Okra       815/;

Parameter  LR(C) Leaching requirements (mm per unit time) to cultivate crop C
/
Cotton     13
Wheat      13
Maize      13
Potato     13
Tomato     13
Barley     13
Clover     13
Cucumber   13
Alfalfa    13
Onion      13
Eggplant   13
Sunflower  13
Sesame     13
Okra       13/;

Parameter E(C) Irrigation efficiency to cultivate crop C
/
Cotton    0.45
Wheat     0.45
Maize     0.45
Potato    0.45
Tomato    0.45
Barley    0.45
Clover    0.45
Cucumber  0.45
Alfalfa   0.45
Onion     0.45
Eggplant  0.45
Sunflower 0.45
Sesame    0.45
Okra      0.45/;
```

```
Parameter QRw(i) Released reclaimed water i  (m^3  per season)
/1-RWA         6000000.00
 2-RWB         6000000.00/;

Table CRw(i,c) Connectivity map of crop c to RW type i
       Cotton  Wheat  Maize  Potato  Tomato  Barley  Clover  Cucumber  Alfalfa  Onion  Eggplant
Sunflower  Sesame  Okra
1-RWA    1    1    1    1    1    1    1    1    1    1    1    1    1    1
2-RWB    1    1    1    0    1    1    1    1    1    0    1    1    1    1;

Table FA_RW_Crop (i,c)  Maximum limit of cultivated Area of Crop C Using RW i
       Cotton  Wheat  Maize  Potato  Tomato  Barley  Clover  Cucumber  Alfalfa  Onion  Eggplant
Sunflower  Sesame  Okra
1-RWA    1000   1000   1000    500    500   1000   750    200    750    150    150    750    250
100
2-RWB    1000   1000   1000     0    500   1000   750    200    750     0    150    750    250
100;

Table Min_FA_RW_Crop (i,c) Minimum limit of cultivated Area of crop C using RW type i
       Cotton  Wheat  Maize  Potato  Tomato  Barley  Clover  Cucumber  Alfalfa  Onion  Eggplant
Sunflower  Sesame  Okra
1-RWA    0     0     0     0    0     0     0     0     0     0     0     0     0     0
2-RWB    0     0     0     0    0     0     0     0     0     0     0     0     0     0;

Parameter  NR(C)  net irrigation requirements (mm  per season)    ;
NR(C)= ETc(c) * (1+(LR(C)/100)) ;    // This equation from Water Reuse Book

Parameter  Lw(C)  crop's hydraulic loading rate (m^3 per ha) ;
Lw(C)= ((NR(c)/E(c))*(10000/1000)) ;       // the (10000/1000) is to convert mm to m^/ha

Parameter Y(C)  Crop Yield (tons per ha)
/Cotton      2.0
Wheat        2.6
Maize        2.26
Potato       15.7
Tomato       19.0
Barley       1.2
Clover       16.25
Cucumber   9.2
Alfalfa      22.4
Onion        7.9
Eggplant    23.0
Sunflower  1.5
Sesame      1.0
```

```
Okra          7.8/;

parameter   P(c)        Crop selling Prices ($ US per ton)
/Cotton       900
Wheat        390
Maize        360
Potato       500
Tomato      485
Barley       345
Clover       125
Cucumber  500
Alfalfa      100
Onion        717
Eggplant   200
Sunflower  795
Sesame      950
Okra          420/;

Parameter CCost(C)     Production cost of crop c excluding water cost ($US per Ha)
/Cotton       1300
Wheat         820
Maize         900
Potato        750
Tomato       1300
Barley         720
Clover         320
Cucumber   1350
Alfalfa       500
Onion         580
Eggplant    1250
Sunflower   550
Sesame      475
Okra          1230/;

Parameter RWc(i)  RW  cost ($ per cubic meter)
 / 1-RWA     0.14
   2-RWB     0.12/;

Parameter Ln(x)   Observed land in production (Ha)
/FA1       111.90
FA2       120.40
FA3       192.90
FA4       128.50
FA5       75.80
```

FA6	116.90
FA7	121.60
FA8	94.40
FA9	34.30
FA10	74.90
FA11	68.50
FA12	64.30
FA13	62.00
FA14	59.20
FA15	57.10
FA16	41.45
FA17	43.50
FA18	42.90
FA19	42.90
FA20	44.50
FA21	60.60
FA22	59.80
FA23	59.40
FA24	58.80
FA25	54.70
FA26	57.90
FA27	54.40
FA28	53.70
FA29	68.40
FA30	56.80
FA31	60.20
FA32	44.80
FA33	51.10
FA34	43.40
FA35	42.20
FA36	43.30
FA37	45.60
FA38	43.40
FA39	22.50
FA40	35.40
FA41	39.20
FA42	34.20
FA43	36.40
FA44	30.70
FA45	31.40
FA46	26.40
FA47	30.90
FA48	31.70
FA49	80.50

