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EVALUATING WATER MANAGEMENT POLICY IN SAUDI ARABIA USING A BILEVEL, MULTI-OBJECTIVE, MULTI-FOLLOWER PROGRAMMING APPROACH

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DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Agriculture, Food and Environment
at the University of Kentucky

By
Jawad Alhashim
Lexington, Kentucky
Director: Dr. David Freshwater, Professor of Agricultural Economics
Lexington, Kentucky
2018

ABSTRACT OF DISSERTATION

EVALUATING WATER MANAGEMENT POLICY IN SAUDI ARABIA USING A BILEVEL, MULTI-OBJECTIVE, MULTI-FOLLOWER PROGRAMMING APPROACH

Over the past five decades, the Saudi government has adopted many agricultural policies aimed to: achieve self-sufficiency of food, increase the participation of the agricultural sector in the economy, and reduce the consumption of irrigation water. Due to conflicts among government objectives and the incompatibility of farmers' objectives with those of some agricultural policies, the government has not been able to fully achieve its objectives.

To accomplish its goals the government, or decision maker needs to understand the farmer, or follower, reaction when s/he adopts a new decision. The dissertation aims to build a model that achieves government goals of minimizing the total irrigation water used while improving the total revenue from agricultural production, while incorporating farmers' objective of maximizing their profit. To do this, linear programming and bi-level multi-objective multi-follower models are developed and applied to six regions of Saudi Arabia, which account for around 70 percent of cropland and consume about 13.131 BCM of irrigation water per year.

The result of the linear programming model appied to the Riyadh region shows there is an unobserved factor effect on the farmers' decisions, including irrigation water demand that comes from the presence of indirect subsidies. On the other hand, the bi-level multi-objective, multi-follower model shows there is the possibility to minimize irrigation water consumption while maintaining current total revenue from crop production through reallocating irrigation water among regions, while applying a variety of crop specific tax and subsidy policies among the regions to alter planting decisions.

KEYWORDS: Bi-level multi-objective multi-follower programming, Saudi Government, Follower, Algorithm, Irrigation water, Agricultural policies.

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EVALUATING WATER MANAGEMENT POLICY IN SAUDI ARABIA USING A BILEVEL, MULTI-OBJECTIVE, MULTI-FOLLOWER PROGRAMMING APPROACH

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11/26/2018
Date

DEDICATION

To the spirit of my father
who was the cause of my presence in this existence
To the spirit of Dr. Bassem Al-Ibrahim
who supported me in order to start the graduate study
To my dear mother
who nurtured me with her love and compassion
To my dear wife Zeinab
who stood beside me until I achieved this achievement
To my children Fatimah, Mohammed and Maryam
To all my brothers and sisters
To all my relatives and friends

ACKNOWLEDGMENTS

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My thanks are extended to the faculty and staff of the agricultural economic department. The faculty and staff were available when I need any help or advice. I would like to acknowledge the support provide by my family during my study and here I have to express my deep gratitude to my wife Zienab Alhashim. Zienab support me and provide great effort to provide the environment that I can study and work for the dissertation. Finally, I wish to thank the respondents of my study King Saud University.

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CHAPTER 1. INTRODUCTION

1.1. Problem Statement

Over the past four decades (1970-2010), the Saudi government has attempted to lead the agricultural sector to achieve food security, reduce the use of irrigation water, diversify the economy, and improve the welfare of citizens. To achieve these objectives of the government requires a better allocation of available resources. In particular, the government has adopted different types of agricultural policy (e.g., support prices, input subsidies and the distribution of free cropland) to achieve a better balancing among the two goals of increasing food security and reducing the use of irrigation water. Unfortunately, some of the policies did not help improve the balance among these objectives, and there are two reasons for this failing. First, some of the policies are consistent with some goals, while they conflict with others. Second, the government objectives can conflict with the farmers' goals of maximizing their profits. When this happens policies chosen by the government induce farmers to behave in ways that the government did not anticipate and does not desire.

In the last four decades, while the demand for irrigation water has increased over time, it has also fluctuated significantly in response to many factors, particularly shifts in government agricultural policies. Some of the forces that have increased irrigation water demand include, increases in the total amount of cropland, changes in crop patterns, and changes in the quality of available irrigation water. Underlying these changes are shifts in government policy that favor the production of some crops over others, and changes in other forms of support for farmers.

Saudi agricultural policy faces two key challenges. The first is an inherent conflict between the desire to increase food self-sufficiency, in an environment where irrigation is required for the vast majority of crop production, and the desire to reduce the rate of groundwater extraction. While greater efficiencies in water use can be achieved, at some point producing more food leads to greater water use. The second challenge is a classic Principal-Agent problem, in that both Saudi government goals can only be achieved through the appropriate actions of farmers who choose both the amount of various crops to produce and how much water to apply to them. Farmers have no direct interest in either national goal, and instead can be thought of as individual profit maximizers. To achieve its goals the Saudi government must develop policies that alter the incentives farmers face in ways that motivate them to make profit maximizing choice that are compatible with government objectives.

Some agricultural policies and regulations are consistent with some goals; but conflict with others. For instance, the wheat support price policy led to reaching self-sufficiency for wheat, satisfying the food security goal and increasing farmers' incomes. On the other hand, the policy conflicted with the goal of reducing irrigation water use because it encouraged farmers to expand the amount of land in wheat, which increased the demand for irrigation water. In 1990 wheat cropland was 770.6 thousand hectares, and represented 55.9 percent of the total farmland. At the same time irrigation water demand grew from 6108 MCM in 1970 to 18,000 MCM in 1990, which means the water demand tripled over ten years (MOWE, 2012). In this case, it is clear the government could not reach a balance between achieving self-sufficiency in wheat and reducing the irrigation water used. In response, the Saudi government in 2005 reduce the support price for wheat to SAR 1000 (266.66 USD) to force the farmers to reduce the irrigation water demand, but this policy leads to reduce the farmer's income and less self-sufficiency.

The dissertation will address the two policy challenges by developing a multi-objective optimization model that incorporates the two government goals of improved food self-sufficiency and reduced irrigation water consumption. The model also incorporated the Principal-Agent challenge by having two levels of decision-makers. Government chooses a desired combination of irrigation water consumption and food security, and is able control the amount of water extracted by farmers. But, without also creating a set of policy incentives for farmers, that leads them to produce the desired mix of crop outputs it is impossible to satisfy the government's food security objective. The dissertation shows that with an appropriate set of policy incentives the government can achieve various combinations of food security and irrigation water use, with the potential to achieve current levels of food security while using significantly less water.

1.2. The objective of the research

The main objective of the dissertation is to contribute to solving the problem of reducing the demand for irrigation water used while achieving an acceptable level of food security. Over recent decades the Saudi government has adopted a variety of policies that have increased agricultural output , but that have often led to more irrigation water use than was initially anticipated. The government then reverses its policies to reduce water demand, but this can lead to a reduction in food security. While at a certain level there can be a direct conflict between the two goals of water use and food security, the main hypothesis of the dissertation is that the problem is largely a consequence of the use of an inappropriate set of policy tools to address the two problem of, conflicting objectives among policies and misaligned incentives between government and farmers. With more appropriate policies it should be possible to provide incentives to fares that lead to satisfying food security objectives and reducing irrigation water consumption.

The specific objectives of the dissertation are

1. Develop a regional model to provide the best crop mix at the regional level that leads to maximizing the net return on activities using groundwater, and understand why there are differences between the optimized crop pattern and the current crop pattern. One of the most important causes of the difference may be the unobserved subsidies. Initially, the model is applied to the Riyadh region and assuming the region is a single farm, where the farmer is the decision maker and has a perfect profit maximizing objective.
2. Develop a national model that aims to explore the best crop mix for six regions in Saudi Arabia by allocating limited farmland and limited groundwater to achieve the government objectives, which is the balancing among minimizing irrigation water consumption and maximizing total farm revenue. The dissertation uses the total revenue as a proxy to measure the acceptable level of food security. Thus, the national model would help the government identify integrated policies that lead to reduced consumption of irrigation water and that maximize the total farm's revenue.

1.3. Approach Followed

The main assumption is that the government can control the distribution of irrigation water between regions. Also, the government is fully aware of the level of food security required. On the other hand, the government has to understand the farmer’s decision-making process since it relies on the farmers to produce crops. Therefore, the dissertation uses two types of model to contribute to solving the problem of reducing irrigation water used while achieving an acceptable level of food security. The first model is the regional model while the second is a national model.

The regional model aims to find the optimal crop pattern that maximizes the farm's profit. The regional model is a part of the national model. The regional model calibrated using the Riyadh region because it has the largest cropland among regions. The primary irrigation water resource in Riyadh is groundwater and Riyadh has multiple aquifers. Therefore, the quality of irrigation water varies among aquifers. An average levels of salinity is used when calculating crop specific gross irrigation water requirements. Initial model results showed a significant gap between historic average levels of output and estimated outputs for a few major crops. To resolve this problem new prices for these crops were calculated that incorporate the benefit from various subsidies that farmers receive. These adjusted prices result in a crop output pattern that is similar to the historic average. This new price set is used in the national model.

The national model covers six regions, where non-renewable groundwater is the main source of irrigation water. This model has two levels of decision makers. The upper level, or the leader, is the government, while the lower level, or the followers, is the regions. The model assumes each region is a single large farm and the farm's objective is maximizing profit. Thus, there are seven optimization problems. The first problem, or the master problem, belongs to the government. The rest of the problems belong the regions. Crucially the government must rely on eh actions of the regions if it is to satisfy its objectives, but the regions do not take government objectives into account when solving their individual problems. The government's problem has two objectives: the first objective is minimizing total irrigation water consumed, while the second objective is maximizing the total agricultural revenue, although in the empirical model this objective enters as a constraint.

Total agricultural revenue is used as a proxy for the acceptable level of food security. Clearly, measuring the actual level of food security is a complex issue that involves both the stock of locally produced and imported food, and the ability of households to purchase available food. However, Saudi food security policy mainly focuses on the level of self-supply, and given that the mix of crops will vary from scenario to scenario, a revenue measure is preferred since it allows direct comparisons of self-supply levels across scenarios. Total revenue is estimated using levels of crop output in each region, while market prices are based on wholesale prices for crops that are not imported and import prices for those crops where imports are common.

The solution mechanics start with the government solving the master problem to minimize irrigation water used, while holding total revenue at some target level. This solution assures the government that a feasible production set exists. The government then allocates a maximum water use level to each region that reflects its solution. Then, the region takes the given amount of irrigation water and optimizes net farm income, or profit, from crop production.

Two different algorithms are used to solve the problem. The first algorithm, named 'Reallocated Irrigation Water Policy' (RIWP), applies uniform prices across all regions, and relies only on the restriction on water use to modify farmers' behavior. . A second algorithm, named 'Integrated Irrigation Water Management Policy' (IIWMP), introduces region specific prices that provide an additional signal to producers to adjust planting decisions if they either over or under produce specific crops when compared to the government's desired crop pattern. These ad valorem taxes or subsidies are applied in cases of over or under production as price signals to alter the crop distribution in each region.

1.4. Dissertation Overview

The balance of the dissertation consists of four chapters. The second chapter provides a background on Saudi Arabia. This background includes Saudi Arabia's water resources, developing the agricultural sector in a region has limited water resources and the agricultural policies that adopted by the government to raise the agricultural sector contribution in the national economy. The third chapter provides the methodology, which contains the regional model, national model, and data requirements. The regional model follows a standard linear programming model of agricultural production that is calibrated as a single profit-maximizing enterprise using one of the large regions (Riyadh) that depend on groundwater. This model is then extended to 5 other major regions. The second model is the national model that include six regions in Saudi Arabia with multiple crops produced and a national government sector that sets its own goals and policies. The national model follows a bi-level, multi-objective, multi-follower optimization structure. Once the data requirements are specified the actual empirical models structures are described, but model results are discussed in the next chapter. Chapter Four presents the results of the regional and national models. The regional model result shows the optimal crop pattern and the indirect subsidies estimation. The national model result shows four scenarios through two level of total revenue and two algorithms. Chapter Five discusses the result of the regional and national model, such as why the regional model shows the gap between the current crop pattern and optimal crop pattern and why the indirect subsidies estimation is the better interpretation. Finally, Chapter Five provides the conclusions, and addressees limitations and opportunities for future work.

CHAPTER 2. INTRODUCTION TO AGRICULTURAL DEVELOPMENT AND WATER RESOURCES IN SAUDI ARABIA

2.1. Introduction

This second chapter provides a brief overview of the context for agricultural development in Saudi Arabia. It describes the water demand situation and how agricultural policies that have led agricultural sector development, have caused an increased demand for a limited amount of water. The chapter consists of five main sections. It begins with background on Saudi Arabia, which focuses on the fact that Saudi Arabia has limited water resources, while there has been considerable growth in water demand over time. The agricultural sector's increasing demand for water is the main reason for this. The chapter then describes the main sources of water, namely, rainfall, groundwater, and seawater desalination. The government has invested in capturing rainfall through building dams, which are used to compensate for groundwater extraction, and provide water for irrigation and household consumption. This section also provides information on the supply of groundwater, which is divided between renewable and non-renewable sources, and then discusses seawater desalination that is an important source of drinkable water in urban areas. The third section focuses on water users, which are: the agricultural sector, the domestic sector, and the industrial sector. However, the agricultural sector is the main water user, with its demand for water fluctuating in response to variations in government goals and policies. The fourth section covers the motivation for agricultural development in Saudi Arabia, and the fifth section covers past and current agricultural policies. The government developed the agricultural sector to reach several objectives, such as, increasing farmer's income and diversifying the rural economy. To achieve its goals the government used different types of agricultural policy, including: distributing farmland free of charge, introducing price supports, providing interest free loans to farmers, providing input subsidies and using direct payments.

2.2. Saudi Arabia Background

Saudi Arabia is located in the arid belt of the earth. Therefore, its summers are long, hot, and relatively dry. The winter season is short and cold with little rain. Annual rainfall averages 100 mm, while the annual evaporation is an average of 3,500 mm/year. Saudi Arabia also represents 70 percent of the Arabian Peninsula. Its total land area is about two million square kilometers (Alsharhan *et al.*, 2001). Moreover, Saudi Arabia lacks permanent and renewable surface water resources, such as streams and lakes. Thus, among Saudi Arabia's natural resources, the one with perhaps the highest value and social significance is groundwater, which has numerous uses in domestic, agricultural, and industrial areas. However, the agricultural sector is the primary consumer of water in Saudi Arabia. Limited water supplies have led to 61 percent of the domestic water demand being supplied by desalination of sea water in 2015 (M.W.E, 2015).

Saudi Arabia, like most countries, has a keen interest in food security. Some of its food comes from the country's self-supply, and there is also a historical basis for agricultural production near oases that is valuable for cultural and local economic development reasons. Moreover, Saudi Arabia has a keen interest to ensure that water is available for Saudi people. However, Saudi Arabia faces a significant water constraint: most water, most of which is used for agriculture, comes from aquifers with very slow recharge rates. Thus, the water policy and the agricultural policy/food security policy are very closely linked.

Historically, the Saudi government encouraged Saudi people to participate in agricultural development through: high domestic farm prices, easy access to water, and money for farm-related investments. As a result, the cultivated area has expanded significantly, as shown in Figure 2.1, which has led to an increased demand for irrigation water. For instance, since 1971, cropland developed from 418.9 thousand hectors to 1.5 million hectors in 1994. Subsequently, the demand from the agricultural sector for water increased from 1,860 million cubic meters (MCM) in 1980 to 7,430 MCM in 1985 (Al-Ibrahim, 1990). Consequently, both renewable and non-renewable groundwater has faced massive depletion, which is not compatible with their very slow rates of replenishment. According to Ghanim and Alrwis (2003) that the agricultural sector depends on non-renewable groundwater for 66.54% of its water, while its dependence on renewable groundwater is 33.46%.

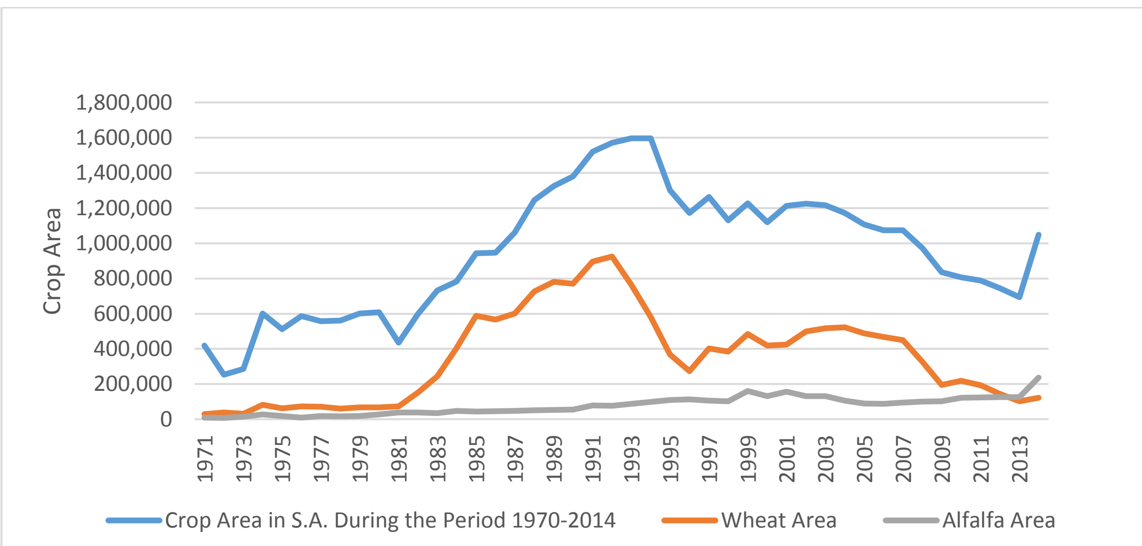


Figure 2-1 the change of Crop Area in Saudi Arabia during the period between 1971-2014

Total cropland within the current system of agriculture, based on the Agriculture Census (2015), is 1.04 million hectors. The agricultural area was utilized as follows:

fodder crops represent about 48 percent, cereal crops account for about 31percent, fruit accounts for about 12 percent, and vegetables account for about 8 percent. Alfalfa occupies the most extensive area among all crops, as it represents 22 percent of the cultivated area, while dates trees account for about 10 percent. Moreover, most of the crops grown in Saudi Arabia are irrigated by modern irrigation systems, such as drip irrigation or sprinkler irrigation, representing about 80 percent of the total irrigated area. Specifically, about 86 percent of the grain and feed area is watered by a sprinkler system, while a drip method irrigates 58 percent of the fruit area. Also, about 60 percent of the vegetables cultivated in open-field areas are irrigated by the modern system, in which a drip irrigation system irrigates around 10 percent, and a sprinkler system irrigates about 70 percent. Table 2.1 presents the percentage of irrigation area of each crop base on the irrigation methods. Correspondingly, the Ministry of Environment, Water, and Agriculture (MEWA) estimated that the agricultural sector consumed about 20,831 MCM of the total water consumed. Thus, even though most cropland is irrigated by high efficiency systems, the demand for agricultural irrigation water has increased. Therefore, decision makers must address the problem of the increasing demand for irrigation water, protect the next generation’s rights to this resource, and provide optimal allocation of water resources among various activities, including satisfying the desire for a higher rate of food self-sufficiency.

Table 2-1 Distributed of crop pattern according to irrigation methods based on a percentage

Crops	Surface	Drip	Sprinkler	Rains	Other
Wheat	0.48	0.01	10.51	0.66	0.01
Barley	0.16	0.02	9.38	0.10	0.00
Sorghum	1.84	0.03	0.57	3.55	0.03
Maize	0.01	0.00	0.20	0.02	0.00
Millet	0.07	0.00	0.01	0.30	0.00
Sesame	0.13	0.00	0.00	0.07	0.00
Other Cereal	0.36	0.03	0.65	1.44	0.02
Tomato (OF)	0.13	0.54	0.31	0.01	0.00
Tomato (GH)	0.00	0.11	0.00	0.00	0.00
Eggplant	0.04	0.11	0.02	0.00	0.00
Squash (OF)	0.06	0.15	0.06	0.01	0.00
Squash (GH)	0.00	0.02	0.00	0.00	0.00
Cucumber (OF)	0.01	0.05	0.01	0.00	0.00
Cucumber (GH)	0.00	0.08	0.00	0.00	0.00
Okra	0.14	0.04	0.02	0.00	0.00
Carrots	0.07	0.03	0.05	0.00	0.01
Potato	0.08	0.29	1.25	0.00	0.01
Dray onion	0.00	0.00	0.25	0.00	0.00
Melon	0.05	0.10	0.16	0.06	0.01
Watermelon	0.14	0.15	0.16	1.87	0.02
other Vegetable (OF)	0.26	0.21	0.46	0.02	0.01
Other Vegetable (GH)	0.00	0.08	0.00	0.00	0.00
Alfalfa	0.59	0.08	40.49	0.05	0.00
Other fodder	0.10	0.02	6.43	0.04	0.00
Dates plum	5.15	5.08	0.00	0.00	0.00
Citrus	0.19	0.25	0.00	0.00	0.00
Grapes	0.08	0.28	0.00	0.00	0.00
Other Fruit	0.46	2.35	0.00	0.00	0.00
Percent of total area	10.60	10.11	70.97	8.19	0.12

Calculated by the author from Agriculture Census (2015)

2.3. Water Resources in Saudi Arabia

Identifying the sources of water in Saudi Arabia is essential. Saudi water sources include surface water, groundwater, desalinated seawater, treated sewage water, and reused agricultural drainage water. Of these, the conventional water resources are surface water and groundwater. This section examines the geomorphology of Saudi Arabia, particularly the Arabian Shield and the Arabian Shelf. The Arabian Shield is located in the western part of Saudi Arabia and extends from the northwest to the southwest, and it covers a third of the Arabian Peninsula. The Arabian Shelf is located east of the Arabian Shield and covers two-thirds of the Arabian Peninsula (Figure 2.2).