```
FA50      78.40
FA51      17.50
FA52      66.90
FA53      60.00
FA54      65.70
FA55      56.50
FA56      59.90
FA57      52.90
FA58      67.80
FA59      76.90
FA60      51.80
FA61      46.90
FA62      78.40
FA63      96.50
FA64      84.70
FA65      88.20
FA66      77.30
FA67      80.90
FA68     109.50
FA69      72.80
FA70      64.90
FA71      64.50
FA72      56.85
FA73      56.00
FA74     138.90
FA75      49.40
FA76      54.95
FA77      54.50
FA78      59.30
FA79      90.50
FA80      61.15
FA81      56.68
FA82      54.08
FA83      46.60
FA84      46.55/;

Parameter TLn(i)  Total Observed Farmlands Areas in the System (ha);
TLn(i)= sum(x,Ln(x));

Parameter RLn(i,x) The Ratio of observed Farmlnad x in the system ;
RLn(i,x)= Ln(x)/TLn(i);

Variables
   F_Y    Farm Yield $
```

```
     C_C     Crop cultivation cost $ per hectare
     RW_C    Reclaimed water cost $ per cubic meter
     Arcp    Irrigated area per crop per farm (ha)
     NRe     Net revenue by RW type_farm  ($ US )
     NbRWA       Net benefit for RW type A ($ US)
     NbRWB       Net benefit for RW type B ($ US)
     TIA     Total Irrigated Areas (ha) per RW type i
     FNB     Net Farm Income ($)

Binary variable
   N(x,i) connectivity by source_farm
   M(x,c) connectivity farm_crop

positive variables
     RW (i,x,c)     Assigned RW from source i to farm x and crop c   (m^3)
     FA (i,x,c)     Assigned Area of Farm x using RW i cultivating crop c (Ha)

Equations
    Consumed_RW_source       Total consumed RW by farms  (m^3)
    RW_cons_by_farm          RW consumed by farm x (m^3)
    RW_by_source_farm_crop   Assigned RW from source i to farm x and crop c   (m^3)
    Irrigated_Area           Irrigated area of farm x to cultivate crop c  (ha)
    Tot_irr_farms            Total farms irrigated area (ha)
    Irr_Area_Crop            Maximum allowed area to be cultivated by each crop
    Conn_source_farm         Connectivity by source_farm
    Conn_farm_crop           Connectivity by farm_crop
    Min_Conn_farm_crop       Minimum number of crops allowed to be cultivated by farm
    TFA_RW_Crop (i,c)        Maximum limit of cultivated crop c Using RW i
    Min_TFA_RW_Crop (i,c)    Minimum limit of cultivated crop c Using RW i
    Farm_Yield (i,x)         Total yield ($ US ) by farm
    Crop_Cost  (i,x)         Cultivation cost ($ US ) by farm
    RW_Cost_Crop (i,x)       Reclaimed water cost  ($ US ) by farm
    Net_Revenue              Net revenue by RW type_farm  ($ US )
    Net_Benefit_RWA          Net benefit for RW type A ($ US)
    Net_Benefit_RWB          Net benefit for RW type B ($ US)
    RW_cons_by_farm          Consumed RW by type_farm (m^3)
    P_NbRWA                  Positive Net benefit for RW type A ($ US)
    P_NbRWB                  Positive Net benefit for RW type B ($ US)
    Tot_Irr_Area             Total Irrigated Farm Lands (ha) Using RW type i
    F_NB (i,x)               Net benefit ($) per farm x using RW type i;

********CONSTRAINTS**********
**1- Reclaimed Water Availability Constraints:
*    1) consumed RW from source i :
```

```
** The following equation is for the PSR demonstration
   RW_by_source_farm_crop (i,x).. sum((c), RW(i,x,c)*M(x,c)*CRw(i,c))=E= RLn(i,x)*QRw(i);
   Consumed_RW_source (i)..   sum((x,c),RW (i,x,c)) =L=  QRw(i);
*   2) Consumed RW by farm x from type i:
   RW_cons_by_farm (i,x)..  sum (c,RW(i,x,c)*M(x,c)*CRw(i,c))=E= sum(c,Lw(c)*FA(i,x,c)*M(x,c)*CRw(i,c));
*   Total consumed RW by farm_rule (m^3)
**2-  Irrigated Farmlands Constraints:
*   1) Irrigated area by farm x and surce i:
  Irrigated_Area(i,x)..    sum((c),FA(i,x,c)*CRw(i,c))=L= Ln(x);  // this was editited to consider the CRw(i,c)
** Here are other constraints limit the cultivated area of some crops
     TFA_RW_Crop (i,c).. sum ((x), FA(i,x,c))=L= FA_RW_Crop (i,c);
     Min_TFA_RW_Crop (i,c).. sum ((x), FA(i,x,c))=G= Min_FA_RW_Crop (i,c);
*  2) Total irrigated farmlands per source i:
     Tot_irr_farms (i)..  sum ((x,c),FA(i,x,c)) =L= sum((x),Ln(x));
**3- Connectivity constraints:
*   1) Connectivity of source i to farm x and crop c constraint M(i,x,c):
    Conn_source_farm (i,x) .. N(x,i)=E=1;
    Min_Conn_farm_crop (i,x)  .. sum (c, M(x,c)) =G= 1;
    Conn_farm_crop (i,x)    .. sum (c, M(x,c)) =L= 4;
    Irr_Area_Crop (i,c).. Arcp(i,c) =e= sum(x, FA(i,x,c)*M(x,c));
***Net revenue by farm x and RW type i:
    Farm_Yield (i,x)   ..  F_Y (i,x) =e= sum (c, P(c)* Y(c)* FA(i,x,c)* M(x,c)*CRw(i,c));
    Crop_Cost  (i,x)   ..  C_C (i,x) =e= sum(c,FA(i,x,c)*CCost(c)*M(x,c)*CRw(i,c));
    RW_Cost_Crop (i,x) ..  RW_C (i,x)=e= sum (c,RW(i,x,c)*RWC(i)*N(x,i)*CRw(i,c));
    Net_Revenue (i,x)  ..  NRe(i,x)  =e= F_Y (i,x) - C_C(i,x) - RW_C(i,x);
*The objective function is to maximize the individual farm  net benefit for each type of RW
Net_Benefit_RWA ('1-RWA')..  NbRWA   =e=   sum((x), NRe ('1-RWA',x)) ;
Net_Benefit_RWB ('2-RWB')..  NbRWB   =e=   sum((x), NRe ('2-RWB',x)) ;
P_NbRWA('1-RWA',x).. NbRWA =G= 1.2* sum [c,((RW('1-RWA',x,c)*RWC('1-RWA')*N(x,'1-RWA')*CRw('1-
RWA',c))+(FA('1-RWA',x,c)*CCost(c)*M(x,c)*CRw('1-RWA',c)))];
P_NbRWB('2-RWB',x)..  NbRWB   =G= 1.2* sum [c,((RW('2-RWB',x,c)*RWC('2-RWB')*N(x,'2-RWB')*CRw('2-
RWB',c))+(FA('2-RWB',x,c)*CCost(c)*M(x,c)*CRw('2-RWB',c)))];;
Tot_Irr_Area (i) .. TIA =E= Sum((x,c), FA(i,x,c)*M(x,c));
F_NB (i,x) .. FNB =E= NRe(i,x) ;
option MINLP=ANTIGONE;
model RW_Allocation /all/ ;
solve RW_Allocation using MINLP maximizing FNB ;
*THE END
```

APPENDIX E

GAMS CODE USED TO SOLVE THE REGIONAL WATER ALLOCATION OPTIMIZATION MODEL USING THREE DIFFERENT WATER RESOURCES FOR FIVE DIFFERENT USES, DEVELOPED IN CHAPTER 8

```
$EOLCOM //
$TITLE REGIONAL WATER ALLOCATION OPTIMIZATION MODEL USING THREE DIFFERENT WATER
RESOURCES FOR FIVE DIFFERENT USES
$OFFSYMXREF OFFSYMLIST OffLISTING OFFUPPER
OPTION LIMROW=000, LIMCOL = 0;
$ONTEXT
*-------------------------------------------------------------------
$OFFTEXT
Set k  Water Reach
/k1/;
Set s  Surface Water Source
/SW1
SW2      // SW1 is the Tigris River, SW2 is the Euphrates River/;
Set g  Groundwater Sources
/GW1       // Groundwater Sources/;
Set u  Water Uses
/
Ind,   //Industrial water use
Irr,   //Irrigation Water Use
Dom,   //Domestic Water Use
Com,   // Commercial Water Use
Rec    //Recreational Water Use
/;
Set i  Demand Nodes
/D1
D2
  .
  .
  .
D49
D50/;
Set l  Water treatment plants  (WTP)
/WTP1
WTP2
    .
    .
    .
WTP19
WTP20
         // WTP1 Karkh Water Project, WTP2 Rasafa Water Project, WTP3 Khadumyia Water Project, WTP4
Al-Rasheed Water Project, WTP5 Al-Qadisyia Water Project
         //WTP6 Al-Baldyiat Water Project, WTP7 Al-Maden Old Water Project, WTP8 Al-Maden New Water
Project, WTP9 Wahda Water Project
```