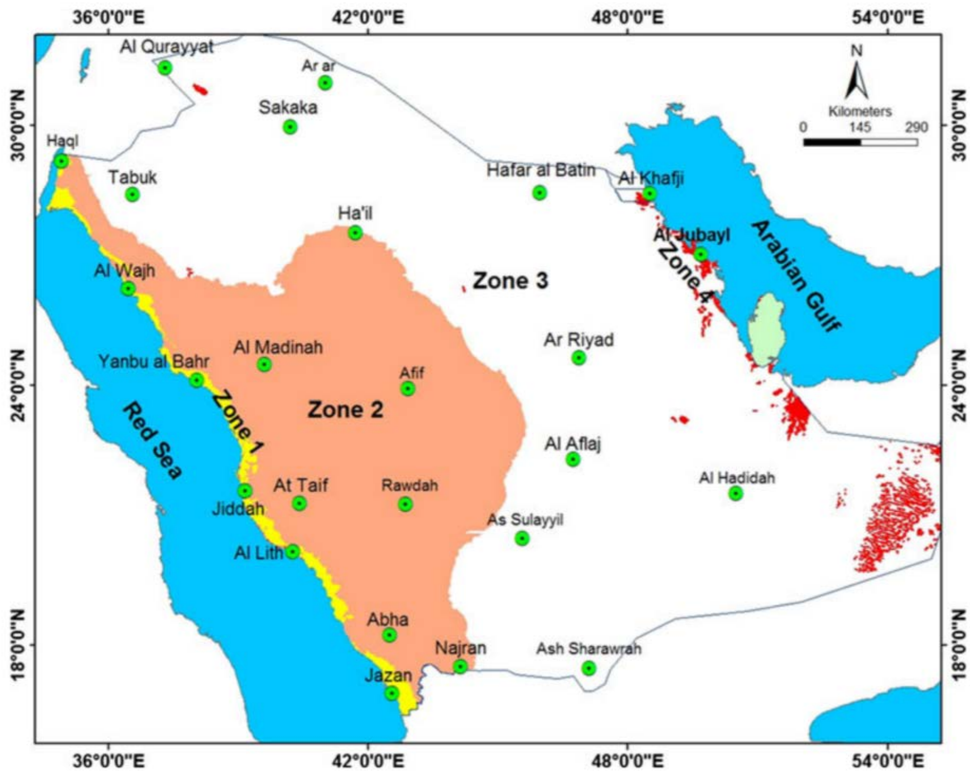


Figure 2-2 General physiography of Saudi Arabia.
(Zone 1 = the eastern coastal plains of the Red Sea; Zone 2 = Escarpment of the Arabian Shield; Zone 3 = the central plateau of the Arabian Shelf; Zone 4 = The Arabian Gulf coastal region; and the green dots are the city locations). Adopted from Youssef and Norbert (2013)

Since the country lacks surface resources (e.g., rivers and lakes), the primary source of surface water is rainfall. On average, Saudi Arabia receives an estimated 158.47 billion cubic meters of rainfall annually (MOWE, 2012). When rain falls in the deserts, where it is difficult to harvest, the evaporation rate is high. The only part of the rainfall that recharges the groundwater is in the Arabian Shelf. Also, according to MOWE (2012), the quantity of annual runoff is estimated at 5,000 million cubic meters (MCM), with most of this water in the western part of Saudi Arabia. Consequently, the Saudi government built 444 dams, holding a total capacity of 2,017 thousand cubic meters of water for irrigation, drinking water, compensation for groundwater extraction and flood control. Two dams with 54 thousand cubic meters of water are used for irrigation; 58 dams with 453 thousand cubic meters are used for drinking water. The rest of the dams are designated for compensation and control (MOA, 2014).

Groundwater is the most critical water source in Saudi Arabia. It is the most significant source of domestic water, providing local water supply needs, and that of the industrial and agricultural sectors. The groundwater in Saudi Arabia is divided into renewable and non-renewable, or fossil, water, which has been stored in different layers of the ground for thousands of years. Renewable aquifers are located in the Arabian Shield and are called shallow alluvial aquifers. These aquifers recharge when the rainfall runs into the valleys. MWE (2012) mentions the renewable aquifers store about 84 BCM and have an average annual recharge of 1,196 MCM.

Fossil or non-renewable groundwater is located in the Arabian shelf. Non-renewable groundwater is divided into primary or principal aquifers, and secondary aquifers. These are categorized based on the volume of water stored in the aquifer, areal extent, and the possibility of development. The principal aquifers are Saq, Wajid, Tabuk, Minjur, Dhruma, Biyadh, Wasia, Dammam, Umm Er Radhuma, and Neogene. The secondary aquifers are Al-Jauf, Al-Khuff, Al-Jilh, the upper Jurassic, Sakaka, the lower Cretaceous, Aruma, Basalts, and Wadi Sediments (MWE, 2012). These aquifers are distributed throughout Saudi Arabia and extend from the western part to the east (Figure 2.3).

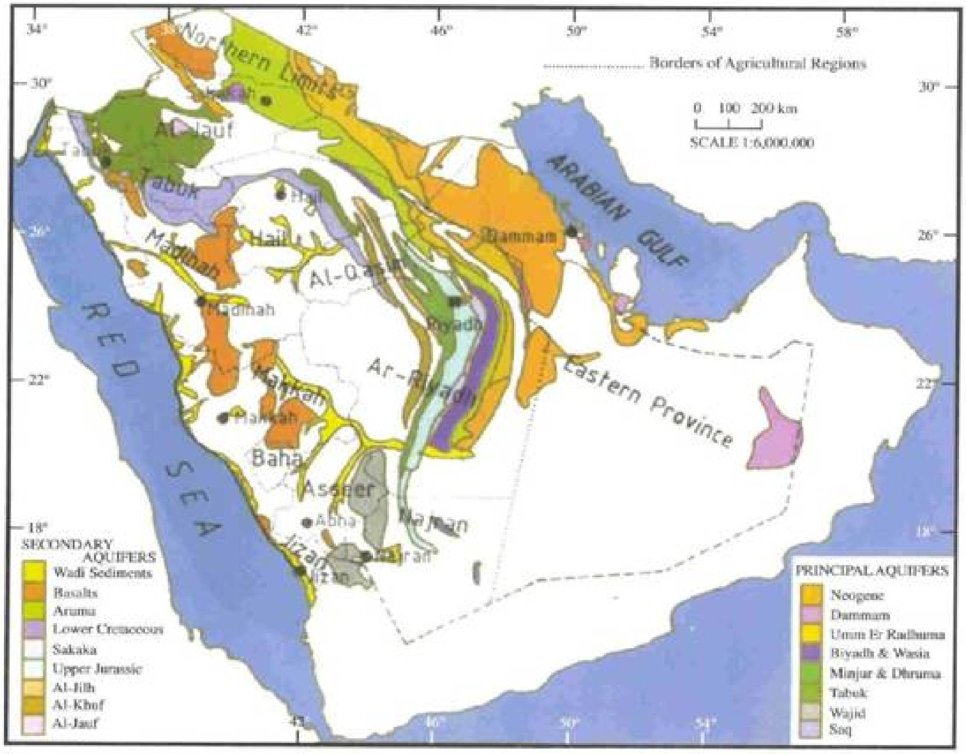


Figure 2-3 Extension of the principle and secondary aquifers in Saudi Arabia (MWE, 2012).

Table 2.2 illustrates the principal aquifers and provides the characteristics of each aquifer's extent. The total thickness of these aquifers varies from a few meters, as in the Neogene aquifer, to around a thousand meters, as shown in the Tabuk aquifer. On the other hand, the quality of the water, which is measured by total dissolved solids (TDS), varies from site to site and among the aquifers. The Neogene aquifer, for example, ranges from 100 and 4000 TDS part per million (ppm), while the Saq aquifer ranges from 500 to 1,500 ppm. Groundwater resources are estimated to be 500 billion cubic meters (BCM), in which the principal aquifers carry around 337 BCM, and the secondary aquifers carry 162.5 BCM (MAW, 1984).

Table 2-2 Primary Aquifer of Non-renewable Groundwater in Saudi Arabia.
A: Proven, B: Probable, C: Possible.

Aquifer	Thickness (m)	Total Dissolved solids (mg/l)	ECe (mS/cm)	Depth from ground surface (m)	Reserve (BCM)			Regions
					A	B	C	
Saq	500–600	500-1,500	0.781-2.34	100-1,500	65	100	200	Tabuk, Hail, Qaseem
Wajid	300–400	500-1,000	0.781-1.56	15-1,100	30	50	100	Riyadh
Tabuk	1000	500-3,500	0.781-5.47	10-1,400	5.6	5.6	5.6	Tabuk,Jouf Hail, Qaseem
Minjur/ Dhurma	Minjur: 360 Dhurma: 100–110	Minjur: 400-1,600	Minjur: 0.625-2.5	Minjur: 1,400	17.5	35	85	Riyadh
Wasia-Biyadh	Biyadh: 100–400 Wasia: 200-230	Wasia: 1,000-3,000	Wasia: 1.56-4.69	Wasia: 230-1,200	120	180	290	Riyadh
Umm er Radhuma	500	300-1,000	0.460-1.56	250-600	16	40	75	Eastern Province
Dammam-Neogene	Dammam: 200 Neogene: 30–100	Dammam: 1,000-6,000 Neogene: 100-4,000	Dammam: 1.56-9.38 Neogene: 0.165-6.25	Dammam: 100-500 Neogene: 10-150	5	5	5	Eastern Province

Reference: Chowdhury and Al-Zahrany (2012).

Furthermore, sources of water consumed for domestic purposes and industry can be divided into conventional resources, such as groundwater and dams, and non-conventional resource, such as desalination of sea water. Conventional resources represented 41 percent of the domestic water demand, while the non-conventional resource described by 59 percent in 2014 (MOWE, 2014). The Saudi government has invested considerable money through the Saline Water Conversion Corporation (SWCC) since the 1970s and built 28 plants throughout this period. Thus, SWCC is the main non-conventional resource in Saudi Arabia and produced 1,695 MCM in 2014.

2.4. Water Use in Saudi Arabia

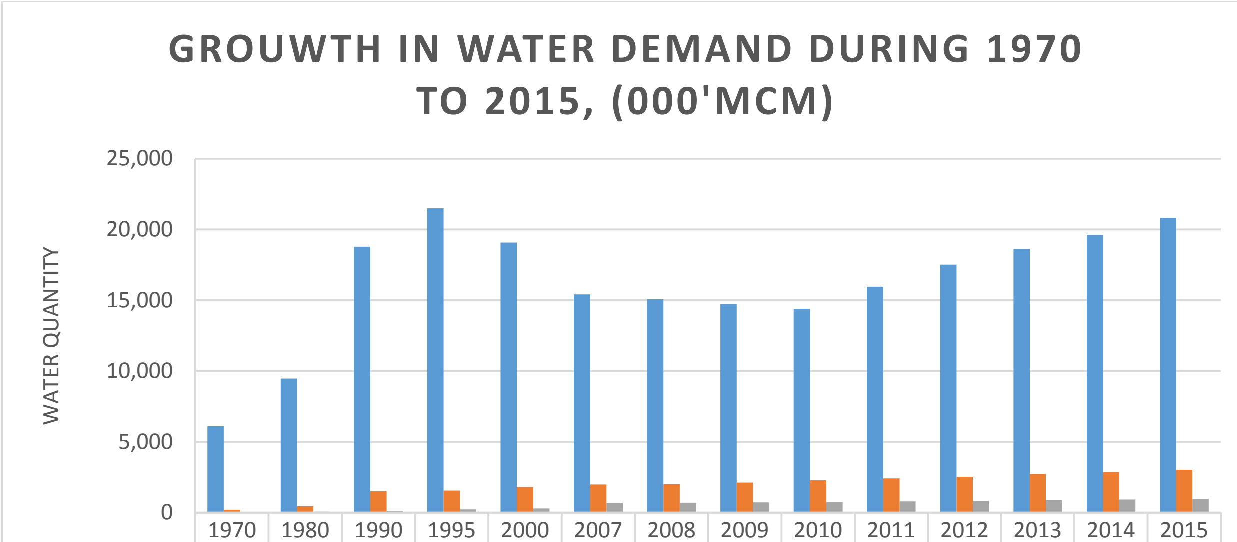
As a result of the Saudi government's policies to increase food production and increase the standard of living, demand for water is growing. The total demand for water in 2015 was 24,844 MCM. The main consumer is the agricultural sector, which consumes 84 percent of the total demand for water while the residential sector consumes 12 percent. The industrial sector uses only 4 percent of the water demand. Figure 4.4 shows the demand for all the sectors on water since 1970 to 2015 and shows the demand for water fluctuating in response to variations in government goals and policies. However, the agricultural sector is the largest user even the government adopted many of policies to reduce the water demand for the agricultural sector.

From the 1980s through 1990s, the Saudi government sought to fulfill its goal of achieving self-sufficiency in an area with limited arable land and fresh water. The desire for self-sufficiency encouraged the government to adopt policies that: caused a change in crop patterns, increased the total cropland, and increased irrigation water demand. For instance, between 1970 and 1995, the agricultural sector's demand for water increased from 6,108 MCM to 21,298 MCM. During that time, the Saudi government provided different types of subsidies to encourage farmers to expand to growing wheat and other crops.

As a result of the subsidy programs intended to develop the agricultural sector, Saudi Arabia achieved self-sufficiency in wheat production in 1980, when it produced around 1.4 million tons of wheat. In 1985, the Saudi government started to export wheat; in 1989, Saudi Arabia exported more than 1.6 million tons of wheat. The development of the agricultural sector moved Saudi Arabia closer to its food independence. In this way, self-sufficiency helped Saudi Arabia reach several broad objectives, including food security, the diversification of the economy, and the improvement of rural welfare.

After 1995, the government tried to balance the conflicting goals self-sufficiency and reducing the agricultural sector's demand for water by reducing the support price for wheat and imposing a production quota for each farmer to reduce the production of wheat.

In 2007, new Saudi government new policies targeted wheat production with an objective of reducing the production of wheat by 12.5 percent annually and stopping dependence on domestic wheat supply and instead depending on the world market (World-Grain.com, 2016). While these policies led to a change in the crop pattern in Saudi Arabia and decreased the water demand for the agricultural sector from 2008 until 2010, since 2011, the demand for agricultural sector has increased as a result of the change in crop pattern that refected another revision to governmetn policies that encouraged fodder produciton. The agricultural water demand increased from 15,979 MCM in 2011 to 20,831 MCM in 2015 (MOWE, 2015). While the new policy caused a change in the crop pattern, it resulted in increased demand for irrigation water.



	1970	1980	1990	1995	2000	2007	2008	2009	2010	2011	2012	2013	2014	2015
Agricultural	6,108	9,470	18,776	21,498	19,074	15,420	15,083	14,747	14,410	15,970	17,514	18,639	19,612	20,831
Domestic	200	446	1,508	1,550	1,800	1,978	2,007	2,123	2,284	2,423	2,527	2,731	2,874	3,025
Industiral	20	56	109	230	290	683	698	714	753	800	843	890	930	977

Figure 2-4 Growth in consumption of water (MCM) in Saudi Arabia between 1970 and 2015
Source: Abderrahman (2005), Ministry of water and electricity (2014 and 2015)

Also, the demand for domestic water in Saudi Arabia has increased as a result of a growing population and a rising tstandard of living. For instance, in 2014, the domestic water demand increased by about 43 percent compared with 2007. In 2008, the domestic water demand was estimated at 2,007 MCM, and it rose to 3,025 MCM in 2015 (MOWE, 2015). Also, the average per capita, per day consumption in Saudi Arabia is 263 liters of fresh water. However, the average consumption per capita per day increased by around 14 percent compared to 2007. So, a growing population and standard of living increased pressure on the domestic water source. Also, there is an essential factor causing an increase in demand for domestic water. Saudi government provides desalinated water with a large price subsidy, while for the other households that use groundwater the government provides the water at no cost. Also, the industrial sector's demand for water is growth since 1970 where the demand was 20 MCM and becomes 977 MCM in 2015.

Even there is a significant growth rate, the industrial sector's demand represents the lowest user in Saudi Arabi while the agricultural sector is the largest water user. Therefore, the Saudi government focus to reduce the agricultural sector's demand for water to reduce the total demand for water.

2.5. Agricultural Development

Diversification of the economy was one of the most important goals for the first Saudi Five-Year Plan in 1970. Increasing agricultural self-sufficiency was a tool to help diversify the economy. In 1974, the agricultural sector contributed 1.8 percent to the GDP. When the government supported the sector, the domestic agricultural product's GDP contribution increased to 4.4 percent in 1985. In 1989, the GDP proportion of the domestic agricultural product rose further to 6.4 percent. During the period between 1999 and 2002, the agricultural sector's contribution to the GDP ranged between 5.11 and 5.8 percent (MOA, 2005). However, when the Saudi government changed its agricultural policies by reducing support to the agricultural sector in 2004, the share of the domestic agricultural product decreased, only contributing 1.9 percent to the GDP in 2013 (MOA, 2014). Therefore, the contribution of the agricultural sector to GDP appears to be dependent on the level of government support.

Self-sufficiency is also driven by the desire of the government to increase rural welfare. Unfortunately, there is no indicator of whether the countryside's welfare improved as a result of the supported agricultural programs. Modern farms can obtain many subsidies that lead to a reduction in the average cost of the output and an increase in the marginal profit per unit. In contrast, traditional farmers find it difficult to compete with modern farmers; this could cause the conventional farmers to exit the market. Self-sufficiency may help to achieve food security, but the cost to the government and society are reductions in several natural resources and the use of a great deal of capital. So, self-sufficiency does not lead to sustainable diversification of the economy or improvement in rural welfare, and food security remains an area of high concern for the Saudi government.

Since 1959, Saudi Arabia has been dealing with the issue of food security as a result of its policy regarding subsidizing imported food. This policy aimed to ensure that food would be available and accessible to the Saudi nation (Nowshirvani, 1987). However, in October 1973, the Ramadan or Yom Kippur War occurred between Egypt and Syria on one side and Israel on the other. The United States supported Israel against Egypt and Syria. Therefore, the Arab members of OPEC led by Saudi Arabia used oil as a political weapon against the United States to encourage if to stop supporting Israel in that War. In response, the United States threatened Arab countries with the use of food as a political weapon against oil. Therefore, food security achieved by self-sufficiency has been an issue of great concern for the Saudi government, and it has become one of the primary objectives of the Five-Year Plans[1]. The subject of food security was evident in the speech of the Minister of Agriculture and Water, Dr. Abdul Rahman Al-Sheikh, who said, “To produce your food on your land, it’s a matter of security” (New York Times, 1985). Consequently, the Saudi government decided to facilitate its food security through self-sufficiency by establishing programs to support the country’s agricultural sector.

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[1] Since 1971, Saudi government established a five-year plan to develop the Saudi economic.

Self-sufficiency regarding food has led the Saudi government to use several different natural resources, such as oil, land, and water. The government invested the revenue from oil in developing agriculture and applied various policies to extend the agricultural sector vertically, thus increasing productivity, and horizontally to increase the land used in farming. Therefore, the Saudi government adopted a different program and policy with the goal of reaching self-sufficiency based on its limited natural resources and high import of technology. The Saudi government also established several governmental institutions that contributed to the implementation of public policy and the development of local agriculture:

1) The Ministry of Agriculture and Water (MAW), which currently called the Ministry of Environment and Water and Agriculture (MEWA);
2) Agricultural Bank, which currently called the Agricultural Development Fund (ADF);
3) The Grain Silos and Flour Mills Organization, which currently called the Saudi Grains Organization (SAGO). Each of these institutions has contributed to the country's agricultural development and helped further progress toward food security.

2.6. Agricultural Policies

The agricultural sector has received increasing attention due to its role in helping the Saudi government achieve its economic development objectives. The objectives include: achieving self-sufficiency regarding food, increasing the incomes of the rural members of the nation, diversifying the production base, reducing the volume of imports, reducing the demand for irrigation water, and reducing the country's dependence on oil as the primary source of national income. Hence, the Saudi government adopted different programs and policies to support and encourage the private sector to invest in the agricultural sector. These programs and policies were designed to provide help to farmers both directly and indirectly. The next section presents many of the agricultural policies that the Saudi government adopted to develop the agricultural sector from 1970 to 2014.

2.6.1. Distribution of farmland free of charge

Agricultural land distribution is one of the policies designed to support farmers with the goal of increasing agricultural production. Distribution of fallow farmland represents one of the most important contributing factors to increases in the total agricultural land in Saudi Arabia as shown in Table 2.3. This policy helps to increase the area of farmland in production; the total cumulative distribution of farmland that is used for plant production and animal production is 3.3 million hectares within the period of 1969 to 2003. In 1984, the government reevaluated the distribution of the farmland fallow system and decided to continue distributing the farmland within areas with renewable water resources, such as southwest regions where the rainfall rate is relatively high. In 2003, the government decided to stop the distribution of the farmland fallow system to stop the exhaustion of groundwater, which represents the most significant source of irrigation water. However, the total cumulative distribution in 1981 was more than a hundred thousand hectors while the agricultural land was more than four hundred thousand hectors as shown in Table 2.3. Thus, as a result of increasing the distribution farmland, the farm area rose to 1.7 million hectors in 1991 and decreased to 1.2 million hectares in 2001. So, the effect of the distribution of land on agricultural area become observe since the 1980s.

Table 2-3 The cumulative distribution of Agricultural land distribution

Year	The total cumulative distribution of agricultural land, Unit (Hactar)	Agricultural land Unit (Hactar)
1981	185,912	434,829
1982	372,386	596,936
1983	487,522	731,269
1984	578,932	782,695
1985	749,052	946,360
1986	841,421	947,381
1987	1,037,244	1,061,773
1988	1,288,590	1,245,063
1989	1,498,120	1,326,156
1990	1,632,516	1,379,189
1991	1,754,515	1,519,758
1992	2,027,693	1,570,818
1993	2,368,624	1,596,405
1994	2,585,091	1,595,549
1995	2,726,207	1,302,361
1996	2,820,558	1,173,311
1997	2,901,522	1,263,263
1998	2,947,510	1,130,493
1999	2,985,760	1,226,507
2000	3,048,108	1,119,949
2001	3,091,639	1,211,579
2002	3,204,338	1,224,502
2003	3,259,844	1,216,038

2.6.2. Agricultural lending policy

The Agricultural Development Fund (ADF), which was established in 1964 and began practice in 1966, is a significant factor in improving the agricultural sector. It is a government credit institution specializing in financing various aspects of agricultural activity in all regions of Saudi Arabia. The goal of the ADF is to support farmers by funding them with interest-free loans and supporting them through subsidies. The ADF finances small farmers from SAR 200 thousand to SAR three million. Also, the ADF finances specialized agricultural projects starting at three million and extending to SAR 20 million. Also, ADF provides an extended grace period from one to six years, depending on the nature of the project.