```
        //  WTP10 Wathbah Water Project, WTP11 Sadder Water Project, WTP12 Shek Hamad Water
Project, WTP 13 Al-Tarmyia Water Project
        // WTP14 Al-Abayji Water Project, WTP15 Compact Units G1, WTP16 Zidan Water Project, WTP17
Al-Mahmoudyia Water Project,
        // WTP18 Al-Yousfyia Central Water Project, WTP19 Al-Yousfyia Village Water Project, WTP20
Compact Units G2/;
Set f  Wastewater treatment plants  (WWTP)
/WWTP1
WWTP2
      .
      .
      .
WWTP10
WWTP11
        // WWTP1 in the Karkh, WWTP2 in the Rustumia,  WWTP3 in Mahmudia, WWTP4 in Madaen,
WWTP5 is in Khadumia, WWTP6 is in Wahda,
      // WWTP7 is in Shek Hamad, WWTP8 is in Al-Tarmyia, WWTP9 is in Al-Bayji, WWTP10 is in Zidan,
WWTP11 is in Yousfyia
/;
Set p  Private wastewater treatmnet plants  (PWWTP)
/PWWTP1       // Dora Refinery PWWTP
/;
*************************************************************************************
Table  TDN(u,i) Types of demand nodes
       D1      D2      D3      D4      D5      D6      D7      D8      D9      D10      D11      D12      D13
D14      D15      D16      D17      D18      D19      D20      D21      D22      D23      D24      D25      D26
D27      D28      D29      D30      D31      D32      D33      D34      D35      D36      D37      D38      D39
D40      D41      D42      D43      D44      D45      D46      D47      D48      D49      D50
Dom     1       1      1       1      1       1       1       1      1       1       1       1       1       1       1
1       1       1       1       1
Irr
1       1       1       1       1       1       1       1       1       1       1       1
Ind
1       1       1       1       1       1       1       1       1
Com
1       1       1       1
Rec
1       1       1       1       1;
*************************************************************************************
// The following set of tables represents the connectivity to demand nodes to sources
Table CWTPSW(s,l) Connectivity of  WTP l to surface sources s
      WTP1      WTP2      WTP3      WTP4      WTP5      WTP6      WTP7      WTP8      WTP9      WTP10
WTP11      WTP12      WTP13      WTP14      WTP15      WTP16      WTP17      WTP18      WTP19
WTP20
```

```
SW1    1      1      1      1      1     1      1      1      1      1      1      1      1
1      1
SW2
1      1      1      1       1;
*********************************************************************************
Table CWTPGW(g,l) Connectivity of  WTP l to groundwater sources g
     WTP1     WTP2     WTP3     WTP4     WTP5     WTP6     WTP7     WTP8     WTP9     WTP10
WTP11     WTP12     WTP13     WTP14     WTP15     WTP16     WTP17     WTP18     WTP19
WTP20
GW1;
*********************************************************************************
Table CSW(s,i) Connectivity of node i to Surface water source s
    D1     D2     D3     D4     D5     D6     D7     D8     D9     D10     D11     D12     D13
D14     D15     D16     D17     D18     D19     D20     D21     D22     D23     D24     D25     D26
D27     D28     D29     D30     D31     D32     D33     D34     D35     D36     D37     D38     D39
D40     D41     D42     D43     D44     D45     D46     D47     D48     D49     D50
SW1
1     1     1      1     1     1     1                                 1     1     1      1
1     1     1      1     1                           1     1     1     1     1
SW2
1     1     1      1     1;
*********************************************************************************
Table CGW(g,i) Connectivity of node i to Groundwater source g
    D1     D2     D3     D4     D5     D6     D7     D8     D9     D10     D11     D12     D13
D14     D15     D16     D17     D18     D19     D20     D21     D22     D23     D24     D25     D26
D27     D28     D29     D30     D31     D32     D33     D34     D35     D36     D37     D38     D39
D40     D41     D42     D43     D44     D45     D46     D47     D48     D49     D50
GW1;
*********************************************************************************
Table CWTP(l,i) Connectivity of node i to water treatment plant l
       D1     D2     D3     D4     D5     D6     D7     D8     D9     D10     D11     D12     D13
D14     D15     D16     D17     D18     D19     D20     D21     D22     D23     D24     D25     D26
D27     D28     D29     D30     D31     D32     D33     D34     D35     D36     D37     D38     D39
D40     D41     D42     D43     D44     D45     D46     D47     D48     D49     D50

WTP1     1     1
1     1
WTP2           1
1     1
WTP3                1
WTP4                     1
WTP5                          1
WTP6                               1
WTP7                                    1
```

```
WTP8                                      1
WTP9                                          1
WTP10                                              1
WTP11                                                   1
WTP12                                                        1
WTP13                                                             1
WTP14                                                                   1
WTP15                                                                        1
WTP16                                                                             1
WTP17                                                                                  1
WTP18
1
WTP19
1
WTP20
1;
*************************************************************************************
Table CRW(f,i) Connectivity of node i to Reclaimed water source f

     D1     D2     D3     D4     D5     D6     D7     D8     D9     D10     D11     D12     D13
D14     D15     D16     D17     D18     D19     D20     D21     D22     D23     D24     D25     D26
D27     D28     D29     D30     D31     D32     D33     D34     D35     D36     D37     D38     D39
D40     D41     D42     D43     D44     D45     D46     D47     D48     D49     D50
WWTP1
1
WWTP2
1
WWTP3
1
WWTP4
1     1
WWTP5
1
WWTP6
1
WWTP7
1
WWTP8
1
WWTP9
1
WWTP10
1
```