2.6.3. Policies that support purchased inputs

The Saudi government focused on supporting farmers through a program that encourages farmers to increase agricultural production through programs that reduce the cost of production. For example, in 1973, the Ministry of Environment and Water and Agriculture (MEWA) established a chemical fertilizer subsidy by providing the farmer 50 percent of the fertilizer cost. However, this support ended in 1982. Also, the ADF provided input subsidies such as

(1) paying half of the official price of the irrigation pumps and equipment,

(2) 45 percent for farm machinery,

(3) 30 percent for poultry and dairy equipment if ADF did not finance the project while the subsidy was 20 percent if the project was financed by ADF(Al-Zahrani, 2003).

In 2004, the ADF was reformed direct subsidies that was provided to farmers such as input subsidies by reducing 25 percent of the total loan value if the lender did not delay the monthly payments. Also, the ADF increased the subsidy of the irrigation system to 75 percent of its cost.

2.6.4. Payment of production subsidies

The objective of price supports is to increase the production of specific products, such as wheat, barley, dates, sorghum, millet, and rice. Under this aim, two types of policies exist, either to directly support the price or to provide a subsidy on the quantity of production. The subsidy on the amount of output covers baby palm trees, dates, sorghum, millet, and rice. The MEWA paid SAR 50 for each baby palm tree and SAR 0.25 per kilogram of dates based on production. This kind of support encouraged farmers to increase the quality and quantity of date palms. Also, farmers who grow sorghum, millet, and rice were offered a direct payment under which the farmers receive SAR 0.25, 0.15, and 0.30 per kilogram, of production respectively (Alghamdi,2000). In October 2011, the government restructured the support program as follows: it stopped subsidies to grow baby palm trees and rice, continued to subsidize sorghum and millet with SAR 0.25 per kilogram, continued to subsidize small farmers with SAR 0.50 per kilogram but only if the farmer uses a modern irrigation system, and stopped subsidizing other forms of irrigated production.

Support for the price of wheat and barley came through the Saudi Grains Organization (SAGO), which represents the primary demand source for wheat in Saudi Arabia. The government offered assistance for growing wheat by direct payment since 1977 and then transferred to a price support program, thus encouraging the private sector to enter agriculture and invest in wheat projects. The support price started from SAR 3,500 (933.33 USD) per ton in 1980. In 1984, the government reduced the support price for wheat to SAR 2000 (533USD) for individuals and SAR 1500 (400 USD) for agricultural companies. The government then further reduced the support price, but the production of wheat increased to more than four million tons in 1994. In response, the government established a quota program to reduce the production of wheat. In 2004, the government cut the support price to SAR 1000 (266.66 US) per ton.

Additionally, the SAGO decreased its wheat purchases annually by 12.5 percent in 2008 and imported wheat to bridge the domestic consumption gap; 2016 was the last year of supported wheat production in Saudi Arabia. The other product with supported price is barley. This program started in 1986, at which time the price was SAR 1000 (266.66 USD), and the program ended in 1998. Furthermore, the government purchases 21 thousand tons of dates annually under the support price, which is SAR 3.5 (0.93 USD) per kilogram and increases the price to SAR 5 (1.33 USD) per kg if the farmer uses drip irrigation system.

Table 2.4 summarizes all of these programming subsidies to show the established date and the timeline of the change in the policy. All of these policies helped Saudi Arabia become more self-sufficient in its various products, especially dates, eggs, milk, fresh vegetables, fruit, chicken, and red meat, but self-sufficiency regarding wheat has not existed since 2008. Therefore, from 1974 until 2013 the MEWA paid more than SAR 4.6[2] billion to farmers as production subsidies that encouraged them to produce more

[2] Calculate by author from different sources

food. On the other hand, ADF provided more than 13.2[3] billion SR to farmers from 1973 until 2013 as input subsidies while ADF lent the farmers, with zero interest, more than 45.2[4] billion SR from 1964 until 2013. All these subsidies aim to increase food production to achieve food security, motivate farmers to adopt modern technology to reduce the demand for irrigation and increase farmers' income. However, the subsidies lead to inefficiency because when the government achieves an objective, it lose the other objectives.

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[3] Calculate by author from different sources
[4] Calculate by author from different sources

Table 2-4 History of Agricultural Policies in Saudi Arabia

Policies	Started of policy	Value	Change		End of policy
Agricultural lending	1965	50%-100%	2004	Reform the lend policy.	Continues
Subsidies of production elements					
Chemical fertilizers	1973	50%	1982	Stop the subsidy	1982
Agricultural machinery	1973	45%	2004	The government reforms the subsidies by stopping the subsites of the production factors and subsidies the lender by 25% if the lender will not delay the monthly payment. Also, the government increased the subsidy of the irrigation system to 75%.	2004
Intensive fodder	1973	50%	2004		2004
Pumps and agricultural engines	1973	50%	2004		2004
Equipment for the production of Dairy	1974	30%	2004		2004
Transfer of cattle by air	1974	100%	2004		2004
Poultry equipment	1973	30%	2004		2004
Fishing boats	1976	Depend	2004		2004
Subsidies of production					
Wheat	1973	0.25 SR/Kg		Stop the subsidy of wheat per Kg	1978
			1978	Establish support price by 2 SR/Kg	
			1979-1984	Increasing support price to 3.5 SR/Ks	
			1985-1994	Reducing support price to 2 SR/kg for farmers and 1.5 for agricultural companies.	
			1995-2004	Reducing support price to 1.5 SR/kg and establish the quota program.	
			2005	Reducing support price to 1 SR/kg	
			2007	Reducing purchasing by 12% and stop at 2016	2016
Rice	1973	0.30 SR/Kg	2011	Stop the subsidy	2011
Sorghum	1973	0.25 SR/Kg	No change		
Millet	1975	0.15 SR/Kg	No change		
Barley	1975	0.15 SR/Kg	1986	Purchasing Barley from a local farm by 1 SR/Kg	
			2003	Stop support growing Barley locally	2003
Dates	1976	0.25 SR/Kg	2011	Increasing subsidy to 0.50 SR/Kg for small farmers if the farmers adopted a modern irrigation system	
Baby Palm tree	1976	50 SR/baby tree	2011	Stop the subsidy	2011
Barren land distribution	1969	Free	-	Start to distribute barren land freely.	
			1984	Stop Distributing agricultural land in into regions that have non-renewable water resources.	2003

CHAPTER 3. MODEL DESIGN, LOGIC AND STRUCTURE

3.1. Introduction

Chapter 3 covers the methodology used to address the problem of the dissertation. The chapter introduces two types of models. The first is a regional linear programming model that optimizes the profit from crop production for each study region, subject to a number of constraints. The main categories of constraint are: the availability of cropland, the availability of irrigation water and an aggregation constraint that limits the magnitude of shifts in production from historic levels. In this section, the methodology developed to estimate the gross irrigation water requirement for each crop is set out.

The second model is a national model that is structured as a bi-level, multi-follower programming model. In the national model the national government has two objectives, to minimize the total irrigation water used and to maximize a target level of the total gross revenue from agricultural production. The dissertation uses total revenue as a proxy for food security. Farmers, defined as a single large farm in each of six distinct regions, in turn incorporate constraints on water use set by the national government into their profit maximizing decision using the regional model.

Because the national model uses an approach that is both complex and relatively novel, the theoretical basis of a bi-level optimization process is discussed and developed into the bi-level, multi-objective, multi-follower optimization approach. Subsequently, a procedure to solve the bi-level, multi-objective, multi-follower optimization is provided. The resulting empirical model and its assumptions are then provided. The last section of the chapter introduces two algorithms that are used to solve the national model. The first algorithm is Reallocated Irrigation Water Policy (RIWP) while the second algorithm is Integrated Irrigation Water Management Policy (IIWMP).

3.2. Methodology

The Saudi government essentially faces a Principal-Agent (PA) problem in trying to reduce water consumption while maintaining food security. The PA problem occurs because, while the governmetn has objectives for irrigation water use and food security, it depends on the actions of farmers to determine whether its objectives are met. And, importantly, farmers do not share the governmetn’s objectives, but instead act to maximiaze their individual profits. For example, suppose the government wants to preserve food security by producing 1.03 million tons of wheat, and 2.2 million tons of vegetables while reducing water use by agriculture. The government might assume there is a social contract with the farmers who use the irrigation water to irrigate their farms to achieve these objectives, but in reality they have different objectives. The farmers use irrigation water use and choose crops to grow to maximize their profit. Therefore, the farmers may grow fodder and use more water than the governmetn suggets to maximize their profit.

Although the government can restrict water consumption by agriculture, it cannot assure an adequate amount of food is produced without the cooperation of farmers. Thus, the policy problem for the government is to find a way to align farmers’ incentives with its objectives. One way to motivate the farmers to act in ways that achieve the government’s objectives through crop specific subsidies or taxation that alter profits. Since conditions vary by region, the government has to adopt region specific policies.

The bi-level, multi-objective, multi-follower optimization method can provide a means for government to idenitify these region specific policies.

3.3. Regional Farm Models

The six regional models all have the same structure, with each region having its own parameters. Historic average crop patterns in the six regions are shown in Figure 3.1 for the four main groups of, grain, vegetable, fodder, and fruits. The crop area for each crop group is the average crop area of the five years (2009-2013) For instance, the crop pattern in Riyadh is presented as the following; the grain group represents 14.2 percent; vegetable group represents 23.2 percent, fodder group represents 40.2 percent, and fruits group represents 22.5 percent. Also, the main irrigation water resource in these regions is groundwater, with the availability and quality of water varying among regions. The quality of irrigation groundwater is not homogeneous within, or across regions even if the regions share an aquifer. For instance, Riyadh has several aquifers, and the quality of these aquifers range between not saline to high saline while the Juof region has a single aquafer. Falatah *et al.* (1999) find the average water salinity in Riyadh is 3.65 dS m^{-1}. Table 3.1 illustrates the average irrigation water quality for each region. Thus, the quality of the irrigation water varies among regions, which affects the gross irrigation water requirement for each crop.

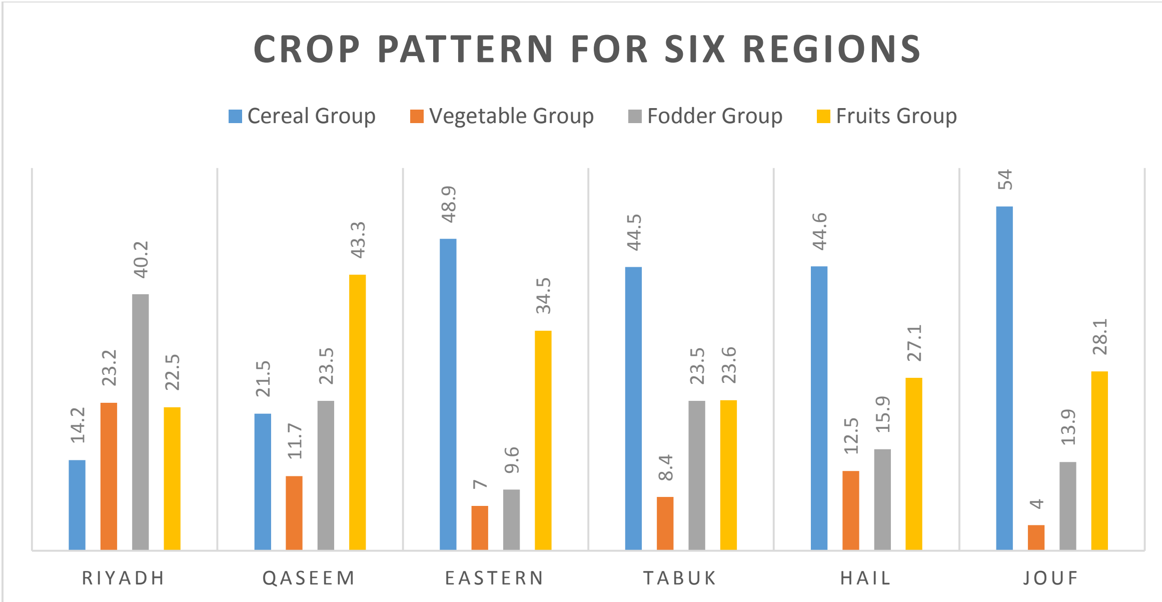

Figure 3-1 Describe crop pattern based on plant groups.

Table 3-1 Data Summary of the Irrigation Water Quality

Region	ECw			
	Min	Max	Average	S.D
Riyadh[a]	0.2	11.9	3.65	2.67
Qaseem[a]	0.7	4.3	2.91	1.48
Easten[a] (AlHasa)	2.9	3.6	3.05	0.34
Tabuk[a]	0.2	2.7	0.71	0.37
Hail[b]	166.4=0.26	2400=3.75	557=0.871	0.24
Jouf[a]	0.8	3.6	2.15	1.05

a: Falatah et al. (1999). Chemical Composition of Irrigation Groundwater Used in Some Agricultural Regions of Saudi Arabia.

b: Al-Turki (2009). Evaluation of well-water quality in the Hael (Hail) region of Central Saudi Arabia.

Each region produces between 21 to 22 crops, as shown in table 3.5, which provide information about the five year average crop area and yield. Yield varies among the regions for several reasons, such as the quality of water irrigation. To keep the yield at its maximum, the irrigation water requirement has to be enough to remove the salinity of the root zone, as well as satisfying the plants direct water needs. Furthermore, the quantity of irrigation water required increases as the degree of salinity increases, because the leaching requirement also increases.

3.4. Estimating Gross Irrigation Water Requirements

A number of concepts are used to estimate the gross irrigation water requirement. The first is the crop water requirement, which means the quantity of water required to actually grow the crop. The second concept is a leaching requirement. When irrigation water carries some salts, they accumulate in the soil over time To flush these salts below the root zone requires adding some fraction of the crop water requirement to keep the root zone free of salinity that would oherwise reduce crop yield. Both elements are used to calculate the total amount of required irrigation water, which is called the gross water requirement.

To elaborate, according to Savva and Frenken (2002), the irrigation water requirement is the amount of water which must be provided by the irrigation system to ensure that the crop obtains its full crop water. Several factors affect the irrigation water requirement, such as crop evapotranspiration, available rainfall, and leaching requirements. The primary component for estimating irrigation water requirement is evapotranspiration (ET). Evapotranspiration consists of two operations, evaporation and transpiration. Evaporation refers to lost water from the soil surface, while transpiration refers to the transfer of the water from plant tissues to the atmosphere. These operations occur simultaneously, and there is no easy way to distinguish between the two processes. The evapotranspiration concept consists of two elements: reference evapotranspiration

ET_0 and crop evapotransporation ET_c. ET_0 represents the evaporative demand of the atmosphere at a particular location and time of the year, and the main factors that affect ET_0 are climatic parameters. There are many different methods to estimate ET_0, and the FAO Penman-Monthith method is the sole recommended method. ET_c refers to the amount of water that a crop needs, which it is affected by climatic paramenters and crop characteristics. In some sense, crop water requirement (CWR) is equal to ET_c, but the CWR refers to the quantity supply required to grow the crops (Savva and Frenken, 2002). The following equation shows how to calucalte the ET_c.

$$ET_\mathrm{c} = k_c \times ET_o \qquad (3.1)$$

However, to estimate ET_c, which is measured by (mm/day), requires knowing the reference crop value ET_0, which is measured by (mm/day), and the value of crop coefficients k_c, which reflect the characteristic of a specific crop. Similarly, environmental conditions within a greenhouse differ from the those in an open field. Specifically, the value of reference evapotranspiration ET_0 and crop evapotransporation ET_c in the greenhouse is lower than in an open field, as Fernandes *et al.* (2003) found. Fernandes *et al.* (2003) found the ET_0 inside the greenhouse is lower than outside the greenhouse by (56%, 63, and 69%), depending on the method used to measure the crop reference inside the greenhouse. So, the value of ET_0 in the greenhouse is reduced by 60 to 70 percent compared to outside the greenhouse. Also, Mpusia (2006) estimated the actual evapotranspiration ET_c for roses and found the actual evapotranspiration ET_c in the greenhouse was 65% of actual evapotranspiration ET_c open field. Also, Singh *et al* (2016) found there was no large difference between the value of reference evapotranspiration ET_0 in the greenhouse and open field, but instead the difference was that reference evapotranspiration ET_0 in open field is higher than in greenhouse by 15.88 percent in total. Also, Singh *et al.* (2016) found the difference in crop coefficients was just 4.61 percent higher in the open field than in a greenhouse, while the actual evapotranspiration ET_c in open field is higher than in a greenhouse by 21.58 percent.

Data for crop water requirements (CWR) usually is available in published papers or an official report. Different sources, such as Alamoudi *et al.* (2010), which is a report that provides the CWR for many crops for different regions were used where available, while estimates for some crop CWRs were estimated using the FAO method. Also, the CWR for trees was obtained from an older study completed by the Saudi Agricultural Ministry (1980). However, since there is no study comparing CWR inside the greenhouse and outside (open field), the analysis assumes the actual evapotranspiration ET_c for the greenhouse is lower than for an open field by 40 percent. Also, the study follows the method developed by Al-Ghobari *et al.* (2003) to transfer data for CWRs from the reference region to the target region by using equation (3.2):

$$(ET_c)_x = (ET_c)_R \left[\frac{(E_P)_x}{(E_P)_R}\right]^2 \tag{3.2}$$

Equation (3.2) shows how to convert crop water requirement data from a reference region, R, to the target region, which is x using historical climate data. The equation uses three variables that must be available: the CWR in the reference region $(ET_c)_R$, pan evaporation in the targeted area $(E_P)_x$, and pan evaporation in the reference region $(E_P)_R$. Pan evaporation rates, $(E_P)_x$ and $(E_P)_x$ were obtained from Al-Ghobari *et al*. (2003) and Alamoud *et al.* (2010).

In Saudi Arabia, many studies have used alfalfa as a crop reference. These studies used the Lysimetric method to estimate crop reference (Al-Ghobari, 2000; Al-Ghobari *et al.*, 2003; Alamoud *et al.*, 2010). The dissertation uses the crop reference data from Alamoud *et al.* (2010) since Alamoud *et al.* (2010) covered nine regions. Unfortunately, there are two regions included in the dissertation that are not covered: Hial and Tabuk. Based on the author's knowledge, no study that estimate the crop reference covers Hail and Tabuk. The study adopts Al-Ghobari *et al.* (2003) method to transpose the reference crop in the Riyadh region to another region. Al-Ghobari *et al.* (2003) used Equation (3.2) to calculate the synthetic data. The data of $(E_P)_x$ and $(E_P)_x$ were obtained from Al-Ghobari *et al.* (2003) and Alamoud *et al.* (2010). The results of the synthetic data illustrates that the data follows the pattern of the data calculated by Alamoud *et al.* (2010). Table 3.2 shows the value of the reference crop for each region.

Table 3-2 Daily evapotranspiration ET_0 average (mm/day)

	Riyadh[1]	Qaseem[1]	Eastern[1]	Hail[2]	Tabuk[2]	Jouf[1]
January	3.6	3.2	3.6	2.94	3.29	2.9
February	4.7	4.3	4.8	3.42	4.06	4.1
March	6.2	5.8	6.5	4.92	5.39	5.8
April	7.9	7.7	8.2	7.00	7.06	8.0
May	9.4	9.5	10.9	8.98	8.43	9.8
June	10.7	10.2	12.7	11.33	9.40	10.8
July	11.3	10.4	12.9	13.11	10.44	11.6
August	10.1	9.5	11.3	12.18	10.25	10.4
September	8.2	8.2	8.9	11.01	9.26	9.1
October	6.2	6.5	6.6	8.64	7.17	6.7
November	4.6	4.6	5.1	5.86	4.78	4.2
December	3.5	3.3	3.5	4.01	3.87	3.1

1: Reference data is from Alamoud et al. (2010).
2: Data Transposing.

Alamoud *et al.* (2010) estimated the crop water requirement for different crops in different regions. The dissertation uses these data to estimate total crop water requirement. Alamoud *et al.* (2010) did not estimate all of the crops that the present study covered in all regions. More specifically, Hail and Tabuk have not covered in Alamoud *et al.* (2010). Consequently, this dissertation follows Al-Ghobari *et al.* (2003) and their use of synthetic crop water requirement (CWR) data in Hail and Tabuk using Equation (3.2).

Also, some crops have no crop water requirement data, ET_c or crop coefficients. In these cases the procedure applied by Allen *et al.* (1998) is used to estimate the crop coefficient and then estimates of the crop water requirement are calculated. Table 3.3 shows the data regarding the water requirement for all crops covered in the study in all regions.

Table 3-3 Crop Water Requirement (ETc) m^3 per hectare

Crops	Riyadh	Qaseem	Eastern	Tabuk	Hail	Jouf
Cereals Group						
Wheat	9,254.9[b]	5,156.0[a]	5,608.0[a]	5,016.2[c]	4,211.3[c]	5,071.0[a]
Barley	6,516.0[a]	8,932.9[c]	7,311.3[c]	8,337.5[c]	6,889.4[c]	4,994.2[c]
Sorghum	3,606.6[c]	3,747.0[c]	3,091.8[c]	4,609.6[c]	6,565.9[c]	1,874.3[c]
Maize	5,956.0[a]	6,234.9[c]	5,129.6[c]	6,363.9[c]	9,025.6[c]	7,050.0[a]
Millet	2,439.5[c]	2,390.1[c]	2,102.6[c]	3,298.1[c]	4,045.6[c]	784.2[c]
Sesame	3,261.6[c]	3,163.3[c]	2,787.9[c]	4,279.8[c]	5,191.6[c]	1,131.1[c]
Other Cereal	4,295.6[e]	3,597.4[e]	4,338.6[e]	5,317.5[e]	5,988.2[e]	3,260.5[e]
Vegetables Group						
Tomato (OF)	5,980.0[a]	5,806.0[a]	4,810.0[a]	4,785.1[c]	4,485.9[c]	4,143.1[c]
Tomato (GH)	3,588.0[f]	3,483.6[f]	2,886.0[f]	2,871.0[f]	2,691.6[f]	2,485.9[f]
Eggplant	5,033.9[d]	5,347.3[d]	5,000.5[d]	5,135.3[d]	5,116.1[d]	5,975.0[d]
Squash (OF)	4,387.5[b]	4,280.0[a]	3,486.1[c]	4,966.7[c]	7,228.5[c]	2,772.7[c]
Squash (GH)	2,632.5[f]	2,568.0[f]	2,091.6[f]	2,980.0[f]	4,337.1[f]	1,663.6[f]
Cucumber (OF)	10,046.9[d]	11,246.1[d]	12,291.9[d]	10,346.7[d]	12,074.9[d]	13,045.6[d]
Cucumber (GH)	6,028.1[f]	6,747.7[f]	7,375.1[f]	6,208.0[f]	7,244.9[f]	7,827.4[f]
Okra	7,894.3[c]	7,994.0[a]	7,142.68[c]	6,727.2[c]	9,373.6[c]	7,635.4[c]
Carrots	3,711.3[d]	3,451.5[d]	3,923.9[d]	3,913.0[d]	4,120.2[d]	3,885.8[d]
Potato	3,916.0[a]	4,996.0[a]	4,159.0[a]	5,975.7[c]	8,494.2[c]	6,908.0[a]
Dray onion	4,485.0[c]	5,089.3[c]	4,188.6[c]	5,641.8[c]	4,899.8[c]	2,289.9[c]
Melon	5,848.0[a]	7,926.3[c]	6,796.3[c]	6,114.7[c]	6,434.5[c]	6,182.6[c]
Watermelon	5,848.0[a]	7,926.3[c]	6,796.3[c]	6,114.7[c]	6,434.5[c]	6,182.6[c]
other Vegetable (OF)	5,601.8[e]	6,406.3[e]	5,859.5[e]	5,972.1[e]	6,866.2[e]	5,902.1[e]
Other Vegetable (GH)	3,361.1[f]	3,843.8[f]	3,515.7[f]	3,583.3[f]	4,119.7[f]	3,541.3[f]
Fodder Group						
Alfalfa	26,329.0[a]	25,356.0[a]	28,957.0[a]	25,585.7[c]	28,499.2[c]	26,377.0[a]
Other fodder	15,653.1[c]	17,049.1[c]	14,600.9[c]	16,199.1[c]	20,422.3[c]	13,075.5[c]
Fruits Group						
Dates plum	16,811.0[g]	17,017.0[g]	17,026.0[g]	15,741.0[g]	17,257.0[g]	17,235.0[g]
Citrus	18,016.0[g]	18,640.0[g]	18,152.0[g]	16,802.0[g]	18,324.0[g]	18,324.0[g]
Grapes	12,451.0[g]	12,393.0[g]	13,125.0[g]	12,288.0[g]	14,158.0[g]	13,583.0[g]
Other Fruit	15,759.3[e]	16,016.7[e]	16,101.0[e]	14,943.7[e]	16,579.7[e]	16,380.7[e]

a: the source of ETc is Alamoudi et al. (2010), b: the source of ETc is Al-Gobari et al. (2003),
c: used transfer data model by the author. d: estimated by FAO method by author
e: Average of ETc of the group f: reduced ETc on the open field by 40%
g: Ministry of agricultural and water (1988)

Recall that one of the most critical factors to estimate the net irrigation requirement is the leaching requirement. The purpose of the leaching requirement is to keep the root zone free of salinity problems. Estimating the leaching fraction (LR) requires two equations: equation (3.3) estimates LR with surface irrigation, while equation (3.4) estimates LR with drip irrigation and sprinkler.

$$LR = \frac{EC_w}{5EC_e - EC_w} \times \frac{1}{Le} \tag{3.3}$$

$$LR = \frac{EC_w}{2\ MaxEC_e} \times \frac{1}{Le} \tag{3.4}$$

where LR is the minimum water requirement to leach the soil of salts. EC_erepresents the electrical conductivity of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction (dS/m), EC_e is the electrical conductivity of the soil saturation extract for a given crop (dS/m), $Max\ EC_e$ is the maximum tolerable electrical conductivity of the soil saturation extract for a given crop (dS/m), and Le is leaching efficiency (Al Omran, 2008). However, appliying these equations for low quality irrigation water leads to unusually high LRs in some regions, such as for okra and cucumber in Eastern Province was 0.62 and .36, while the LR for carrots was more than 1. Thus, a standard leaching fraction of 15 percent was adopted for all regions, based on Paranchianakis and Chartzoulakis (2005) in which they said the common leaching fraction recomanded is between 15 and 20 percent.

Then, the net irrigation requirement and gross irrigation requirement are estimated through equations (3.5) and (3.6).

$$IR_n = \frac{CWR}{1 - LR} \tag{3.5}$$

$IR_g = \frac{IR_n}{E}$ where E is the overall efficiency of the irrigation project. (3.6)

The overall efficiency of irrigation was also estimated for each region because there is no data available about the overall efficiency of irrigation in Saudi Arabia. For estimation purposes the efficiency of drip irrigation system is assumed to be 90 percent, the efficiency of sprinkler irrigation system is 75 percent, and the efficiency of surface irrigation system is 60 percent. Then, irrigation efficiency is estimated by the following steps and generalizing the result to all region.

(1) Find the total cropland for the crop from Detailed Result of the Agriculture Census (2015) and the sub cropland for that crop based on the irrigation system.

(2) Calculate the proportion of the cropland base on each irrigation system and multiply it by the irrigation efficiency.

(3) Sum the results above to represent the overall irrigation system for the crop.

Table 3.4 shows the gross irrigation requirement for the six regions. Equation (3.5) is used to calculate applied water, while equation (3.6) is used to calculate the gross irrigation requirement.

Table 3-4 Gross crop water requirements (m3 per hectare)

Crops	Riyadh	Qaseem	Eastern	Tabuk	Hail	Jouf
Cereals Group						
Wheat	14,517.5	8,087.8	8,796.9	6,688.2	6,606.0	6,761.3
Barley	10,221.2	14,012.5	11,468.7	11,116.7	10,806.9	6,658.9
Sorghum	5,657.4	5,877.7	4,849.9	6,146.1	10,299.5	2,499.1
Maize	9,342.7	9,780.3	8,046.4	8,485.3	14,157.8	9,400.0
Millet	-	-	-	-	-	-
Sesame	-	-	-	-	-	-
Other Cereal	7,628.2	6,388.4	7,704.4	8,026.5	10,633.9	4,921.5
Vegetables Group						
Tomato (OF)	8,971.3	8,710.3	7,216.0	6,101.9	6,729.9	5,283.3
Tomato (GH)	4,690.2	4,553.7	3,772.5	3,190.1	3,518.4	2,762.1
Eggplant	7,823.4	8,310.3	7,771.3	6,783.8	7,951.1	7,893.0
Squash (OF)	6,865.9	6,697.7	5,455.3	6,606.4	11,311.7	3,688.1
Squash (GH)	3,441.2	3,356.9	2,734.2	3,311.1	5,669.4	1,848.5
Cucumber (OF)	15,163.4	16,973.4	18,551.7	13,273.5	18,224.3	16,735.9
Cucumber (GH)	7,879.9	8,820.5	9,640.7	6,897.8	9,470.6	8,697.1
Okra	17,132.4	17,348.7	15,501.1	12,409.6	20,342.6	14,084.8
Carrots	7,099.5	6,602.6	7,506.3	6,362.7	7,881.8	6,318.4
Potato	6,065.1	7,737.8	6,441.5	7,866.9	13,155.8	9,094.3
Dray onion	7,080.7	8,034.6	6,612.7	7,570.9	7,735.4	3,072.9
Melon	9,229.9	12,510.1	10,726.7	8,203.3	10,155.7	8,294.4
Watermelon	9,178.2	12,440.0	10,666.6	8,157.3	10,098.8	8,247.9
other Vegetable (OF)	9,579.0	10,954.6	10,019.7	8,680.4	11,741.2	8,578.6
Other Vegetable (GH)	4,393.6	5,024.5	4,595.7	3,981.4	5,385.3	3,934.7
Fodder Group						
Alfalfa	41,300.4	39,774.1	45,422.7	34,114.3	44,704.6	35,169.3
Other fodder	24,553.9	26,743.7	22,903.4	21,598.7	32,035.0	17,433.9
Fruits Group						
Dates plum	29,611.7	29,974.5	29,990.4	23,567.9	30,397.3	25,804.8
Citrus	31,461.0	32,550.7	31,698.5	24,939.9	31,998.9	27,199.1
Grapes	21,743.0	21,641.7	22,920.0	18,239.6	24,723.9	20,161.8
Other Fruit	27,520.2	27,969.6	28,116.9	22,181.5	28,952.8	24,314.5

3.5. Farm Revenue

The farm's revenue function for each crop is represented by equation (3.7). In the equation, TR_{cjr} represents the total revenue per hectare of crop c using j farm types (open field or green house), while *r* represents a region. P_{cr} is the price of output per ton, while Y_{cjr} represents the actual crop yield per hectare of crop c using j farm type, for region r.

$$TR_{cjsr} = P_{cr} Y_{cjr} X_{cjr} \tag{3.7}$$

Estimating the total revenue for each region requires the yield and price for each crop. The dissertation used the average crop area and yield for the last five years of available data, which started from 2009 to 2013 (M.O.A, 2014) to determine the planted area and yield for each crop. Also, the price of crops is one of the most critical parameters required in the dissertation. The source of this data is the Ministry of Agriculture and the FAO website. Precisely, the source of the price data for the cereals group and the fodder group was the FAO website, and these prices represent the average import value for six years between 2008 and 2013. The source of price data for the vegetables and the fruits group was the Ministry of Agriculture. These prices reflect the average wholesale price over six-years, between 2009 and 2014. Wholesale price are considered to be a proxy for the farm gate price.

The total production as measured in tons of any crop equals the yield (in tons per hectare) multiplied by the cropland (hectare). Then, the total revenue measured in Sadi arabian rials (SAR) equals the total production (ton) of the crop multiplied by the price of the crop (SAR/Ton). Thus, table 3.6 shows the prices of the crops for all regions for all the crops and the total revenue for each region.

3.6. Regional Model

The model assumes the farmer aims to maximize t profit, for that, s/he asks how many hectare in region r using farm technology type j should be planted with crop c, which it is X_{rjc}. Also, the farmer faces a limited amount of cropland and irrigation water in region r. The next sections provide the model that answers the objective above.

3.6.1. Objective Function of the Model

The objective function describes the annual profit of the farm or region, which is maximized by selecting the optimal crop production pattern. Equation (3.8) shows the objective function where Z_r is the farmers' profit in the region r. R_{cjr} is the coefficient vector of net return per hectare (without the presence of policy) and, the decision variable X_{cjr} is the area of crop c under farm type j, and r represent a region. The second term of the objective function Pol_r represents the agricultural policy, where, Pol_r could be a tax charged per ton of production, or it could be a per ton subsidy.

$$Max\ Z_r = \sum_j^J \sum_c^C (R_{cjr} - Pol_r)\, X_{cjr} \tag{3.8}$$

To measure the net return $R_{cjr} = P_{cr}Y_{cjr} - c_{cjr}$, which is equal to the total revenue minus the total cost. The total revenue equals the price of crop c in region r multiplied by the yield (ton per hectare), Y_{cjr} of crop c under farm type j in region r. The crop production cost per hectare is another crucial parameter the model requires. Most of the cost data comes from a study presented to the Riyadh Economic Forum in the fourth session in December 2009. The title of the study is “water and food security and sustainable development.” One element the study provided was the average cost of producing per ton of crops, such as grain, feed, and fruit, while the average cost per tons for vegetables was differentiated between greenhouses and field production.

The average cost of production per ton and per hectare used in the analysis is shown in Table 3.6. The average cost per hectare is estimated by multiplying the yield (ton per hectare) by the cost per ton. However, there are some crops where the average cost of production was not available in the 2009 study, such as for open field and greenhouse production of other vegetables, other cereals, other fruits, and carrots. For these, the average production cost of the group was used. Also, the average cost of production of tomatoes in the Riyadh region under greenhouse seems to be overestimated when compared to another study. For instance, Al-Abdulkader estimated the enterprise budget of some greenhouse vegetable crops in Saudi Arabia, and he estimated the total cost of production of tomatoes to be SAR. 175,374.09 per ton. Then, by assuming the yield of tomatoes is 81.3 ton per hectare, the average cost of production is SAR. 2,157.12 per ton. Also, Al-Kahtani and Ismaiel (1997) estimated the total, average and marginal cost function for tomatoes. They found, the average cost for a quantity of 81.3 tons is 2,391.09. The cost estimate of both studies is close to each other. Given this, the dissertation adopts the Al-Kahtani and Ismaiel (1997) estimates.

3.6.2. Constraints

The model has three primary types of constraints: cropland constraints, water availability and an aggregate constraint. The model has two cropland constraints. The first is cropland availability that is shown in equation (3.9). This constraint limits farmland availability, so that the sum of the area of the various enterprises X_{cjr} selected by farmer cannot exceed the available cropland given by A_r. Cropland availablity is estimated by the average cropland available between 2009 and 2013 for each region. Equation (3.10) blocks changes in the area of perennial crops, which are Dates, Citrus, Grapes and Other Fruit because the study assumes that moving from perennial crops to non-perennial crops or moving from non-perennial crops to perennial crops requires a long time interval that is beyond the scope of the dissertation. $\bar{X}_{cjr}$ represents the amount of cropland of the perennial crops and it is determined by the average cropland for five years.

$$\sum_j^J \sum_c^C X_{cjr} \leq A_r \tag{3.9}$$

$$X_{cjr} \leq \bar{X}_{cjr} \quad \text{(Constraint for perennial crops)} \tag{3.10}$$

The water constraint is shown in equation (3.11), which represents the water availability in region *r*. W_{cjr} is a parameter which represents the gross crop water requirement (GWR) for crop *c* under farm type j while W_{0r} represents the availblilty of water in region *r*. This equation limits the amount of irrigation water availble in the region and cannot be exceeded. The value for irrigation water availbility is initially determined by multipling the gross water requirement per hectare for each crop by the cuurent cropland for that crop and summing the result for all crops for each region.

$$\sum_j^J \sum_c^C X_{cjr} W_{cjr} \leq W_{0r} \tag{3.11}$$

Table 3.5 shows cropland availability, irrigation water availability and the perennial crops for each region.

Additionally, the study may suffer from aggregation error because it treats each region as a single farm, while in reality in a region farms are both numerous and heterogeneous in structure and size. Farms are not homogenous, because they have differences in the type of soil, the level of technology used, experience, and in access to capital. To this end, using aggregate data for region can result in an unrealistic solution. To develop a more appropriate solution, Onal and McCarl (1989) offer a method using aggregate data that enables the elimination of aggregation error. Equation (3.12) accounts for the aggregation constraint. This restriction imposes crop production activities to fall into a convex combination of historical crop mixes (Onal and McCarl, 1991, Kahil, et al., 2015). For that, there is no way the farmers have a single crop solution. h indicates the number of years, and α_h represents the weight assigned to each year of the crop mix observation. Equation (3.10) represents the standard non-negative constraints.

$$X_{cjr} = \sum_h \alpha_h X_{cjhr} \; ; \sum_h \alpha_h = 1 \; ; \alpha_n \geq 0 \tag{3.12}$$

$$X_{cjr} > 0 \tag{3.13}$$

By using an approach based on the work of Onal and McCarl (1989) that resolves aggregation error, the model does not suffer from the heterogeneity problem.

3.7. National Model

The national model assumes the Saudi government has two potentially conflicting objectives: to reduce the total demand for irrigation water and to achieve an acceptable level of food security. The model uses total revenue from crop production as a proxy to measure food security. Although the government has other objectives, such as, increasing farmers' income, increasing the contribution of the agricultural sector to GDP, diversifying teh rurla economy and minimizing the government expenditure on the agricultural sector; the dissertation focuses on the two objectives as the government's objectives.

The food security objective has a positive relationship with total irrigation water used, so increasing the level of food security requires an increase in the consumption of irrigation water. As a result, there is also a potential conflict between the government's objective and the farm's objective. The government looks to maximize the total revenue to maximize the value of food production, while the farm's objective is to maximize profit.

The law in Saudi Arabia states that all the natural resources under the ground are owned by the country and managed by the government. Therefore, there is an unwritten contractual relationship between the government and farmers when using groundwater resources. The government expects that when it lets farmers use groundwater that farmers will help to achieve the acceptable level of food security and will use the irrigation water in ways that minimize the use of irrigation water. However, the farmers have their objectives, which is maximizing the profit and farmers do not pay for the water they use. Consequently, the Saudi government faces at Principle-Agent problem because objectives of the two parties are not aligned the government allows farmers to use the groundwater with the expectation they will act in ways that satisfy its objectives, while the farmers will use the water to maximize their profit.

To model this relationship where two parties have different objectives that are linked through behavior a bi-level, multi-objective, multi-follower structure is used.

In the national model, the leader is the government, and it aims to minimize the total irrigation water used by allocating some given quantity of irrigation water among the regions (farms) in a way that can satisfy a specific total revenue constraint. Each farm can then use no more than its allocated quantity of irrigation water to maximize its profit. However the profit maximizing crop choice is unlikely to satisfy the government's total revenue objective. The next section provides the theoretical model, the empirical model and the two algorithms that are used to solve the bi-level, multi-objective, multi-follower optimization problem.

3.7.1. Theoretical Model

3.7.1.1. General Formulation of Bi-level Programming Problem (BLPP)

According to Bard (1988) and Colson *et al.* (2007), a Stackelberg type game is the starting point to solve a bi-level programming problem. The basic framework of a Stackelberg game considers the case of a single leader (upper-level decision maker) and a follower (lower level decision maker), or multiple-followers. Each of the leader and follower(s) has a strategy. Suppose, the leader has the strategy $x \in X \subseteq \mathbb{R}^{n1}$ where x is the decision vector that is an element of set $X \subseteq \mathbb{R}^{n1}$. On the other hand, each follower individually has a strategy set Y_p where the follower selects $y_p(x)$ to optimize its objective where $y_i \in Y_i \subseteq \mathbb{R}^{n2_i}$ where *i*=1, 2… I is the number of followers. The objective of the leader is denoted as $F(x, y)$ while the follower's objective is $f_i(x, y_i)$. Assume the leader goes first and selects *x* to optimize the objective function $F(x, y(x))$, where $y(x)$ shows the leader's problem is implicitly the y variable. Therefore, the follower observes *x*, then optimize their objective function $f_i(x, y_i)$ subject to follower constraints for the value of x chosen. The general formulation of the bi-level programming problem is given in Definition 3.1.

Definition 3.1 based on Bard (1988) and Colson *et al.* (2007) for $x \in X \subseteq \mathbb{R}^{n1}, y \in Y \subseteq \mathbb{R}^{n2}$, $F: X \times Y \to \mathbb{R}$, and $f: X \times Y \to \mathbb{R}$, the general bi-level programming problem defined as:

$$min_{x \in X, y}\ F(x, y) \qquad \text{(Leader)} \qquad (3.14)$$

subject to $G(x, y) \leq 0\}$,

where for each *x* given by the upper level, *y* solves the lower level problem:

$$min_y f(x, y) \qquad \text{(Follower)}$$

$$\text{subject to} \quad g(x, y) \leq 0$$

where the decision variables for the leader and follower are *x* and *y* respectively. The functions F and f are the leader and follower objective function respectively. Similarly, the vector valued functions $G: \mathbb{R}^{n1} \times \mathbb{R}^{n2} \to \mathbb{R}^{m1}$ and $g: \mathbb{R}^{n1} \times \mathbb{R}^{n2} \to \mathbb{R}^{m2}$ are the leader and follower respective constraints.

Definitions 3.2 Bard (1988), Colson *et al.* (2007) and Zhang *et al.* (2015)

a) Constraint region of bi-level linear programming problem (BLPP)

   $S = \{(x, y): x \in X, y \in Y, G(x, y) \leq 0\ and\ g(x, y) \leq 0\}$

b) Projection of the constraint region onto Leader's decision space

   $S(X) = \{x \in X: \exists\ y \in Y, G(x, y) \leq 0\ and\ g(x, y)\}$

c) Follower's feasible region for $\bar{x} \in X$ fixed

   $P(\bar{x}) = \{y \in Y: g(\bar{x}, y) \leq 0\}$

d) Follower's rational reaction set for $x \in S(X)$

$R(\bar{x}) = \{y \in Y: y \in argmin\{f(\bar{x}, \hat{y}): \hat{y} \in P(\bar{x})\}\}$

e) Inducible region or feasible region of the leader

$IR = \{(x, y): x \in S(X), y \in R(x)\}$

Also, Bard (1988) has the following assumption to ensure the problem above has an optimal solution.

Assumption 1. S is nonempty and compact.

Assumption 2. The follower has some room to respond to the leader's decision, $R(x) \neq \emptyset$

Assumption 3. $R(x)$ is a point to point map with respect to *x*.

3.7.1.2. Bi-level multi-follower programming problem (BLMF)

The bi-level programming problem, described above, has a single leader and follower with independent objectives. However, in the real world, the leader's decision is often affected by the objectives and choices of many follower decision. Therefore, each follower has his or her reaction to the leader's choices. Also, the leader's decision is influenced by the relationship among the followers, and the relationship among followers may vary. The followers may share decision variables or have a common objective function or share the constraints. Also, they may have a combination of several elements such as each follower has individual decision variables and objective function but they share the constraints. Therefore, Zhang *et al.* (2015) explain the main kinds of the relationship among followers, which is determined by the form of sharing of decision variables and these relations are provided by Lu *et al.* (2006):

(1) Uncooperative situation: in this situation the followers are not sharing of decision variables between them. In other words, the followers do not share the objective function and constraints.

(2) Cooperative situation: in this situation the followers share the decision variables. So, the followers share the decision variables on objective function and constraints.

(3) Semi-cooperative situation: in this situation, the followers share the decision variables, therefore they may share objective function, but they do not share the decision variables on constraints, on vice versa.

(4) Reference-uncooperative situation: in this situation the followers have individual decision variables, but each follower takes other followers variables as a reference when s/he makes the decision.

Also, Zhang *et al.* (2015) and Lu *et al.* (2012) provide concepts that reflect the features of Bi-level Multi-follower (BLMF) programming problem. These concepts identify and classify the BLMF as the following:

(1) Neighborhood entities: two decision entities are at the same level and led by the leader.
(2) Cooperative entities: two neighborhood entities share their decision variables, objective functions, and constraints.
(3) Semi-cooperative entities: two neighborhood entities share their decision variables, but each entity has own objective function and constraints.

(4) Uncooperative entities: two neighborhood entities have individual decision variables, objective function, and constraints.