```
WWTP11
1       1;
************************************************************************************
Table CPRW(p,i) Connectivity of node i to private reclaimed water source (PWWTP) p
        D1      D2      D3      D4      D5      D6      D7      D8      D9      D10      D11      D12      D13
D14      D15      D16      D17      D18      D19      D20      D21      D22      D23      D24      D25      D26
D27      D28      D29      D30      D31      D32      D33      D34      D35      D36      D37      D38      D39
D40      D41      D42      D43      D44      D45      D46      D47      D48      D49      D50
PWWTP1
1;
************************************************************************************
Table CNSW(s,i) Connectivity of node i to Surface water source s (nodes as suppliers)
     D1      D2      D3      D4      D5      D6      D7      D8      D9      D10      D11      D12      D13
D14      D15      D16      D17      D18      D19      D20      D21      D22      D23      D24      D25      D26
D27      D28      D29      D30      D31      D32      D33      D34      D35      D36      D37      D38      D39
D40      D41      D42      D43      D44      D45      D46      D47      D48      D49      D50
SW1
1      1      1      1      1      1      1      1      1                          1      1      1
1      1
SW2
1      1      1      1      1;
************************************************************************************
Table CNGW(g,i) Connectivity of node i to groundwater source g (nodes as suppliers)
     D1      D2      D3      D4      D5      D6      D7      D8      D9      D10      D11      D12      D13
D14      D15      D16      D17      D18      D19      D20      D21      D22      D23      D24      D25      D26
D27      D28      D29      D30      D31      D32      D33      D34      D35      D36      D37      D38      D39
D40      D41      D42      D43      D44      D45      D46      D47      D48      D49      D50
GW1
;
************************************************************************************
Table CWWTPSW(s,f) Connectivity of  WWTP f to surface sources s  ( WWTP as a supplier)
     WWTP1    WWTP2     WWTP3    WWTP4   WWTP5     WWTP6     WWTP7     WWTP8
WWTP9     WWTP10     WWTP11
SW1     1      1           1     1      1      1      1      1
SW2
;
************************************************************************************
Table CWWTPGW(g,f) Connectivity of  WWTP f to groundwater sources g  ( WWTP as a supplier)
     WWTP1    WWTP2     WWTP3    WWTP4   WWTP5     WWTP6     WWTP7     WWTP8
WWTP9     WWTP10     WWTP11
GW1
;
************************************************************************************
Table CNWWTP(f,i) Connectivity of  nodes to WWTP  (nodes as suppliers)
```

```
        D1       D2       D3       D4       D5       D6       D7       D8       D9       D10       D11       D12       D13
D14      D15      D16      D17      D18      D19      D20      D21      D22      D23      D24      D25      D26
D27      D28      D29      D30      D31      D32      D33      D34      D35      D36      D37      D38      D39
D40      D41      D42      D43      D44      D45      D46      D47      D48      D49      D50
WWTP1      1                            1
1       1
WWTP2            1       1                     1                          1       1       1
1       1
WWTP3
1
WWTP4                                               1       1
WWTP5                       1
WWTP6                                                       1
WWTP7                                                                                  1
WWTP8                                                                                         1
WWTP9                                                                                                1
WWTP10                                                                                                                 1
WWTP11
1       1

;
*************************************************************************************
Table  CNPWWTSW(s,p) Connectivity of PWWTP p to Surface source s (PWWTP as supplier)  //
      PWWTP1
SW1      1
SW2
;
*************************************************************************************
Table  CNPWWTGW(g,p) Connectivity of PWWTP p to Groundwater  source g  (PWWTP as supplier) //
      PWWTP1
GW1
;
*************************************************************************************
Table CNPWWTP(p,i) Connectivity of PWWTP to demand nodes  (nodes as suppliers)
      D1       D2       D3       D4       D5       D6       D7       D8       D9       D10       D11       D12       D13
D14      D15      D16      D17      D18      D19      D20      D21      D22      D23      D24      D25      D26
D27      D28      D29      D30      D31      D32      D33      D34      D35      D36      D37      D38      D39
D40      D41      D42      D43      D44      D45      D46      D47      D48      D49      D50
PWWTP1
1;
*************************************************************************************
Table Q(k,i) Water demand (1000m^3 per day) at node i     //////// check this table
** Water demand assumption id 85% of the WTPs treatment capacity  plus 250 from WTP1 to D2
```