(5) Reference-uncooperative entities: two neighborhood entities have individual decision variables, objective function, and constraints but consider others' decision as a reference. For example, there are two followers (A) and (B). Each follower has own decision variables, objective function, and constraints but A looks to B decision variable as a reference to determine its decision variables. For that, B's decision variables may show into A's objective function or constraints.

The dissertation assumes the relationship between followers is uncooperative in which followers have individual decision variables, objective functions, and constraints. The following section provides the general formulation of bi-level programming with uncooperative multi-followers. The general framework of the bilevel multi-follower programming problem with an uncooperative situation can be defined as Definition 3.3.

Definition 3.3 (Bard, 1988 and Zhang *et al.* 2015) for $x \in X \subseteq \mathbb{R}^{n1}$ and $y_i \in Y_i \subseteq \mathbb{R}^{n2_i}$, $i=1, 2, 3, \ldots, I$, the general bi-level programming problem with multi-follower defined as:

$min_{x \in X, y}\ F(x, y)$ (leader)

(3.15)

Subject to $G(x, y) \leq 0\}$,

Where for each x given by the upper level, y_i solves the lower level problem

$min_{y_i} f_i(x, y_i) \quad where\ i = 1,2, \ldots, I$ (Follower i)

Subject to $g_i(x, y_i) \leq 0$

Where x and y_i are the decision variables of the leader and follower (i) respectively, $i \geq 2$ is the number of the follower. The function $F: \mathrm{X} \times Y_1 \times \dots . \times Y_I \to \mathbb{R}$ and $f_i: \mathrm{X} \times Y_1 \times \dots . \times Y_I \to \mathbb{R}$ are the leader and follower objective function respectively. The vector valued functions $G: \mathbb{R}^{n1} \times \mathbb{R}^{n2_1} \times \dots . \times \mathbb{R}^{n2_I} \to \mathbb{R}^{m1}$ and $g: \mathbb{R}^{n1} \times \mathbb{R}^{n2_1} \times \dots . \times \mathbb{R}^{n2_I} \to \mathbb{R}^{m2_i}$ are the leader and lower constraints respectively.

So, for each value of x given by the leader, the follower will react by choosing the value of its decision variable y_i under its constraints. In turn, the leader will be affected by the followers' selection. Therefore, the model assumed the leader has full information about the followers' behavior and understands their rational reaction set, $R(x)$. Thus, solution concepts can be defined as Definition 3.4:

Definition 3.4 (Zhang *et al.* (2015), Bard (1988) and Colson *et al.* (2007))

a) Constraint Region of bi-level linear programming problem (BLPP)

   $S = \{(x, y_1, \dots, y_I) \in \mathrm{X} \times Y_1 \times \dots . \times Y_I : G(x, y) \leq 0 \; and \; g(x, y) \leq 0, i = 1,2, \dots, I\}$

b) Projection of constraint region onto Leader's decision space

   $S(X) = \{x \in X : \exists \; (y_1, \dots, y_I) \in Y_1 \times \dots . \times Y_I, (x, y_1, \dots, y_I) \in S\}$

c) Follower i's a feasible region for $\bar{x} \in X$ fixed

   $P_i(\bar{x}) = \{y_i \in Y_i : g_i(\bar{x}, y) \leq 0\}$

d) Follower rational reaction set

   $R_i(\bar{x}) = \{y_i \in Y_i : y_i \in argmin\{f_i(\bar{x}, y) : y \in P_i(\bar{x})\}\}$

e) Inducible region or feasible region of the leader

$IR = \{(x, y_1, \dots, y_I) : x \in S(X), y_i \in R_i(x), i = 1, \dots, I\}$

Where the assumptions are;

Assumption 1. S is nonempty and compact.

Assumption 2. $R(x) \neq \emptyset$

Assumption 3. $R_i(x)$ is a point to point map with respect to *x*.

3.7.1.3. Bi-level multi-objective multi-follower programming problem (BLMOMF)

3.7.1.3.1. THE BASIC CONCEPT IN MULTI-OBJECTIVE OPTIMIZATION

In reality, the decision-maker faces a multi-objective situation, and these objectives could be complementary, conflicting, or independent. Therefore, the decision-maker faces a difficult-to-solve problem. If the decision-maker solves each objective subject to the constraints, the base solution of each problem can optimize one objective, but the others will not be optimized. So, a multi-objective programming problem has no unique solution, but there will be a set of solutions, and the best solution depends on the preferences of the decision-maker. Thus, a multi-objective optimization problem formulates in general as follows:

$$Max\ F(\boldsymbol{x}) = [\ f_1(x), f_2(x), \dots, f_P(x)] \tag{3.15}$$

Subject to

$g_i(x) \leq 0$ where *i*=1, 2, 3… m , $x_i \geq 0$

Based on Cohon and Marks (1975), and Yamashita *et al.* (2016): $F(\boldsymbol{x})$ a vector of P objective is a function $f_p(x)$ where p *=1,..,P*, Function $g_i(x) \leq 0$ represents the constraints of the problem, $x \in X \subset \mathbb{R}^n$ is a vector of decision variables where n is the number of independent variables x_i , X represents the feasible decision space and is defined as

$X = \{x: g_i(x) \leq 0, x_i \geq 0\}$,

Also, the feasible objective space Z is mapping from the feasible decision space through implies each value of $x \in X$ into $f_p(x)$, and then Z defined on the *p*-dimensional vector space,

$Z = \{z: z = F(x), x \in X\}$.

Definition 3.4 (Marler and Arora, 2004) the feasible solution $x^* \in X$ is Pareto optimal for decision maker if and only if there does not exist another solution. $x \in X$, such as$F(x) \leq F(x^*)$, and $F_p(x) \leq F_p(x^*)$ for at least one function.

Definition 3.5 (Marler and Arora, 2004), Weakly Pareto optimal point: a point, $x^* \in X$, is weakly optimal if and only if there does not exist another point, $x \in X$, such that $F(x) < F(x^*)$.

Solving a multi-objective programming problem usually does not provide a single solution, but instead, a set of Pareto Optimal points and these points can be shown to be a feasible objective region. A Pareto Optimal point represents a vector of the decision variable which, if there is no other vector, optimizes some objective function without causing simultaneous negative or positive effects, on at least one other objective function. So, the Pareto Optimal subset that optimizes the value of the objective function represents the set of efficient trade-offs among objectives. This subset could be called a nondominated solution (or Pareto curve, or Pareto front), and all of the points on this curve are strictly or strongly Pareto Optimal. Often, mathematical programming algorithms provide a solution that is not Pareto Optimal, but it may satisfy other criteria and can be considered to be weakly Pareto Optimal. A Pareto Optimal point is a weakly Pareto Optimal point if no other point improves all objective functions simultaneously. In other words, the solution is weakly Pareto Optimal when "there is no other alternative way for resource allocation to make any individual better off" (Cho *et al.*, 2016). Hence, all points on the Pareto curve have an equally acceptable solution for the decision-maker, and the point that the decision-maker selects represents the highest-level preference of the decision-maker. Therefore, the multi-objective optimization problem is classified based on the preferences of a decision-maker regarding three categories: (1) *a priori* Preference approach, (2) Progressive Preference approach, and (3) *a posteriori* Preference approach, Sinha, (2011).

An *a priori* Preference approach can be described as shown in Figure 3.2.a where the decision-maker provide his/her preference before computing the solution. This method assumes that the decision-maker has prior information about his/her preference, how the objectives are interdependent, and the feasible objective values. For instance, the decision-maker could order or rank the objectives from most important to least. For that, Hakanen. *et al.* (2013)[5] mention the properties of this method as follows: (1) There is an accessible path to obtain the preference information through asking the decision-maker directly, and (2) For all possible preferences, the solution found is Pareto Optimal. (3) Each Pareto Optimal solution can be found with some preference. However, no approach

[5] The main reference is a lecture in http://users.jyu.fi/~jhaka/uppsala/

satisfies all of the above properties. On the other hand, this method faces some problems, such as (1) The decision-maker may not know the feasible region, (2) The decision-maker may not know or understand his/her preferences very well, and (3) This method has no feedback, and there is a possibility that the best solution could be missed. Also, this approach features a group of techniques such as the Weighted Sum, Utility Theory, Fuzzy Logic, Goal Programming, and Lexicographic approaches (Andersson, 2000).

The second method shown in Figure 3.2.b describe the Progressive Preference approach. The technique of this method operates in three stages: (1) Find the Pareto front where there is no a priori preference information. (2) The decision-maker provides a reaction regarding the Pareto front and modifies the preference for the objectives. (3) Repeat the two previous steps until the decision-maker is satisfied (Chiandussi *et al.*, 2012). The advantage of this method is that no prior preference information is required, and the preference develops from learning. On the other hand, the solutions depend on the decision maker's preference, and when the preference changes, the solutions also change. Thus, all of these methods would solve the multi-objective optimization problem and would provide a Pareto Optimal solution, but the main difference lies in how the decision-maker affects the Pareto Optimal outcome.

The third method is the *a posteriori* Preference approach is shown in Figure 3.2.c where the decision-maker searches for the solution space and then makes the decision. With this method, the decision maker's preference is independent of the solution. Hence, the decision-maker will get a set of Pareto Optimal outcomes that do not change, since there is no change in the problem description. In contrast, the decision-maker would face a large selection of possible solutions, and it could be difficult to choose the best one.

Another disadvantage is that some of the approaches need significant computational resources. A *posteriori* Preference approach offers a set of approaches to find out the solution, and Andersson (2000) divided this method into two parts: multiple-run approaches and multi-objective genetic algorithm. The current study focuses on multiple-run approaches such as weighted sum approaches and the ε-constraint approach. Solving these approaches provides a set of points on the Pareto Optimal front. The dissertation uses a *posteriori* Preference approach since there is no available preference information for the decision-maker.

Figure 3.2a: A priori Preference approach

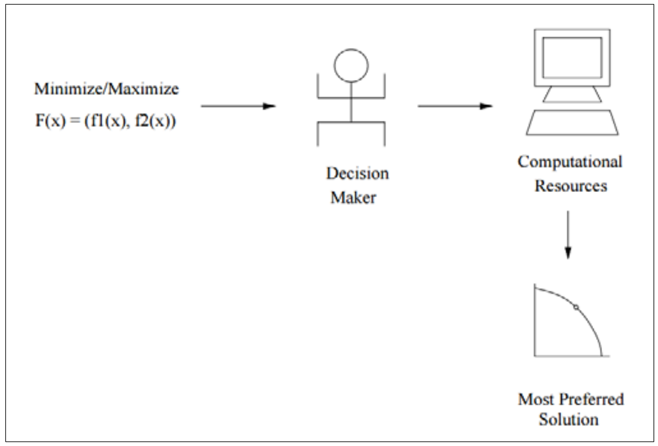

Figure 3.2.b: Progressive Preference approach

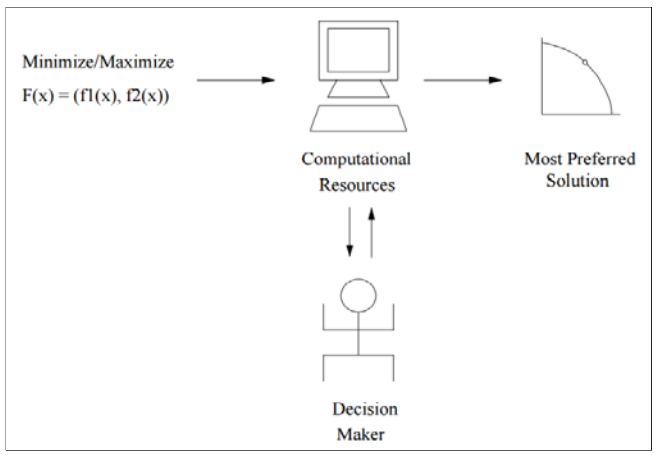

Figure 3.2.c: posterior Preference approach

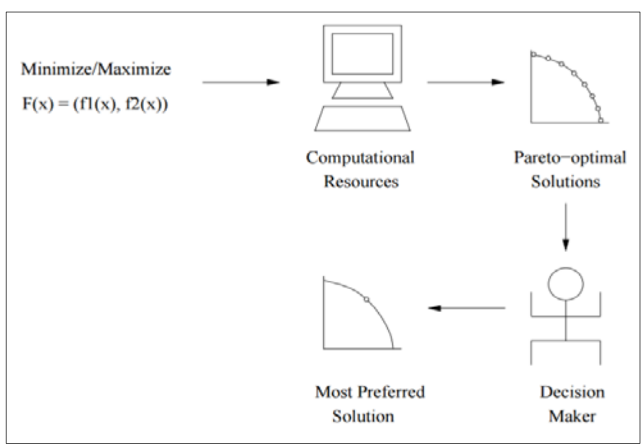

Figure 3-2 How decision maker under multi-objective chooses the decision
Source: Sinha, A. (2011).

3.7.1.3.2. *THE BASIC CONCEPT OF BI-LEVEL MULTI-OBJECTIVE MULTI-FOLLOWER PROGRAMMING PROBLEM (BLMOMF)*

This section provides the general formulation for a bi-level multi-objective leader with multi-followers who have a single objective. The general framework of BLMOMF problem follows Definition 3.6

Definition 3.6 for $x \in X \subseteq \mathbb{R}^{n1}$ and $y_i \in Y_i \subseteq \mathbb{R}^{n2_i}$, *i=1, 2, 3, …,I* , the general bi-level programming with multi-objective and multi-follower problem defined as:

$$min_{x \in X, y}\ F(x, y) = \left(F_1(x, y), F_2(x, y), \dots, F_p(x, y)\right)\ where\ p = 1,2, \dots, P \text{(Leader)} \quad (3.16)$$

Subject to $G(x, y) \leq 0\}$,

Where for each x given by the upper level, y_i solves the lower level problem

$$min_{y_i} f_i(x, y_i) \quad where\ i = 1,2, \dots, I \qquad \text{(Follower } i\text{)}$$

Subject to $g_i(x, y_i) \leq 0$

Where x and $y = y_1, \dots, y_I$ are the decision variables of the upper level decision maker and lower level (i) decision maker respectively, i is the number of the follower. The function $F_p: \mathbb{R}^{n1} \times \mathbb{R}^{n2_1} \times \mathbb{R}^{n2_2} \times \dots . \times \mathbb{R}^{n2_I} \rightarrow \mathbb{R}$ and $f_i: \mathbb{R}^{n1} \times \mathbb{R}^{n2_1} \times \mathbb{R}^{n2_2} \times \dots . \times \mathbb{R}^{n2_I} \rightarrow \mathbb{R}$ are the upper level and lower level objective function respectively, where p is the number of the objective function of the upper level. The vector valued functions $G: \mathbb{R}^{n1} \times \mathbb{R}^{n2_1} \times \mathbb{R}^{n2_2} \times \dots . \times \mathbb{R}^{n2_I} \rightarrow \mathbb{R}^{m1}$ and $g: \mathbb{R}^{n1} \times \mathbb{R}^{n2_1} \times \mathbb{R}^{n2_2} \times \dots . \times \mathbb{R}^{n2_I} \rightarrow \mathbb{R}^{m2_i}$ are the upper level and lower level constraints respectively.

Definition 3.6 (Zhang *et al.* (2015), Bard (1988) and (Xu, *et al.*, 2016)

a) Constraint Region of bi-level linear programming problem (BLPP)

$S = \{(x, y_1, \dots, y_I) \in \mathrm{X} \times Y_1 \times \dots . \times Y_I : G(x, y) \leq 0 \; and \; g(x, y) \leq 0,$

$i = 1,2, \dots, I\}$

b) Projection of constraint region onto Leader's decision space

$S(X) = \{x \in X : \exists \; (y_1, \dots, y_I) \in Y_1 \times \dots . \times Y_I, (x, y_1, \dots, y_I) \in S\}$

c) Follower i's a feasible region for $\bar{x} \in X$ fixed

$P_i(\bar{x}) = \{y_i \in Y_i : g_i(\bar{x}, y) \leq 0\}$

d) Follower rational reaction set

$R_i(\bar{x}) = \{y_i \in Y_i : y_i \in argmin\{f_i(\bar{x}, y) : y \in P_i(\bar{x})\}\}$

e) Inducible region or feasible region of the leader

$IR = \{(x, y_1, \dots, y_I) : x \in S(X), y_i \in R_i(x), i = 1, \dots, I\}$

So, the final step is to search about Pareto Optimal solution in the inducible region and that defined in definition 3.7:

Definition 3.7 (Xu et al., 2016) (x^*, y^*) is a Pareto optimal solution if and only if there exists on other $(x, y) \in IR$ such that $F_p(x, y) \geq F_p(x^*, y^*)$ for all p = *1,2,…,*P with strict inequality for at least one *p*.

3.7.1.3.3. SOLVING THE BI-LEVEL MULTI-OBJECTIVE WITH MULTI-FOLLOWER PROGRAMMING PROBLEM (BLMOMF)

The dissertation focuses on multiple run approaches, such as weighted sum, ε-constraint approach. Solving these approaches obtains a set of efficient solutions and there is a subset point of the Pareto Optimal front.

The ε-constraint method is one of the simplest approaches and could be one of the most widely used to optimize the multi-objective problem. The main goal of this method is to transfer the multi-objective optimization problem into a single-objective optimization problem through the decision-maker keeps only one objective and reformulated the rest of objective as constraints. In other words, the other objective functions are incorporated into the constraints as shown below:

$Min\ Max\ f_1(x,y)$ (Leader problem) (3.17)

Subject to

$f_j(x,y) \geq e_j$ where j=2, 3, … p

$g_i(x,y) \leq 0$ where i=1, 2, 3… m

$min_{y_i}\ f_i(x,y_i)$ $where\ i = 1,2,\ldots,I$ (Follower problem)

Subject to $g_i(x,y_i) \geq 0$

The leader has one prime objective, and the rest of the objectives became constraints. So, the right-hand side of the leader constraints represents by (e_i) which is the efficient solutions or the leader optimization objectives of the problem. By changing the constraint values, e_j, and running the problem mulitple times provides different points that are optimal. Therefore, this method could be used for non-convex multi-objective optimization problesm. However, this method has some disadvantage, such as: the solution of this probem depends on the range of the e_j value, where the $e_j$value range lie between the minimum and maximum value of each objective function, Also, the decision-maker needs more information for choices of e_j ,where increasing the number of objectives that are reformuated as constriants.

Also, Mavrotas (2009) finds the ε-constraint approach has some advantage over the weighting approach. Such as, the weighting approach involves scaling the objective function and that influences the result, while the ε-constraint approach does not require scaling the objective function. Also, the user in the ε-constraint approach “can control the number generated efficient solutions by properly adjusting the number of grid points in each one of the objective function ranges. This is not so easy with the weighting method”.

The dissertation uses the ε-constraint method because it is the simplest method and the focus of the dissertation is on developing a model that could help decision-makers in Saudi Arabia reach an acceptable level of total revenue while reducing water use in agriculture without imposing extra conditions on the nature of the objective function.

3.8. Empirical model

The model used in this dissertation assumes there are two levels of decision makers and each decision maker on each level tries to optimize its objectives. Therefore, the model contains seven problems. The first problem is the government problem in which the government has two conflicting objectives, which are, minimizing irrigation water used, F_1equation (3.18), and maximizing total return from agricultural production F_2 equation (3.19). To solve the government problem, the model adopts the ε-constraint method where the government aims to minimize irrigation water and uses the second objective as a constraint. The rest of the problems are for each region and apply the regional model where each region (farm) solves its own sub-problem to find the crop pattern that maximizes profit. The government problem starts from equations (3.20) to (3.26), while the sub-problem starts from equations (3.21) to (3.26) which represent the regional model for each region.

Initially, the government solves the master problem to minimize the total irrigation water requirement, equation (3.20), subject to a specific choice for the second objective, which is the maximum of the total revenue, and the farm problem for all regions. GWR_{cjr} represents the average of five years gross water requirement of crop c per hectare under j farm type in region r. Y_{cjr} represents the average of five years of crop yield production per hectare of crop c under j farm type in region r and X_{cjr} is the decision variable of the area of crop c under farm type j, in region r.

When the government minimizes the total irrigation water used, it also calculates the maximum output that must be produced in each region to satisfy the total revenue constraint. If the total revenue is less than the target (current) level, the government increases the total irrigation water used until the total revenue is greater or equal than the current level. With this water level, the government knows it is technically feasible to produce current total revenue with its chosen quantity of irrigation water. After that, the government assigns irrigation water quantities to each region through equation (3.24) where W_{cjr} is the parameter that determines by the government. The total water availability,W_{0r} is calculated by the government through, $\sum_c^C \sum_j^J GWR_{cjr} X_{cjr}$ which is the summation of all gross crop irrigation requirements for all the crops under the different farm technologies. Farms (regions) then maximize profit subject to the new irrigation water availability through applying equations (3.22) to (3.26), which is the regional model.

Farm output from the six regions may or may not reach the government's total revenue target, because farmers maximize profit while the government focus is on total revenue that is used as a proxy to measure the level of the food security target. If farm production does not satisfy the total revenue constraint, the government has to provide more water or other policies that encourage farmers to satisfy the total revenue constraint. The policies could be subsidies or taxation.

$$Min\ F_1 = \sum_r^R \sum_c^C \sum_j^J GWR_{cjr} X_{cjr} \quad (3.18)$$

$$Max\ F_2 = \sum_r^R \sum_c^C \sum_j^J P_{cr} Y_{cjr} X_{cjr} \quad (3.19)$$

$$Min\ F_1 = \sum_r^R \sum_c^C \sum_j^J GWR_{cjr} X_{cjr} \quad \text{Leader Problem} \quad (3.20)$$

Subject to

$$\sum_r^R \sum_c^C \sum_j^J P_{cr} Y_{cjr} X_{cjr} \geq Total\ Return \quad \text{(Second objective)} \quad (3.21)$$

$$Max\ Z_r = \sum_j^J \sum_c^C (R_{cjr} - Pol_r)\, X_{cjr} \quad \text{Follower problem} \quad (3.22)$$

$$\sum_j^J \sum_c^C X_{cjr} \leq A_r \quad (3.23)$$

$$\sum_j^J \sum_c^C X_{cjr} W_{cjr} \leq W_{0r} \quad \text{where } W_{0r} = \sum_c^C \sum_j^J GWR_{cjr} X_{cjr} \quad (3.24)$$

$$X_{cjr} = \sum_h \alpha_h X_{cjhr}; \sum_h \alpha_h = 1\ ; \alpha_n \geq 0 \quad (3.25)$$

$$X_{ijr} \geq 0, W_{0r} \geq 0 \quad (3.26)$$

3.9. Key assumption of model

To solve the model, there are four main assumption

1. Prices used are accurate representation of prices that farmers face.
2. Crop yield functions are accurate.
3. The aggregation constraints allows sufficient flexibility in crop choice, while satisfying the government's desire for relatively stable levels of output for each crop.
4. Total crop revenue is a reasonable proxy for food security.

3.10. Algorithms for solving the bi-level model

The dissertation provides two algorithms to solve the bi-level, multi-objective, multi-follower problem. The first algorithm is reallocated irrigation water policy (RIWP) while the second algorithm is Integrated Irrigation Water Management Policy (IIWMP).

Figure 3.3 shows the steps of the Reallocated Irrigation Water Policy (RIWP) algorithm. The government minimizes the total irrigation water used among regions by distributing a specific quantity of irrigation water among the regions that it knows is technically enough to satisfy its food security constraint. In this approach the government implicitly assumes that there is no PA problem between its objectives and the region objectives. First the government optimizes its objective function by minimizing the total irrigation water subject to, achieving the desired total revenue level and the constraints of all six regional models. Then the government determines the quantity of irrigation water available for each region. Based on the government's water allocation, each farm will maximize profits subject to the new irrigation water availability and other constraints. The algorithm operates only by reallocating the quantity of irrigation water among the regions to minimize total irrigation water consumption and does not introduce any feedback from farmers' actions. However, farmers' decisions may or may not meet the government's objectives. Farmers will not meet government objectives when a gap exists between the government's and farmers' objectives. Because the two sets of objectives are fundamentally different simply altering the irrigation constraint is unlikely to produce an acceptable outcome for the government. Therefore, the government has to intervene through other policies, such as subsidies or taxation, in addition to reallocating irrigation water.

The second approach to solving the national problem introduces crop and region specific subsidies to align the two sets of objectives. Figure 3.4 shows the IIWMP algorithm that closes the gap between the farmers' objective and the government's objectives. The algorithm starts by solving the government problems to minimize the total irrigation water used in the same way as in the first algorithm. However, if the solution of farmers does not satisfy the government's objectives, the government compares the crop allocations made by farmers to those in its solution and provides appropriate subsidies and taxes alter the relative returns from crops. The government then solves the problem again and reexamines the output choices of farmers, and if needed alters the subsidies and taxes to move the farm (region) choices further toward its desired output mix. The algorithm keeps looping until these policies motivate farmers to adopt the government's objectives and crop mix.

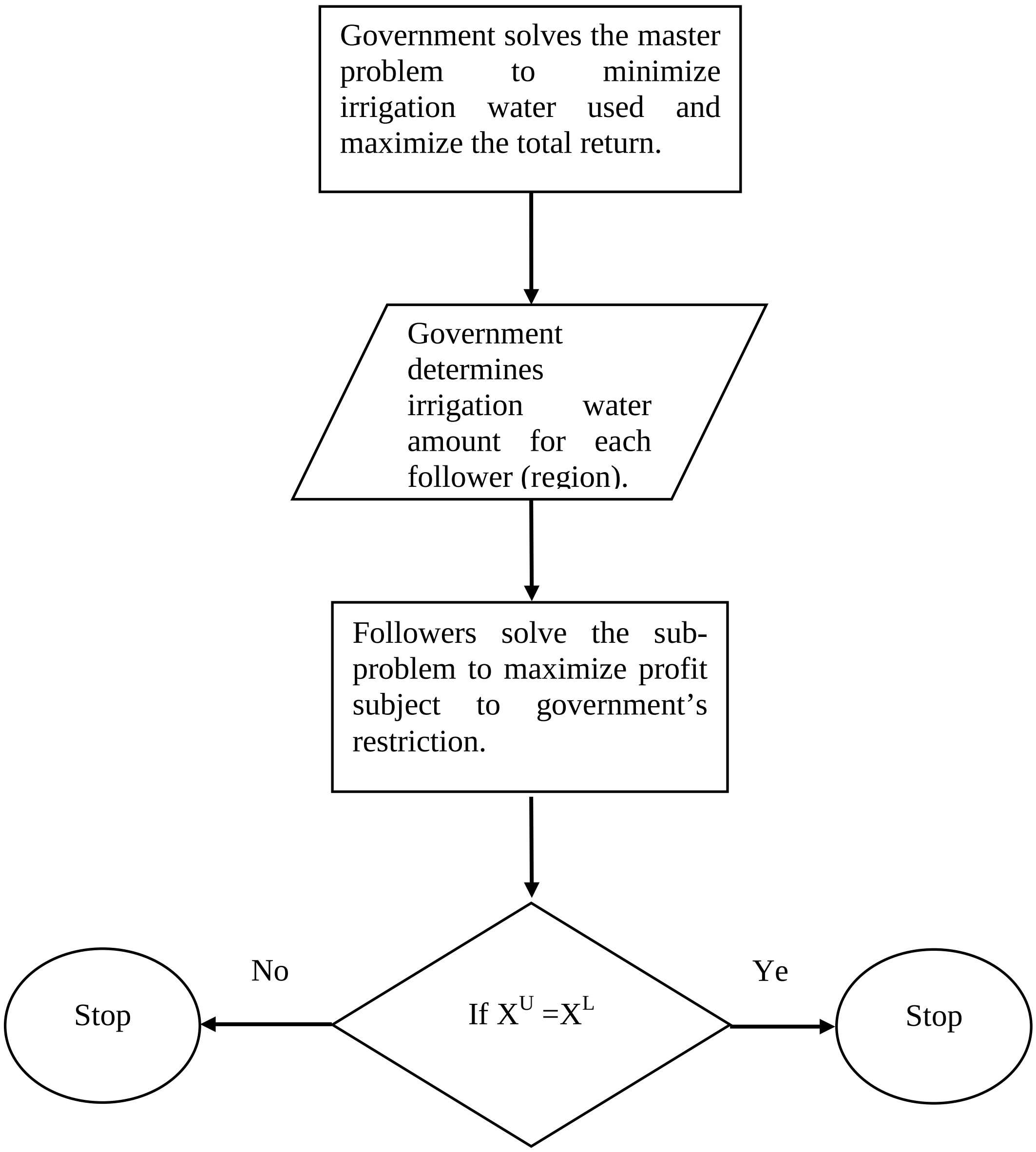

Figure 3-3 Reallocated Irrigation Water Policy Algorithm to solve the bi-level optimization

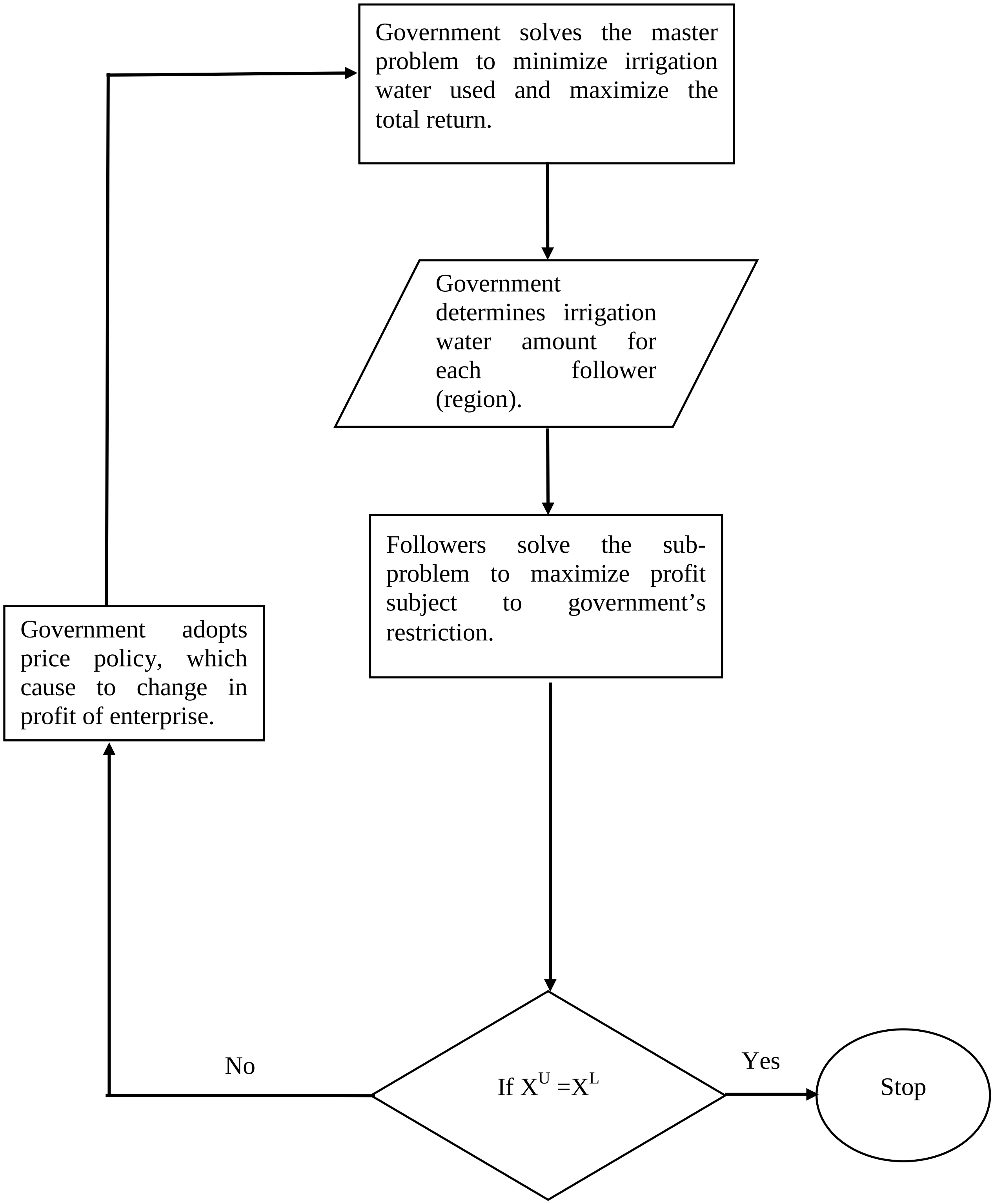

Figure 3-4 Integrated Irrigation Water Management Policy Algorithm to solve the bi-level optimization

Table 3-5 Observed Total Crop Area for the regions under study

	Riyadh		Qaseem		Eastern		Tabuk		Hail		Jouf	
Return(W.P)	9,544,190,906.7		3,674,119,444.1		2,713,291,096.3		963,804,032.7		1,909,263,947.9		1,277,654,214.6	
Profit (W.P)	5,038,510,451.3		2,342,006,328.1		1,754,885,946.9		477,806,680.8		1,152,909,311.0		381,393,061.1	
Cropland used	234,877.4		101,254.4		53,762.2		44,405.8		81,628.2		94,481.2	
Irrigation water	5,814,121,725.4		2,470,307,806.0		991,029,384.9		745,725,539.4		1,641,141,954.0		1,470,900,621.3	
Crops	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**
Wheat	30,646.2	5.1	20,308.6	5.4	25,853.4	4.8	19,486.6	6.4	22,721.8	7.2	49,967.0	7.1
Barley	570.0	6.3	68.2	6.6	113.2	6.3	271.0	7.9	261.0	7.5	646.6	8.5
Sorghum	207.4	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maize	1,852.2	4.5	1,355.0	4.6	120.0	4.1	4.0	3.5	13,422.4	6.2	435.8	5.5
Millet	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sesame	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other Cereal	40.2	3.6	21.4	2.4	182.6	3.9	0.0	0.0	9.0	2.4	13.6	5.0
Tomato	3,735.1	15.3	112.4	20.3	533.5	18.6	534.9	19.9	88.8	19.3	649.5	14.1
Tomato (GH)	1,734.5	81.3	588.4	79.4	598.9	81.4	77.3	92.8	486.6	67.2	114.9	99.9
Eggplant	1,790.4	14.6	159.4	17.4	105.6	20.5	37.2	13.7	236.2	16.6	33.2	17.6
Squash	3,003.0	19.3	892.5	16.9	157.1	15.7	24.7	13.4	380.4	16.5	102.5	16.0
Squash (GH)	21.2	114.0	42.5	98.2	43.1	79.1	41.7	57.7	4.8	101.4	22.1	67.9
Cucumber	191.2	20.5	44.5	16.7	9.0	19.3	18.3	20.4	31.8	20.1	23.5	15.3

Continue table	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**	**Area (ha)**	**Yield Ton/ha**
Cucumber (GH)	1,432.0	87.9	308.9	68.7	192.6	84.1	221.9	102.9	49.6	55.0	61.7	86.4
Okra	1,122.2	14.1	135.6	16.3	183.0	13.9	19.8	11.2	62.0	14.4	88.4	11.4
Carrots	1,680.8	15.8	1,389.0	17.8	12.2	19.6	3.6	20.1	24.4	16.3	74.8	18.4
Potatoes	4,512.6	22.8	3,737.4	23.3	40.8	21.0	1,468.2	26.3	4,843.4	29.1	1,282.6	26.1
Dry Onion	1,091.4	28.1	277.4	23.6	126.0	15.6	351.0	28.1	335.6	23.3	1,188.8	29.2
Melon	10,924.4	19.1	672.2	26.2	150.0	15.6	164.2	24.8	135.4	23.3	31.0	20.1
Watermelon	12,983.6	19.5	981.6	19.6	59.6	15.4	171.0	17.9	3,318.4	24.8	35.8	17.8
Other Vegetables	9,367.4	18.7	2,466.0	22.0	1,358.8	19.1	555.6	18.5	164.5	16.9	77.1	14.9
Other Vegetables	805.2	59.1	66.8	70.3	220.0	120.2	30.2	80.3	14.7	71.9	4.9	106.3
Alfalfa	60,820.0	20.1	19,104.8	21.5	2,695.0	19.2	9,849.6	20.8	8,280.0	21.4	12,603.4	23.1
Other Fodder	33,511.2	20.5	4,683.6	16.4	2,476.6	14.0	581.6	20.0	4,701.4	17.7	510.2	18.3
Dates	42,419.6	6.5	39,140.0	5.1	14,403.8	10.9	3,302.6	6.8	17,214.0	6.0	5,215.0	8.7
Citrus	3,374.4	8.3	1,584.6	6.0	759.2	15.7	1,187.6	13.1	1,441.2	9.4	716.8	7.0
Grapes	2,806.8	11.6	1,662.2	13.0	149.0	30.7	1,227.4	4.8	1,121.2	10.1	1,371.8	15.1
Other Fruits	4,234.4	4.6	1,451.4	8.2	3,219.2	12.3	4,775.8	8.4	2,279.6	7.7	19,210.2	4.1

Table 3-6 wholesale prices of crops, total return, and profit for regions under study

	Riyadh		**Qaseem**		**Eastern**		**Tabuk**		**Hail**		**Jouf**	
Return	9,544,190,906.7		3,674,119,444.1		2,713,291,096.3		963,804,032.7		1,909,263,947.9		1,277,654,214.6	
Profit	5,038,510,451.3		2,342,006,328.1		1,754,885,946.9		477,806,680.8		1,152,909,311.0		381,393,061.1	
Crops	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**
Wheat	1,120[a]	7,155.8[d]	1,120.0[a]	6,383.9[d]	1,120.0[a]	4,646.8[d]	1,120.0[a]	3,748.9[d]	1,120.0[a]	7,097.8[d]	1,120.0[a]	5566.5[d]
Barley	1,115[a]	10,435.4[d]	1,115.0[a]	5,823.9[d]	1,115.0[a]	6,604.0[d]	1,115.0[a]	9,595.3[d]	1,115.0[a]	3,921.4[d]	1,115.0[a]	8337.5[d]
Sorghum	1,880.7[b]	7,600.2[e]	1,880.7[b]	0.0	1,880.7[b]	0.0	1,880.7[b]	0.0	1,880.7[b]	0.0	1,880.7[b]	0.0
Maize	1,101[a]	6,932.8[e]	1,101.0[a]	4,738.8[e]	1,101.0[a]	4,098.4[e]	1,101.0[a]	3,119.1[e]	1,101.0[a]	4,734.2[e]	1,101.0[a]	4836.8[e]
Millet	1,226[a]	-	1,226.0[a]	-	1,226.0[a]	-	1,226.0[a]	-	1,226.0[a]	-	1,226.0[a]	-
Sesame	5,357[a]	-	5,357.0[a]	-	5,357.0[a]	-	5,357.0[a]	-	5,357.0[a]	-	5,357.0[a]	-
Other Cereal	2,506[a]	5,478.4[e]	2,506.0[a]	2,466.1[e]	2,506.0[a]	3,932.3[e]	2,506.0[a]	-	2,506.0[a]	1,852.2[e]	2,506.0[a]	4376.0[e]
Tomato	2,368[c]	22,990.5[d]	3,104.0[c]	12,299.8[d]	3,064.0[c]	13,332.3[d]	2,236.0[c]	8,465.2[d]	2,296.0[c]	2,177.9[d]	2,158.0[c]	21178.5[d]
Tomato (GH)	2,368[c]	247,149.5[f]	3,104.0[c]	285,114.3[d]	3,064.0[c]	54,387.4[d]	2,236.0[c]	28,026.0[d]	2,296.0[c]	22,966.2[d]	2,158.0[c]	71208.8[d]
Eggplant	2,060[c]	12,090.3[d]	2,158.0[c]	7,309.7[d]	2,792.0[c]	18,908.4[d]	1,532.0[c]	10,144.7[d]	2,222.0[c]	3,431.5[d]	2,248.0[c]	3564.2[d]
Squash	3,620[c]	13,619.2[d]	2,800.0[c]	13,333.0[d]	3,878.0[c]	13,721.6[d]	2,380.0[c]	9,199.3[d]	3,392.0[c]	15,840.0[d]	2,588.0[c]	30616.9[d]
Squash (GH)	3,620[c]	157,696.7[d]	2,800.0[c]	296,630.9[e]	3,878.0[c]	76,666.0[d]	2,380.0[c]	250,978.8[d]	3,392.0[c]	158,095.7[d]	2,588.0[c]	41539.8[e]
Cucumber	3,088[c]	9,259.3[d]	2,304.0[c]	7,507.3[d]	2,854.0[c]	16,197.7[d]	2,074.0[c]	13,323.8[d]	2,552.0[c]	17,682.3[d]	2,768.0[c]	2509.3[d]
Cucumber (GH)	3,088[c]	195,322[d]	2,304.0[c]	168,148.7[d]	2,854.0[c]	379,212.6[d]	2,074.0[c]	97,927.8[d]	2,552.0[c]	56,919.5[d]	2,768.0[c]	44125.3[d]
Okra	8,462[c]	21,554.4[d]	6,588[c]	6,933.5[d]	11,706[c]	29,130.6[d]	8,268[c]	6,474.8[d]	7,874[c]	2,388.8[d]	6,694[c]	5143.4[d]
Carrots	2,048[c]	13,369[e]	1,454[c]	8,285.1[e]	3,226[c]	23,425.3[e]	1,720[c]	11,407.4[e]	1,414[c]	9,690.1[e]	2,144[c]	12343.5[e]
Potatoes	1,406[c]	8,567.2[d]	1,218[c]	14,928.3[d]	1,740[c]	9,697.5[d]	1,120[c]	12,772.5[d]	1,304[c]	40,436[d]	1,452[c]	15385.2[d]
Dry Onion	1,590[c]	22,218.4[d]	1,062[c]	7,495.6[d]	1,698[c]	13,636.8[d]	1,748[c]	6,240.4[d]	1,054[c]	2,911.7[d]	1,276[c]	12631.9[d]
Melon	2,658[c]	5,685.7d	1,848.0[c]	7,227.4[d]	2,500[c]	31,076.4[d]	1,865[c]	16,239.4[d]	1,988.0[c]	17,528.2[d]	1,910.0[c]	8126.1[d]
Watermelon	2,728[c]	5,794.4d	1,536.0[c]	5,423.4[d]	2,240[c]	30,703.6[d]	2,914[c]	11,744.3[d]	1,680.0[c]	18,657.0[d]	1,556.0[c]	7206.3[d]
Other Vegetables	4,401[c]	15,810.1e	4,325.3[c]	10,268.5[e]	6,740[c]	22,829.9[e]	4,770[c]	10,484.2[e]	4,359.0[c]	10,033.4[e]	3,956.7[c]	9998.2[e]
Other Vegetables (GH)	4,401[c]	125,502.4[e]	4,325.3[c]	212,180.4[e]	6,740[c]	190,684[d]	4,770.0[c]	47,255.5[e]	4,359.0[c]	70,382.6[e]	3,956.7[c]	65081.1[e]
Alfalfa	1,346[a]	11,228.3[d]	1,346.0[a]	6,229.0[d]	1,346[a]	8,658.5[d]	1,346.0[a]	6,539.9[d]	1,346.0[a]	6,224.6[d]	1,346.0[a]	8777.1[d]
Other Fodder	1,532[a]	28,198[d]	1,532.0[a]	6,590.5[d]	1,532[a]	9,545.3[d]	1,532.0[a]	11,186.5[d]	1,532.0[a]	5,940.6[d]	1,532.0[a]	13267.8[d]

Continue of Table 3.6

	Riyadh		**Qaseem**		**Eastern**		**Tabuk**		**Hail**		**Jouf**	
Crops	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**	**Prices SR/Ton**	**Cost SR/ha**
Dates	9,219[c]	24,350.8[d]	10,122.3[c]	15,555.5[d]	9,451.2[c]	35,359.2[d]	12,094.9[c]	63,061.2[d]	6,017.3[c]	8,335.7[d]	8,859.5[c]	38099.6[d]
Citrus	3,043[c]	30,677.4[d]	2,641[c]	4,038.4[d]	4,841[c]	12,209.3[d]	2,395.8[c]	21,958.3[d]	2,314.0[c]	4,778.3[d]	2,048.3[c]	14857.7[d]
Grapes	5,028[c]	28,328.5[d]	2,641[c]	24,612.9[d]	5,806[c]	17,448.5[d]	2,804[c]	4,049.7[d]	4,772.0[c]	1,725.3[d]	4,680.0[c]	15230.9[d]
Other Fruits	4,928[c]	15,105.2[e]	4,040[c]	15,499.3[e]	5,834[c]	18,834.5[e]	2,810[c]	32,829.8[e]	4,794.7[c]	5,348.4[e]	4,433.3[c]	10219.4[e]

a. The price represents the value of imported price per ton for the period started from 2008 to 2013, and the source of the data is FAO.
b. The price represents the value of imported price per ton for the period started from 2002 to 2007, and the source of the data is FAO.
c. The price represents the whole price per ton for the period starting from 2009 to 2014, and the source of the data is MOA.
d. The source of data is "Water and Food Security and Sustainable Development," 2009.
e. These data are represented as the average of the crop group.
f. An estimate by Al-Kahtani and Ismaiel (1997) equation.