```
      D1     D2     D3     D4     D5     D6     D7     D8     D9     D10     D11     D12     D13
D14     D15     D16     D17     D18     D19     D20     D21     D22     D23     D24     D25     D26
D27     D28     D29     D30     D31     D32     D33     D34     D35     D36     D37     D38     D39
D40     D41     D42     D43     D44     D45     D46     D47     D48     D49     D50
k1     900     975     95.2     76.5     76.5     191.25     18.7     57.8     32.3     57.8     76.5     18.7     51
11.22     107.1     17.0     45.1     17.85     9.35     107.1     1000     1000     800     500     800
500     500     770     815     1660     695     150     28.8     9.86     16.5     6.3     3.56     1.92
37.26     6.3     6.58     10     10     10     10     10     10     10     10     10
;
************************************************************************************
Table TCWTP (k,l) Treatment Capacity (1000 m^3 per day) of Water Treatment Plant l
   WTP1     WTP2     WTP3     WTP4     WTP5     WTP6     WTP7     WTP8     WTP9     WTP10
WTP11     WTP12     WTP13     WTP14     WTP15     WTP16     WTP17     WTP18     WTP19
WTP20
k1   1300     910     112     90     90     225     22     68     38     68     90     22
60     13.2     126     20     53     21     11     126
;
************************************************************************************
Table TCWWTP (k,f)  Treatment Capacity (1000 m^3 per day) of Wastewater Treatment Palnt f
     WWTP1     WWTP2     WWTP3     WWTP4     WWTP5     WWTP6     WWTP7     WWTP8
WWTP9     WWTP10     WWTP11
k1     405     600     40     40     60     20     15     40     15     15     40
**                          // WWTP1 is Karkh, WWTP2 is Rasafa, WWTP3 is Mahmudia, WWTP4 is
Madaen
;
************************************************************************************
Table TCPWWTP (k,p) Treatment Capacity (1000 m^3 per day) of the Private Wastewater Treatment Plant
p
    PWWTP1
k1     18
**          PWWTP1 is at Dora Oil Refinery
;

************************************************************************************
Table QSWav (k,s) Surface Water availability (1000 m^3 per day)of source s
      SW1     SW2
k1     7800     4350
*      17300     5000
*k1       9000     3000
;
************************************************************************************
Table QGWav (k,g) Groundwater availability (1000 m^3 per day)of source g
    GW1
k1
```

```
;
*********************************************************************************
Table QLUSR (k,i) Water Losses by user i
       D1      D2      D3      D4      D5      D6      D7      D8      D9      D10      D11      D12      D13
D14      D15      D16      D17      D18      D19      D20      D21      D22      D23      D24      D25      D26
D27      D28      D29      D30      D31      D32      D33      D34      D35      D36      D37      D38      D39
D40      D41      D42      D43      D44      D45      D46      D47      D48      D49      D50
k1     331.5   232.05    28.56    22.95     22.95    57.375    5.61     17.34     9.69     17.34     22.95      5.61
15.3      3.366      32.1      5.1      13.53      5.4      2.8      32.13      1000      1000      800      500      800
500      500      770      815      1660      695      150      11.52      7.95      13.15      5.21      2.74      1.64
29.86      5.21      5.21      4      4      4      4      10      10      10      10      10
;
*********************************************************************************
Table QLWTP (k,l) Water Losses by WTP l
      WTP1      WTP2      WTP3      WTP4      WTP5      WTP6      WTP7      WTP8      WTP9      WTP10
WTP11      WTP12      WTP13      WTP14      WTP15      WTP16      WTP17      WTP18      WTP19
WTP20
k1     65       45.5       5.6       4.5       4.5       11.25      1.1       3.4       1.9       3.4       4.5       1.1
3.0       0.66       6.3       1.0       2.65       1.05       0.55       6.3
;
*********************************************************************************
Table QLWWTP (k,f) Water Losses by WWTP f
      WWTP1      WWTP2      WWTP3      WWTP4      WWTP5      WWTP6      WWTP7      WWTP8
WWTP9      WWTP10      WWTP11
k1     60.75      90      6      6      9      3      2.25      6      2.25      2.25      6

;
*********************************************************************************
Table QLPWWTP (k,p) Water Losses by PWWTP p
      PWWTP1
k1     2.7
;
*********************************************************************************
Table PRIRW (k,u) Priority to use RW by type of use u
      Ind      Irr      Dom      Com      Rec
k1             1.0
*********************************************************************************
Variables
*********************************************************************************
  QS (k,i,s)    Amount of surface water sent from source s to user i without treatment
  QG (k,i,g)    Amount of groundwater sent from source g to user i without treatment
  QT (k,i,l)    Amount of treated water sent from water treatment plant l to user i
  QRW(k,f,i)    Amount of reclaimed water sent from WWTP f to user i
  QRWPU(k,p,i)  Amount of reclaimed water sent from PWWTP p to user i
```

```
  QWS (k,i,s)    Amount of wastewater sent from user i to surface source s
  QWG (k,i,g)    Amount of wastewater sent from user i to groundwater source g
  QWT (k,i,f)    Amount of wastewater sent from user i to wastewater treatment plant f
  QWPT(k,i,p)    Amount of wastewater sent from user i to the private wastewater treatment plant p
  QST (k,s,l)    Amount of surface water sent from surface source s to water treatment plant l
  QGT (k,g,l)    Amount of groundwater sent from groundwater source g to water treatment plant l
  QRWS(k,f,s)    Amount of reclaimed water sent from WWTP f to surface source s
  QRWG(k,f,g)    Amount of reclaimed water sent from WWTP f to groundwater source g
  QRWPS(k,p,s)    Amount of reclaimed water sent from PWWTP p to surface source s
  QRWPG(k,p,g)    Amount of reclaimed water sent from PWWTP p to groundwater source g
  RQSWD          Sum of the remaining surface water flow downstream the system
  TF_DN (k,i)    Total water diverted  to demand node i
  RWRE           Amount of RW used