CHAPTER 4. MODEL SCENARIO RESULTS

4.1. Introduction

The chapter covers the primary analysis various model scenarios that were presented in Chapter 3. The first part of the chapter examines how well the regional model replicated the historical crop pattern for Riyadh region. The desired result is that the observed crop pattern and the optimal crop pattern from the model will be similar. However, while the initial results showed general consistency, there were four important crops that were not produced while they are in the current crop pattern. Increasing the price of these crops pushed the model to produce them in amounts that are similar to their historical levels while not causing major reductions in other crops from their historical amounts. This new set of the prices is called, the adjusted prices, and uses observed prices for all but the four crops. The adjusted prices lead to increased total revenue over the base model that used estimated market prices.

The second part of the chapter compares four scenarios that use two different algorithms to help the government to achieve its objectives. The first algorithm is reallocated irrigation water policy (RIWP) where the government relies only on water restrictions as an instrument to alter farmer behavior. The second algorithm is an integrated irrigation water management policy (IIWMP) where the government relies on water restrictions and crop-specific taxes and subsidies to alter farmer behavior. Each algorithm is applied to both the historic market price and adjusted price sets of crop prices.

Initially two pairs of the scenarios are considered. The first pair is RIWP and IIWMP algorithm using estimated market prices, while the second pair is RIWP and

IIWMP algorithm using the adjusted prices. The first pair of scenarios show that if the government only relies on only constraints on irrigation water to align farmers' behavior with governent objectives farmers will not produce enough to satisfy the food security objective. On the other hand, the second pair of scenarios show that if the government introduces a system of crop specific taxes and subsidies, this can lead farmers to produce a level of output that satisfies food security constraint and reduces irrigation water used.

4.2. Results for Riyadh Regional Model

The Riyadh region is the largest administration region in Saudi Arabia, representing around 30 percent of the national agricultural irrigated area on average between 2009 and 2013. The region has several aquifers, and the quality of these aquifers range between not saline to high saline. Falatah *et al.* (1999) find the average water salinity is 3.65 dS m^{-1} and the study adopted their result to calculate the gross irrigation water requirement for the Riyadh region.

The analysis used a five-year average data set to observe current crop patterns. Assuming decision-makers are rational and aim to maximize profits by allocating their limited resources, the results of the observed crop mix suggests that farmers achieved profits of SAR 5.04 billion, consumed 5.8 BCM of irrigation water, and used 234.8 thousand hectares of land resources. Four plants groups consumed the irrigation water: cereals, vegetables, fodder, and fruits. The fodder group consumed 57.35 percent of all irrigation water, while the fruit group consumed 26.5 percent, the cereal group consumed 8.07 percent while the vegetable group consumed 8.08 percent. The model aims to replicate the actual crop pattern and output for Riyadh using average prices and historic average water consumption.

4.2.1. Model Result Compared to Historic Average

Table 4.1 shows the results of the regional model for the Riyadh region using market prices. The objective function maximizes profits, which increased from SAR 5.04 billion in the observed crop pattern to SAR 5.19 billion. Profit increased by just 2.2 percent while total revenue decreased by 14.5 percent. Farmers reallocated limited resources with a 13.7 percent decrease of cropland used and a 7 percent decrease in irrigation water. Therefore, the decrease in the irrigation water consumption was mainly a result of decreased cropland and adjustments in crop mix.

In detail, the optimal solution suggests eliminating all of the wheat, barley, maize, and tomatoes (GH) to optimize profit. The rest of the crops fluctuate between a maximum of 10 percent and a minimum of 13 percent of the current crop mix. This fluctuation is mainly due to some assumptions of the model. These include: treating the region as a single large farm, using an average quality of water for the entire region, and assuming strict short term profit maximizing behavior. In addition the aggregate constraint may have limited adjustments. This constraint allows some crop diversification but it limits the scope for large shifts. For instance, alfalfa and other fodder increased by 1.1 and 4.4 percent respectively. These results are very close to the current crop while cucumbers (GH) increased by 10.5 percent and sorghum decreased by 13.6 percent. Even though the aggregate constraint puts the optimal crop pattern close to the current crop mix; there were four crops not included in the optimal crop pattern because these crops had a negative net return.

Table 4-1 Crop pattern based on observed and optimization with different level of prices

	Current Crop Solution		**Optimal Solution (Wholesale Piece)**		**Optimal Solution (Indirect Subsidies)**		
Return	**9,544,190,906.7**		**9,113,007,023**		**9,709,247,678**		
Profit	**5,038,510,451.3**		**5,194,002,128**		**5,250,248,433**		
Cropland	**234,877.4**		**202,646.8**		**234,499.8**		
Water irrigation	**5,814,121,725.4**		**5,405,852,254**		**5,814,121,725**		
Crops	**Crop Area Observed (ha)**	**Wholesale price SAR**	**Optimal Crop Area (ha)**	**Different from Area %**	**Indirect Subsidies SAR**	**Optimal Crop Area (ha)**	**Different from Area %**
Cereals Group							
Wheat	30,646.2	1,120.0	0	-100	656.0	30,184.8	-1.5
Barley	570.0	1,115.0	0	-100	755.0	584.7	+2.6
Sorghum	207.4	1,880.7	179.1	-13.6	0.0	189.9	-8.5
Maize	1,852.2	1,101.0	0	-100	713.0	1,850.9	-0.1
Millet	0.0	1,226.0	0	0	0.0	0.0	0.0
Sesame	0.0	5,357.0	0	0	0.0	0.0	0.0
Other Cereal	40.2	2,506.0	38.8	-3.4	0.0	40.6	+1.0
Vegetables Group							
Tomato (OF)	3,735.1	2,368.0	3,927.1	+5.1	0.0	3,822.4	+2.3
Tomato (GH)	1,734.5	2,368.0	0.0	-100	680.0	1,463.0	-15.7
Eggplant	1,790.4	2,060.0	1,762.6	-1.6	0.0	1,811.2	+1.2
Squash (OF)	3,003.0	3,620.0	2,965.7	-1.2	0.0	3,006.4	+0.1
Squash (GH)	21.2	3,620.0	22.0	+3.8	0.0	22.0	+3.8
Cucumber (OF)	191.2	3,088.0	190.3	-0.5	0.0	190.5	-0.3
Cucumber (GH)	1,432.0	3,088.0	1582	+10.5	0.0	1,582.0	+10.5
Okra (OF)	1,122.2	8,462.0	1,062.2	-5.3	0.0	1,139.3	+1.5
Carrots (OF)	1,680.8	2,048.0	1,670.1	-0.6	0.0	1,702.3	+1.3
Potato (OF)	4,512.6	1,406.0	4,602.0	+2.0	0.0	4,582.9	+1.6
Dray onion (OF)	1,091.4	1,590.0	1,119.6	+2.6	0.0	1,096.3	+0.5
Melon (OF)	10,924.4	2,658.0	10,700.3	-2.1	0.0	10,775.3	-1.4
Watermelon (OF)	12,983.6	2,728.0	13,166.6	+1.4	0.0	12,977.4	0.0
Other Vegetable (OF)	9,367.4	4,401.0	9,558.9	+2.0	0.0	9,603.8	+2.5
Other Vegetable (GH)	805.2	4,401.0	767.0	-4.7	0.0	767.0	-4.7
Fodder Group							
Alfalfa	60,820.0	1,346.0	61,509.8	+1.1	0.0	61,158.7	+0.6
Other fodder	33,511.2	1,532.0	34,987.5	+4.4	0.0	33,113.1	-1.2
Fruits Group							
Dates plum	42,419.6	9,219.0	42,419.6	0.0	0.0	42,419.6	0.0
Citrus	3,374.4	3,043.0	33,74.4	0.0	0.0	33,74.4	0.0
Grapes	2,806.8	5,028.0	28,06.8	0.0	0.0	28,06.8	0.0
Other Fruit	4,234.4	4,928.0	42,34.4	0.0	0.0	42,34.4	0.0

4.2.2. Possible Explanation of Solution

The best explanation for the absence of these crops in the model when they were actually produced is that observed market prices used in the model do not fully reflect actual prices received by farmers when hidden subsidies are present. Prices in the dissertation were obtained from two sources. The first source is the international import price for grains and fodder. The second source is average wholesale prices for vegetables and fruits. While wholesale prices most likely includes domestic subsidies to farmers, it is less likely that international import prices fully reflect domestic subsidies to farmers.

The Saudi government provides direct and indirect subsidies (implicit subsidies); Chapter 2 explained all direct subsidies. Howevert, farmers also receive different kinds of indirect subsidies, such as for fuel and electricity, to support crop production. These indirect subsidies could affect farmers' decisions, but the indirect subsidies do not show in production costs. For instance, the government subsidizes fuel and electricity wherein farmers pay a lower price for these utilities, so the full price of fuel and electricity do not show in production costs. This section estimates the minimum implicit subsidies that farmers receive indirectly through estimate the new prices set. The aim of the new prices set that lead farmer to produce observed crop pattern and output with historical water use.

Indirect subsidies are estimated for the four crops in a two step process. First, estimate the price that causes the crops to show in the observed crop pattern and then estimate the implicit subsidy as the difference between this price and the market price. In the first step, a GAMS program is used to estimate the adjusted prices by running the model at different price levels for one crop of the four crops until the crop is included in the optimal solution at a level similar to that observed. For instance, wheat is observed in the optimal solution when the price of the crop increases to SAR 1,776 (470.93 USD). Similarly, the adjusted price for barley, maize, and tomatoes are grown in greenhouses are SAR 1,870 (498.66 USD), 1,814 (483.73 USD), and 3,048 (812.80 USD), respectively.

The second step is estimating the indirect subsidy for each crop. The difference between the observed price per ton and the adjusted price per ton represents the minimum implicit subsidies farmers received indirectly. Implicit subsidies are SAR 656 (174.93 USD), 755 (201.33 USD), 713 (190.13 USD), and 680 (181.33 USD) for wheat, barley, maize, and tomatoes are grown in greenhouses, respectively. These indirect subsidy values represent the minimum implicit subsidies needed to achieve production at amounts similar to those observed, as there may be some implicit subsidies that are not calculated. However, comparing the implicit subsidies per ton with the average cost per ton shows that farmers receive a high number of implicit subsidies. The estimation shows that implicit subsidies represent 46.75, 45.54, 46.65, and 22.37 percent of adjusted prices for wheat, barley, maize, and tomatoes are grown in greenhouses, respectively. The results show that grains receive more than 40 percent of their average cost per ton as implicit subsidies, which encourages farmers to produce these crops.

4.2.3. Model Result with new adjusted prices

The implicit subsidies lead to changes in prices, and the changes have a significant effect on farmers' decision to allocate limited resources to grow the crops. Importantly, all adjusted prices for crops are either at the same level or a higher level than they are in the observed price set so an increase in crop production should occur. The new optimal solution with indirect subsidies generates 5.25 billion SAR in profit compared to 5.03 billion SAR under the historic crop pattern. The new optimization solution has higher profit by 4.2 percent and higher total return by 1.73 percent than the profit and total return of the current crop mix. Increases in profit and total return largely result from the increase in the price of wheat, barley, maize and tomato (GH). Importantly the new optimal solution is similar to the observed crop mix. Adjusted prices lead the farmer to reallocate available resources to maximize the profit, while the aggregate constraint succeeds in keeping the difference between the observed crop pattern and now crop pattern within an acceptable range of fluctuation.

The new optimal solution used the same amount of irrigation water used and 377 less hectares of cropland when compared to the current crop mix. Table 4.1 shows that the wheat area is less than the observed area by about 1.5 percent, while barley is greater by 2.6 percent. The optimal solution results in almost the same amount maize, while tomatoes grown in a greenhouse were less by about 15.7 percent.

In general, this crop mix is the closest simulation to the observed crop pattern as the new adjusted prices almost replicate the actual crop pattern and output for Riyadh. This suggests the model is a good representation of actual condition. As the Saudi government applies identical agricultural policies in all regions of Saudi Arabia, the dissertation assumes that each region receives the same amount of indirect subsidies for the same crops. This allows the use of adjusted prices from the Riyadh region in all other regions. Based on this assumption, the study includes two sets of prices: market prices, collected from different sources, and adjusted prices, representing the market price plus indirect subsidies.

4.3. Scenarios using Estimated Market Prices

The study includes two status quo points, as shown in Figure 4.3, with each point representing a specific level of food security that corresponds to historic levels of production. Each status quo point reflects the government's solution to its problem of minimizing water needed to produce a target level of food security. Because different crop price sets are used in the two cases, different levels of total revenue occur. In both instances, while crop prices differ, the level of food output is determined by the historic average output of crops over a five year interval. The first status quo point can be described as the current situation, using observed prices, where total irrigation water used is 13.131 BCM, and total revenue is 20.815 billion SAR. The second status quo point assumes the use of adjusted prices where total irrigation water used remains at 13.131 BCM, but total revenue is 21.7 billion SAR because crop prices are higher or at least as high as for the first status quo point. These points are the references for comparing scenario results since they can be thought of as reflecting current policy and behavior.

As the study covers six regions and uses a five-year average data set to illustrate the observed crop pattern for each region, total irrigation water used is distributed among the regions as follows: Riyadh 44.3 percent, Qassem 18.8 percent, Eastern Province 7.5 percent, Tabuk 5.7 percent, Hail 12.5 percent, and Jouf 11.2 percent. The distribution of irrigation water among plant groups is as follows: cereal group 13.0 percent, vegetable group 5.9 percent, fodder group 43.5 percent, and fruit group 37.6 percent. Meanwhile, the total revenue distributed among the regions is as follows: Riyadh 45.9 percent, Qassem 17.7 percent, Eastern Province 13.0 percent, Tabuk 5.3 percent, Hail 9.2 percent, and Jouf 8.9 percent. The total cropland of the entire region is 610.4 thousand hectares.

The cultivated area distributed among regions is as follows: Riyadh 38.5 percent, Qassem 16.6 percent, Eastern Province 8.8 percent, Tabuk 7.3 percent, Hail 13.4 percent, and Jouf 15.5 percent.

The next sections show the result of applying the RIWP and IIWMP algorithms to prices based on observed market conditions. Two scenarios are considered – one for each algorithm. The first scenario represents the results from the RIWP algorithm based on the observed price set, while the second scenario presents the results from the IIWMP algorithm using the same price set.

4.3.1. Scenario One: RIWP algorithm

Scenario one shows that the government reduces the total irrigation water consumption by reallocating the irrigation water among the regions, but does not take any feedback from farmers' actions. Government first obtains a feasible solution that optimizes its objective function by minimizing the total irrigation water used among the six regions while satisfying the total revenue constraint. The government then uses this quantity of irrigation water used as a constraint in the six regional farm models to alter farm choices through the RIWP algorithm.

Table 4.2 shows the results, with the first column of the table illustrating the current crop mix, while the second column shows results from the RIWP algorithm. Both the result from the government's solution to the master problem and the solution of the farmer's subproblem are presented. The government's result suggests reducing irrigation water consumption to 11.518 BCM. The government then reallocates the irrigation water used among the regions as follows: Riyadh has 43.2 percent, Qassem 21.4 percent, Eastern Province 5.6 percent, Tabuk 6.7 percent, Hail 10.5 percent, and Jouf 12.6 percent. The government would expect the farmers to use 540.0 thousand ha of cropland, and the farmers would reallocate the cropland among the crop groups as follows: cereal group 24.7 percent, vegetable group 17.1 percent, fodder group 25.8 percent, and fruit group 32.3 percent.

The farmers take the quantity of irrigation water as given, and then each farm solves a subproblem to maximize profits. Unfortunately, the farmers do not satisfy the government's goals. In particular, the government aims to hold the total revenue from agricultural production at 20.815 billion, but the farmers only achieve 19.414 billion of the target return, or 93% of the target revenue. A 7 percent gap exists between the government's desires and farmers' actions. This gap causes a shortfall in the food security objective. This gap reflects farmers' lack of interest in meeting the government's goal of achieving a desired level of food security. For example, the reduction in irrigation water among the regions led to a 61 percent decline in wheat production and a 47 percent drop in tomato production. On the other hand, the redistribution also led to increases of the other vegetables by more than 60 percent. All these changes happened because the farmers focused on maximizing profit, while the government failed to motivate the farmer to adopt the food security objective.

While the government's solution for the master problem led to an 11.26 percent reduction of irrigation water consumption, compared to the quantity consumed in the observed crop mix, the total consumption by farmers decreased by 12.28 percent. Farmers actually use less water than was allocated, and the farmers produce less output than the government wants. Also, the farmers use irrigation water to produce different crop mix then the government desires. While the government assumed that the crop pattern farmers adopted would be similar to the crop pattern that the government determined from solving the master problem (leader problem), the result shows that farmers do not satisfy the government's objectives.

4.3.2. Scenario Two: IIWMP algorithm

The government uses the same irrigation water constraint as in the first solution, but also provides crop specific taxes and subsidies for each region to motivate farmers to produce the crop mix government desires. In this case, the government first solves the leadership problem as before and determines the quantity of irrigation water used for each region. Each region, which is represented as a single farm, then solves the farm problem to maximize profits as before. Now however, if the farms' optimal solution does not provide the government's desired level of food security and crop mix, the government then adopts a feedback policy of new crop prices that motivates the farmers to satisfy its objectives and the region problem is resolved. This process is repeated until the output of eh six region models converges with the government solution.

Table 4.2 shows the result of the process. The third column of Table 4.2 shows that the optimal solution of this scenario minimizes irrigation water at 9.415 BCM and reaches the total revenue target. The IIWMP algorithm runs many times to reach this result, and the solution suggests reducing the irrigation water consumption to 9.415 BCM and the cropland to 500.4 thousand hectares. In each iteration farmers respond by using new prices and the limited amount of irrigation water to maximize their profits. Farmers determined the final amount of cropland for each crop in each region, as shown in Table 4.2. To summarize the result, the total crop area was distributed as follows: Riyadh 152.1

thousand hectares, Qassem 101.1 thousand hectares, Eastern Province 26.5 thousand hectares, Tabuk 44.4 thousand hectares, Hail 81.6 thousand hectares, and Jouf 94.5 thousand hectares. More precisely, the solution suggests encouraging farmers in Riyadh to allocate the total crop area as follows: 36.1 percent vegetables, 28.7 percent fodder, and 34.7 percent fruits. Meanwhile, the distribution of the total crop area in Qassem would be cereal 30.4 percent, 43.3 fruits, fodder 13.9 percent, and vegetables 12.4 percent. These two regions represent around 50 percent of the total crop area, as suggested by the solution. However, the solution focuses on reducing the fodder area to reduce irrigation water consumption, which was observed in the distribution of cropland among the plant groups. For instance, the fodder cropland represents 30.9 percent of the total crop for the current crop pattern while the solution suggests reducing the fodder cropland to 17 percent of the total cropland of the solution.

4.3.3. Comparison of the First Two Scenarios to Status Quo

The status quo point shows the current crop mix used 13.13 BCM of water and the total revenue was 20.7 billion SAR. Scenario (1) used the RIWP algorithm to reduce the irrigation water consumption to 11.518 BCM, but it did not achieve the government’s goal of achieving the target revenue. The total revenue fell to 19.4 billion SAR indicating that farms cannot achieve the desired food security level. Scenario (1) also shows the farmers’ crop mix does not match up the government’s crop mix desire, indicating that the irrigation water constraint alone is not enough to change the farm's choices. So, the weakness of this algorithm is that no motivation affects the farmers’ decision to adopt the government’s goals. Scenario (2) shows how additional government intervention in the form of crop and region specific taxes and subsidies can reduce the irrigation water used and satisfy the total revenue constraint.

Scenario (2) used IIWMP algorithm shows the government uses policies besides the irrigation water constraint. The scenario suggests that each region requires region specific policies to motivate farmers to satisfy the government's objectives. For instance, the solution suggests the government should deal with the Hail region to impose taxation on barley, other cereals, alfalfa, and other fodder, while imposing subsidies for wheat and potatoes. These combinations of policies lead guide the farmer to satisfy the government's objectives.

4.4. Scenarios Using Adjusted Prices

Adjusted prices result from the question of, why is there a difference between the optimal crop mix and the observed current crop mix. The answer is that farms can receive hidden or indirect subsidies that motivate the farms to adopt the observed crop mix. Estimates of indirect subsidies for the Riyadh region are calculated and generalized to other regions. Total revenues are then estimated based on adjusted prices which equal the wholesale price plus the indirect subsidies. Thus, the total revenue for status quo point 2 is 20.815 billion SAR, which establishes the new target level of food security that is higher than the first status quo point.

Therefore, the initial point, in this case, is that the agricultural crop area in the six regions consumes 13.131 BCM and produces 21.7 billion SAR of the total product revenue, as shown in Table 4.3. The two scenarios using this price set follow the same procedure as above case would have the same procedure of the first case, which means the RIWP algorithm is applied in the third scenario while the IIWMP algorithm is applied in the fourth scenario.

4.4.1. Scenario Three: RIWP algorithm

Again, the government uses restrictions on irrigation water to modify farmers' choice. The scenario assumes that adjusted prices are applied to all regions, and uses the RIWP algorithm. Table 4.3 shows the results indicating that the farmers (i.e., followers) do not satisfy the government's objectives. The solution for the leader problem suggests that the government can reduce the irrigation water to 11.711 BCM when it reallocates the irrigation water used among all regions and still meet its food security target. The government distributes irrigation water among the regions as follows: Riyadh 5.437 BCM, Qassem 2.158 BCM, Eastern Province 0.891 BCM, Tabuk 0.681 BCM, Hail 1.113 BCM, and Jouf 1.341 BCM. Farmers then take the quantity of irrigation water as a given and solve their subproblem to maximize their individual profits. The results show that the farmers' decision does not meet the target revenue. Total revenue produced by the farmers would be 20.677 billion SAR, which is 4.7 percent less than the target revenue, while irrigation water consumption is the amount allocated. This gap shows that the higher price regime associated with adjusted prices fails to motivate the farmers to adopt the government's objectives. Therefore, the government needs to review the subsidy policy to guide farmers to the government's objectives. On the other hand, the RIWP algorithm with adjusted prices resulted in greater total revenue than in Scenario 1 reducing the gap between the government wishes and farm decisions. Some regions (e.g., Jouf) matched the crop pattern suggested by the government, whereas others (e.g., Qassem and Eastern Province) matched up to around 90 percent or more.