*********************************************************************************
Positive Variables
  QS      Amount of surface water sent from source j to user i without treatment
  QG      Amount of groundwater sent from source g to user i without treatment
  QT      Amount of treated water sent from water treatment plant l to user i
  QRW     Amount of reclaimed water sent from WWTP f to user i
  QRWPU   Amount of reclaimed water sent from PWWTP p to user i
  QWS     Amount of wastewater sent from user i to surface source s
  QWG     Amount of wastewater sent from user i to groundwater source g
  QWT     Amount of wastewater sent from user i to wastewater treatment plant f
  QWPT    Amount of wastewater sent from user i to the private wastewater treatment plant p
  QST     Amount of surface water sent from surface source s to water treatment plant l
  QGT     Amount of groundwater sent from groundwater source g to water treatment plant l
  QRWS    Amount of reclaimed water sent from WWTP f to surface source s
  QRWG    Amount of reclaimed water sent from WWTP f to groundwater source g
  QRWPS   Amount of reclaimed water sent from PWWTP p to surface source s
  QRWPG   Amount of reclaimed water sent from PWWTP p to groundwater source g
  RQSWD   Remaining surface water flow downstream the system
  TFDN    Total water diverted to demand node i
Equations
 QN (k,i)      Demand constraints for user i
 QUSR (k,i)    Mass balance constraint for user i
 QWTP (k,l)    Mass balance constraint for WTP l
 QWWTP (k,f)   Mass balance constraint for WWTP f
 QPWWTP (k,p)  Mass balance constraint for PWWTP p
 MQWTP (k,l)   Capacity constraint for WTP l
 MQWWTP (k,f)  Capacity constraint for WWTP f
 MQPWWTP (k,p) Capacity constraint for PWWTP p
 MQS (k,s)     Surface water availability constraint from source s
 MQG (k,g)     Groundwater availability constraints from source g
```

```
  MQRW (k,f)    Reclaimed water availability constraint from WWTP f
  MQPRW (k,p)   Reclaimed water availability constraint from PWWTP p
  MQTW (k,l)    Treated water availability constraint
  Re_WC (k,s)   Remaining surface water flow rate downstream the system Constraint
  RSWD (k,s)    Total remaining surface water flow DS the system
  TF_DN (k,i)   Total water diverted  to demand node i
  PRI_RW (k,u)  Reclaimed water priority constraint by type of use
** Objective
  RW_Reuse (k)  Amount of RW used by users ;
**** Constraints
*** 1) Demand Constraints
*** This set of linear constraints forces the demand for each user i to be satisfied
  QN (k,i) .. sum(s, QS(k,i,s) * CSW(s,i))+ sum(g, QG (k,i,g) * CGW(g,i)) + sum(l, QT (k,i,l) * CWTP(l,i))
          + sum(f, QRW(k,f,i)* CRW(f,i)) + sum(p, QRWPU(k,p,i) * CPRW(p,i)) =E= Q(k,i);
*** 2) Mass Balance Constraints
***2.1) For Users
  QUSR (k,i) .. sum (s, QS(k,i,s) * CSW(s,i)) + sum(g,QG (k,i,g) * CGW(g,i))+ sum (l, QT (k,i,l) * CWTP(l,i)) +
sum(f, QRW(k,f,i) * CRW(f,i))
           + sum(p, QRWPU(k,p,i) * CPRW(p,i))     // nodes as consumers
           - sum(s, QWS (k,i,s) * CNSW(s,i)) - sum(g, QWG (k,i,g) * CNGW(g,i)) - sum(f, QWT (k,i,f) *
CNWWTP(f,i))
          - sum(p, QWPT(k,i,p) * CNPWWTP(p,i) )     // Nodes as suppliers
            =G= QLUSR (k,i);  /// QLUSR (k,i) water losses at user i
***2.2) For Water Treatment Plant
  QWTP (k,l) .. sum(s, QST (k,s,l) * CWTPSW(s,l)) + sum(g, QGT (k,g,l) * CWTPGW(g,l))
            - sum(i, QT (k,i,l) * CWTP(l,i)) =L=  QLWTP (k,l)  ;  /// QLWTP (k,l) Losses at WTP l
***2.3) For Wastewater Treatmnet Plant
  QWWTP (k,f) ..sum(i, QWT (k,i,f) * CNWWTP(f,i)) - sum(i,QRW(k,f,i) * CRW(f,i))- sum(s, QRWS(k,f,s) *
CWWTPSW(s,f))
                 - sum(g,QRWG(k,f,g) * CWWTPGW(g,f)) - QLWWTP (k,f) =E= 0.00 ;  /// QLWWTP (k,f) Losses at
WWTP f
***2.4) For Private Wastewater Treatment Plant
  QPWWTP (k,p).. sum(i, QWPT(k,i,p) * CNPWWTP(p,i)) - sum(i, QRWPU(k,p,i) * CPRW(p,i)) - sum(s,
QRWPS(k,p,s) * CNPWWTSW(s,p))
             - sum(g, QRWPG(k,p,g) * CNPWWTGW(g,p)) =G=   QLPWWTP (k,p)  ; /// QLPWWTP (k,p) Losses
at PWWTP p
***3.) Capacity Constraints: These linear constraints limit the water entring a treatment plant to its
capacity
***3.1) Water Treatment Plants
  MQWTP (k,l) ..sum(s, QST (k,s,l) * CWTPSW(s,l)) + sum(g, QGT (k,g,l) * CWTPGW(g,l)) =L= TCWTP (k,l)  ;
***3.2) Wastewater Treatment Plants
  MQWWTP (k,f) .. sum(i, QWT (k,i,f) * CNWWTP(f,i)) =L= TCWWTP (k,f)    ;
***3.3) Private Wastewater Treatment Plants
  MQPWWTP (k,p) .. sum(i, QWPT(k,i,p) * CNPWWTP(p,i)) =L= TCPWWTP (k,p)   ;
```

```
***4. Water Availability Constraints
***4.1) Surface Water Availability Constraints
 MQS (k,s) .. QSWav (k,s) - sum(i, QS (k,i,s) * CSW(s,i)) - sum(l, QST (k,s,l) * CWTPSW(s,l)) + sum(i, QWS
(k,i,s) * CNSW(s,i))
          + sum(f, QRWS(k,f,s) * CWWTPSW(s,f)) + sum(p, QRWPS(k,p,s) * CNPWWTSW(s,p)) =G= 0.00  ;
***4.2) Groundwater Availability Constraints
 MQG (k,g) .. QGWav (k,g) - sum(i, QG (k,i,g) * CGW(g,i)) - sum(l, QGT (k,g,l) * CWTPGW(g,l)) + sum (i,
QWG (k,i,g) * CNGW(g,i))
         + sum(f, QRWG(k,f,g) * CWWTPGW(g,f)) + sum(p, QRWPG(k,p,g) * CNPWWTGW(g,p) ) =G= 0.00 ;
***4.3) Reclaimed Water Availability  from WWTP f Constraints
  MQRW (k,f) .. sum(i, QRW(k,f,i) * CRW(f,i)) + sum(s, QRWS(k,f,s) * CWWTPSW(s,f)) + sum(g, QRWG(k,f,g)
* CWWTPGW(g,f)) =L= TCWWTP (k,f);
***4.4) Reclaimed Water Availability from PWWTP p constraint
  MQPRW (k,p) .. sum(i, QRWPU(k,p,i) * CPRW(p,i)) + sum(s, QRWPS(k,p,s) * CNPWWTSW(s,p)) + sum(g,
QRWPG(k,p,g) * CNPWWTGW(g,p)) =L=  TCPWWTP (k,p);
***4.5) Treated water availability constraint
  MQTW (k,l) .. sum(i, QT(k,i,l) * CWTP(l,i)) + QLWTP (k,l) =L= TCWTP (k,l)  ;   // This is a new constraint
**** Remaining surface water flow rate downstream the system
***4.6) Remaining Surface water Downstream the System Constraint
 Re_WC (k,s)..   sum(i,QS(k,i,s)*CSW(s,i)) + sum(l, QST(k,s,l)*CWTPSW(s,l))  =L= QSWav (k,s) + sum(i,
QWS(k,i,s) * CNSW(s,i)) + sum(f, QRWS(k,f,s)*CWWTPSW(s,f)) + sum(p, QRWPS(k,p,s)*CNPWWTSW(s,p));
**** Remaining water flow downstream the system
 RSWD (k,s)..   RQSWD(k,s) =E= QSWav (k,s)- sum(i,QS(k,i,s)*CSW(s,i)) - sum(l, QST(k,s,l)*CWTPSW(s,l))+
sum(f, QRWS(k,f,s)*CWWTPSW(s,f)) + sum(p, QRWPS(k,p,s)*CNPWWTSW(s,p));
*****Total water diverted to demand node i
 TF_DN (k,i).. TFDN(k,i) =E= sum(s, QS(k,i,s) * CSW(s,i))+ sum(g, QG (k,i,g) * CGW(g,i)) + sum(l, QT (k,i,l) *
CWTP(l,i))
                  + sum(f, QRW(k,f,i)* CRW(f,i)) + sum(p, QRWPU(k,p,i) * CPRW(p,i))  ;
****5. Priority constraint to use RW by type of use u
 PRI_RW (k,u).. sum((f,i),  QRW(k,f,i) * CRW(f,i)* TDN(u,i)) =L=  PRIRW (k,u) * (sum((f,i), QRW(k,f,i) *
CRW(f,i)));
*** Objective Function
RW_Reuse (k).. RWRE  =E= sum((f,i),  QRW(k,f,i) * CRW(f,i)) +  sum((p,i), QRWPU(k,p,i) * CPRW(p,i));
model Regional_Water_Allocation /all/ ;
Solve Regional_Water_Allocation using LP Maximizing RWRE;
** The End
```