4.4.2. Scenario Four: IIWMP algorithm

This scenario used the IIWMP algorithm, in which the government uses both irrigation water constraints and specific crop policies to better align farm-level decisions with government objectives. The integration between controlling irrigation water use and agricultural policies encourages farmers to align objectives for both levels. The third column of Table 4.3 shows the results of this scenario.

The solution suggests that government sets the irrigation water availability at 10.264 BCM. With this solution, the government distributes irrigation water among the regions as follows: Riyadh 4.363 BCM, Qassem 2.158 BCM, Eastern Province 0.891 BCM, Tabuk 0.618 BCM, Hail 1.113 BCM, and Jouf 1.121 BCM. Furthermore, the government should pay about 1.926 billion SAR in net subsidies to encourage farmers to meet its objectives. The total subsidies would be distributed among the crop groups as follows: cereal group 46.6 percent, vegetable group 42.1 percent, and the fodder group 11.27 percent. Hence, the solution suggests providing a subsidy for fodder in Riyadh, while imposing a tax on growing fodder in the Eastern Province and Hail regions. This mix of agricultural policies could lead the farmers to minimize their irrigation water consumption and achieve the government's target total revenue of total agricultural production.

4.4.3. Comparison of the Second Two Scenarios to Status Quo

Based on the adjusted price set, the status quo shows the current crop mix requires 13.13 BCM of water, and a total revenue of 21.7 billion SAR. The current level of total revenue represents the status quo solution with indirect subsidies. However, when the government controls the irrigation water used to alter the farmers choice as shown in scenario (3), irrigation water consumption is reduced to 11.71 BCM, but total revenue decreases to 20.677 billion SAR. This reduction in the total revenue represents a decline in the level of food security. Thus, only controlling irrigation water use does not achieve the government's target revenue goal.

On the other hand, Scenario (4) used IIWMP algorithm where the government uses price adjustment policies in addition to an irrigation water constraint. The scenario uses region specific policies to motivate farmers to satisfy the government's objectives. The result of these integrated policies is: achieving the total revenue target, reducing irrigation water used and increasing the farm-level profit. Irrigation water used is reduced to 10.264 BCM, and the farm profit increases to 16.8 billion SAR, whereas the status quo crop mix has profits of 12.6 billion SAR. The increased profit reflects the subsidies provided by the government that are required to achieve its desired crop mix and level of food security.

Also, cropland decreases as a response to irrigation water consumption constraints in scenario (3) or integrated policies as in scenario (4). The difference in the cropland used between the two scenarios is not significant. Thus, the major factor that leads to minimize irrigation water used and maximize the total revenue is the integrated policies.

4.5. Comparison of Four Scenarios

The four scenarios reflect combinations of two sets of prices (observed and adjusted) and two solution algorithms (one using only water restrictions and one using an iterative price adjustment process and water restrictions). While specific comparisons among all four scenarios are difficult because each is based on different starting points some generalizations can be made. The first is that while water restrictions alone can lead to significant reductions in water use while in principle maintaining current levels of food security, the principle agent problem associated with a mismatch between government and farm level objectives leads to food security objectives not being achieved. This is true for both price regimes.

To address the principal-agent problem the government must find a way to align the two leaves of objectives. One way to do this is to adopt region and crop specific taxes and subsidies to better link farm level profits with government food security desires. The algorithm that uses this approach is able to lead farms to produce the government's target crop mix while significantly reducing water use, but at a cost of a net transfer to farmers from government. While a tax and subsidy approach may not be the only way to resolve the principal agent problem, it does provide an estimate of what it might cost Saudi Arabia to achieve the current level of food security while reducing water use.

Table 4-2 Detail result for crop pattern for all-region at the first case where total revenue estimated base on the wholesale prices.

	Current Crop Pattern	RIWP Algorithm result		IIWMP Algorithm result	
		Leader solution	Follower solution		
Total Revenue (Billion SAR)	20.815	20.815	19.414	20.815	
Profit (Billion SAR)	11.751	11.770	12.290	12.259	
Total irrigation water used (BCM)	13.131	11.652	11.518	9.415	
Total Cropland (ha)	610,409.2	543,957.0	464,700.4	500,393.5	
Riyadh					
Total Revenue (Billion SAR)	9.556	9.219	8.656	8.815	
Profit (Billion SAR)	5.051	4.959	5.148	5.044	
Total irrigation water used (BCM)	5.814	5.037	5.037	3.237	
Total Cropland (ha)	234,877.4	195,716.7	187,827.8	152,153.2	
	Cropland	Leader Cropland	Follower Cropland	Cropland	Subsidies (+/-)
Cereal Group					
Wheat	30,646.2	0.0	0.0	0.0	0.0
Barley	570.0	552.8	0.0	552.8	1,164.0
Sorghum	207.4	179.1	189.9	179.1	79.3
Maize	1,852.2	0.0	0.0	0.0	0.0
Millet	0.0	0.0	0.0	0.0	0.0
Sesame	0.0	0.0	0.0	0.0	0.0
Other Cereal	40.2	38.8	40.6	38.8	0.0
Vegetables Group					
Tomato	3,735.1	3,927.1	3,822.4	3,927.1	0.0
Tomato (GH)	1,734.5	1,873.0	0.0	1,873.0	762.0
Eggplant	1,790.4	1,762.6	1,811.2	1,762.6	0.0
Squash	3,003.0	2,965.7	3,006.4	2,965.7	0.0
Squash (GH)	21.1	21.0	22.0	21.0	0.0
Cucumber	191.2	190.3	190.5	190.3	0.0
Cucumber (GH)	1,432.0	1,411.0	1,582.0	1,411.0	0.0
Okra	1,122.2	1,062.2	1,139.3	1,062.2	0.0
Carrots	1,680.8	1,670.1	1,702.3	1,670.1	0.0
Potato	4,512.6	4,602.0	4,582.9	4,602.0	0.0
Dry Onion	1,091.4	1,119.6	1,096.3	1,119.6	0.0
Melon	10,924.4	10,700.3	10,775.3	10,700.3	0.0
Watermelon	12,983.6	13,166.6	12,977.4	13,166.6	1,772.0
Other Vegetable	9,367.4	9,558.9	9,603.8	9,558.9	0.0
Other Vegetable (GH)	805.2	847.0	767.0	847.0	0.0
Fodder Group					
Alfalfa	60,820.0	52,245.9	61,158.7	8,682.3	0.0
Other Fodder	33,511.2	34,987.5	20,524.6	34,987.5	303.0

Fruits Group					
Dates	42,419.6	42,419.6	42,419.6	42,419.6	0.0
Citrus	3,374.4	3,374.4	3,374.4	3,374.4	0.0
Groups	2,806.8	2,806.8	2,806.8	2,806.8	0.0
Other Fruits	4,234.4	4,234.4	4,234.4	4,234.4	0.0
Qassem					
Total Revenue (Billion SAR)	3.674	3.799	3.442	3.797	
Profit (Billion SAR)	2.342	2.374	2.459	2.371	
Total irrigation water used (BCM)	2.470	2.496	2.362	2.165	
Total Cropland (ha)	101,254.4	101,254.4	80,815.5	101,254.4	
	Cropland	Leader Cropland	Follower Cropland	Cropland	Subsidies (+/-)
Cereal Group					
Wheat	20,308.6	20,299.9	0.0	30,761.3	980.0
Barley	68.2	0.0	270.8	0.0	0.0
Sorghum	0.0	0.0	0.0	0.0	0.0
Maize	1,355.0	0.0	172.2	0.0	0.0
Millet	0.0	0.0	0.0	0.0	0.0
Sesame	0.0	0.0	0.0	0.0	0.0
Other Cereal	21.4	11.7	10.7	0.0	0.0
Vegetables Group					
Tomato	112.4	119.1	102.1	119.1	0.0
Tomato (GH)	588.4	780.0	0.0	780.0	520.0
Eggplant	159.4	183.7	179.3	183.7	0.0
Squash	892.5	872.1	869.4	872.1	0.0
Squash (GH)	42.5	34.0	0.0	34.0	300.0
Cucumber	44.5	41.6	42.3	41.6	0.0
Cucumber (GH)	308.9	605.0	0.0	605.0	496.0
Okra	135.6	178.5	158.3	178.5	0.0
Carrots	1,389.0	1,422.3	1,478.3	1,422.3	0.0
Potato	3,737.4	3,585.2	3,583.1	3,585.2	0.0
Dry Onion	277.4	302.8	306.6	302.8	0.0
Melon	672.2	714.8	676.4	714.8	0.0
Watermelon	981.6	988.5	1,014.2	988.5	0.0
Other Vegetable	2,466.0	2,738.9	2,718.8	2,738.9	0.0
Other Vegetable (GH)	66.8	29.0	95.0	29.0	0.0
Fodder Group					
Alfalfa	19,104.8	20,157.5	21,185.5	9,707.0	0.0
Other Fodder	4,683.6	43,51.4	4,114.3	4,351.4	0.0

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Fruits Group					
Dates	39,140.0	39,140.0	39,140.0	39,140.0	0.0
Citrus	1,584.6	1,584.6	1,584.6	1,584.6	0.0
Groups	1,662.2	1,662.2	1,662.2	1,662.2	0.0
Other Fruits	1,451.4	1,451.4	1,451.4	1,451.4	0.0
Eastern Province					
Total Revenue (Billion SAR)	2.713	2.53	2.861	3.013	
Profit (Billion SAR)	1.755	1.973	2.031	2.033	
Total irrigation water used (BCM)	0.991	0.651	0.651	0.651	
Total Cropland	53,762.2	26,470.7	26,077.9	26,470.7	
	Cropland	Leader Cropland	Follower Cropland	Cropland	Subsidies (+/-)
Cereal Group					
Wheat	25,853.4	0.0	0.0	0.0	0.0
Barley	113.2	0.0	0.0	0.0	0.0
Sorghum	0.0	0.0	0.0	0.0	0.0
Maize	120.0	0.0	0.0	0.0	0.0
Millet	0.0	0.0	0.0	0.0	0.0
Sesame	0.0	0.0	0.0	0.0	0.0
Other Cereal	182.6	189.0	189.0	189.0	0.0
Vegetables Group					
Tomato	533.5	616.2	616.2	616.2	0.0
Tomato (GH)	598.9	618.0	618.0	618.0	0.0
Eggplant	105.6	137.5	137.5	137.5	0.0
Squash	157.1	177.2	177.2	177.2	0.0
Squash (GH)	43.1	44.0	44.0	44.0	0.0
Cucumber	9.0	12.8	12.8	12.8	0.0
Cucumber GH	192.6	390.0	0.0	390.0	1,746.0
Okra	183.0	211.8	211.8	211.8	0.0
Carrots	12.2	12.2	12.2	12.2	0.0
Potato	40.8	77.4	77.4	77.4	0.0
Dry Onion	126.0	170.5	170.5	170.5	0.0
Melon	150.0	139.8	139.8	139.8	0.0
Watermelon	59.6	111.8	0.0	111.8	20.0
Other Vegetable	1,358.8	1976.6	1,976.6	1,976.6	0.0
Other Vegetable (GH)	220.0	592.0	592.0	592.0	0.0
Fodder Group					
Alfalfa	2,695.0	0.0	109.0	0.0	0.0
Other Fodder	2,476.6	2462.6	2,462.6	2,462.6	0.0

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Fruits Group					
Dates	14,403.8	14,403.8	14,403.8	14,403.8	0.0
Citrus	759.2	759.2	759.2	759.2	0.0
Groups	149.0	149.0	149.0	149.0	0.0
Other Fruits	3,219.2	3,219.2	3,219.2	3,219.2	0.0
Tabuk					
Total Revenue (Billion SAR)	1.108	1.161	1.152	1.176	
Profit (Billion SAR)	0.493	0.534	0.545	0.556	
Total irrigation water used (BCM)	0.746	0.779	0.779	0.779	
Total Cropland	44,405.8	44,405.8	43,417.1	44,405.8	
	Cropland	Leader Cropland	Follower Cropland	Cropland	Subsidies (+/-)
Cereal Group					
Wheat	19,486.6	18,104.6	16,966.0	18,118.6	34.0
Barley	271.0	0.0	0.0	0.0	0.0
Sorghum	0.0	0.0	0.0	0.0	0.0
Maize	4.0	0.0	0.0	0.0	0.0
Millet	0.0	0.0	0.0	0.0	0.0
Sesame	0.0	0.0	0.0	0.0	0.0
Other Cereal	0.0	0.0	0.0	0.0	0.0
Vegetables Group					
Tomato	534.9	588.1	570.8	588.1	0.0
Tomato (GH)	77.3	44.0	90.0	90.0	812.0
Eggplant	37.2	40.6	40.0	40.6	0.0
Squash	24.7	32.7	33.1	32.7	0.0
Squash (GH)	41.7	47.0	0.0	40.0	2,030.0
Cucumber	18.3	17.8	18.7	17.8	0.0
Cucumber (GH)	221.9	283.0	220.0	220.0	0.0
Okra	19.8	18.9	20.9	18.9	0.0
Carrots	3.6	5.1	4.6	5.1	0.0
Potato	1,468.2	1,248.7	1,259.1	1,248.7	0.0
Dry Onion	351.0	381.9	396.2	381.9	0.0
Melon	164.2	184.4	185.6	184.4	0.0
Watermelon	171.0	207.9	201.0	207.9	0.0
Other Vegetable	555.6	761.7	757.9	761.7	0.0
Other Vegetable (GH)	30.2	22.0	32.0	32.0	0.0
Fodder Group					
Alfalfa	9,849.6	10,822.5	11,109.7	10,822.5	0.0
Other Fodder	581.6	1,101.4	1,017.1	1,101.4	0.0

Continue of Table 4-2 next page

Fruits Group					
Dates	3,302.6	3,302.6	3,302.6	3,302.6	0.0
Citrus	1,187.6	1,187.6	1,187.6	1,187.6	0.0
Groups	1,227.4	1,227.4	1,227.4	1,227.4	0.0
Other Fruits	4,775.8	4,775.8	4,775.8	4,775.8	0.0
Hail					
Total Revenue (Billion SAR)	1.909	1.796	1.464	2.066	
Profit (Billion SAR)	1.153	0.957	1.124	1.212	
Total irrigation water used (BCM)	1.643	1.219	1.219	1.113	
Total Cropland	81,628.2	81,628.2	40,594.2	81,628.2	
	Cropland	Leader Cropland	Follower Cropland	Cropland	Subsidies (+/-)
Cereal Group					
Wheat	22,721.8	43,778.9	0.0	48,068.1	480.0
Barley	261.0	0.0	434.4	0.0	-55.0
Sorghum	0.0	0.0	0.0	0.0	0.0
Maize	13,422.4	0.0	0.0	0.0	0.0
Millet	0.0	0.0	0.0	0.0	0.0
Sesame	0.0	0.0	0.0	0.0	0.0
Other Cereal	9.0	0.0	8.2	0.0	-56.0
Vegetables Group					
Tomato	88.8	180.7	149.2	161.2	0.0
Tomato (GH)	486.6	509.0	509.0	509.0	0.0
Eggplant	236.2	269.3	244.5	272.9	0.0
Squash	380.4	399.8	410.2	398.0	0.0
Squash (GH)	4.8	4.0	4.0	4.0	0.0
Cucumber	31.8	40.5	33.2	51.6	0.0
Cucumber (GH)	49.6	96.0	96.0	96.0	0.0
Okra	62.0	54.1	59.6	44.7	0.0
Carrots	24.4	57.4	35.5	103.7	0.0
Potato	4,843.4	6,021.4	0.0	6,451.7	968.0
Dry Onion	335.6	233.2	314.9	110.3	0.0
Melon	135.4	180.7	154.0	193.3	0.0
Watermelon	3,318.4	3,281.6	3,442.0	2,870.7	0.0
Other Vegetable	164.5	228.5	197.5	222.9	0.0
Other Vegetable (GH)	14.7	14.0	14.0	14.0	0.0
Fodder Group					
Alfalfa	8,280.0	0.0	7,855.9	0.0	-866.0
Other Fodder	4,701.4	4,222.9	4,575.9	0.0	-982.0

Continue of Table 4-2 next page

Fruits Group					
Dates	17,214.0	17,214.0	17,214.0	17,214.0	0.0
Citrus	1,441.2	1,441.2	1,441.2	1,441.2	0.0
Groups	1,212.2	1,212.2	1,212.2	1,212.2	0.0
Other Fruits	2,279.6	2,279.6	2,279.6	2,279.6	0.0
Jouf					
Total Revenue (Billion SAR)	1.854	1.877	1.839	1.948	
Profit (Billion SAR)	0.958	0.972	0.983	1.043	
Total irrigation water used (BCM)	1.471	1.470	1.470	1.470	
Total Cropland	94,481.2	94,481.2	85,967.9	94,481.2	
	Cropland	Leader Cropland	Follower Cropland	Cropland	Subsidies (+/-)
Cereal Group					
Wheat	49,967.0	49520.2	40,370.6	49,520.2	200.0
Barley	646.6	975.4	0.0	975.4	315.0
Sorghum	0.0	0.0	0.0	0.0	0.0
Maize	435.8	0.0	0.0	0.0	0.0
Millet	0.0	0.0	0.0	0.0	0.0
Sesame	0.0	0.0	0.0	0.0	0.0
Other Cereal	13.6	16.4	12.9	16.4	0.0
Vegetables Group					
Tomato	649.5	599.2	672.8	599.2	0.0
Tomato (GH)	114.9	108.0	108.0	108.0	0.0
Eggplant	33.2	41.5	31.2	41.5	0.0
Squash	102.5	179.5	89.4	179.5	0.0
Squash (GH)	22.1	40.0	40.0	40.0	0.0
Cucumber	23.5	28.3	29.6	28.3	0.0
Cucumber (GH)	61.7	76.0	76.0	76.0	0.0
Okra	88.4	103.3	81.7	103.3	0.0
Carrots	74.8	56.1	52.9	56.1	0.0
Potato	1,282.6	1772.4	1,305.9	1,772.4	0.0
Dry Onion	1,188.8	854.6	1,246.8	854.6	0.0
Melon	31.0	19.7	39.4	19.7	0.0
Watermelon	35.8	70.7	94.3	70.7	0.0
Other Vegetable	77.1	161.8	49.9	161.8	0.0
Other Vegetable (GH)	4.9	8.0	8.0	8.0	0.0
Fodder Group					
Alfalfa	12,603.4	12320.759	14,622.1	12,320.8	0.0
Other Fodder	510.2	1015.526	522.4	1,015.5	0.0

Continue of Table 4-2 next page

Fruits Group					
Dates	5,215.0	5,215.0	5,215.0	5,215.0	0.0
Citrus	716.8	716.8	716.8	716.8	0.0
Groups	1,371.8	1,371.8	1,371.8	1,371.8	0.0
Other Fruits	19,210.2	19,210.2	19,210.2	19,210.2	0.0

Table 4-3 Detail result for crop pattern for all-region at the first case where total revenue estimated base on the support prices.

	Current Crop Pattern		**RIWP Algorithm result**			**IIWMP Algorithm result**	
			Leader Solution		**Followers Solution**		
Total Revenue (Billion SAR)	21.700		21.700		20.677	21.700	
Profit (Billion SAR)	12.636		12.413		12.658	16.836	
Total irrigation water used (BCM)	13.131		11.711		11.711	10.264	
Total Cropland (ha)	610,481.2		582,388.5		561,389.3	556,385.5	
Riyadh							
Total Revenue (Billion SAR)	9.751		9.592		9.227	9.560	
Profit (Billion SAR)	5.246		5.215		5.201	5.475	
Total irrigation water used (BCM)	5.814		5.437		5.437	4.363	
Total Cropland (ha)	234,877.4		206,857.0		219,133.5	180,853.7	
Crops	Cropland	Subsidies (+/-)	Leader Cropland (ha)	Follower Cropland (ha)	Subsidies (+/-)	Cropland	Subsidies (+/-)
Cereal Group							
Wheat	30,646.2	656.0	0.0	30,184.8	656.0	0.0	656.0
Barley	570.0	755.0	552.8	584.7	755.0	552.8	1,164.0
Sorghum	207.4	0.0	179.1	189.9	0.0	179.1	79.3
Maize	1,852.2	713.0	1,876.3	1,850.9	713.0	1,876.3	1,239.0
Millet	-	-	-	-	-	-	-
Sesame	-	-	-	-	-	-	-
Other Cereal	40.2	0.0	38.8	40.6	0.0	38.8	1.0
Vegetables Group							
Tomato	3,735.1	0.0	3,927.1	3,822.4	0.0	3,927.1	0.0
Tomato (GH)	1,734.5	680.0	1,873.0	1,463.0	680.0	1,873.0	762.0
Eggplant	1,790.4	0.0	1,762.6	1,811.2	0.0	1,762.6	0.0
Squash	3,003.0	0.0	2,965.7	3,006.4	0.0	2,965.7	0.0
Squash (GH)	21.1	0.0	21.0	22.0	0.0	21.0	0.0
Cucumber	191.2	0.0	190.3	190.5	0.0	190.3	0.0
Cucumber (GH)	1,432.0	0.0	1,411.0	1,582.0	0.0	1,411.0	0.0
Okra	1,122.2	0.0	1,062.2	1,139.3	0.0	1,062.2	0.0
Carrots	1,680.8	0.0	1,670.1	1,702.3	0.0	1,670.1	0.0
Potato	4,512.6	0.0	4,602.0	4,582.9	0.0	4,602.0	0.0
Dry Onion	1,091.4	0.0	1,119.6	1,096.3	0.0	1,119.6	0.0
Melon	10,924.4	0.0	10,700.3	10,775.3	0.0	10,700.3	0.0
Watermelon	12,983.6	0.0	13,166.6	12,977.4	0.0	13,166.6	1,772.0
Other Vegetable	9,367.4	0.0	9,558.9	9,603.8	0.0	9,558.9	0.0
Other Vegetable (GH)	805.2	0.0	847.0	767.0	0.0	847.0	0.0
Fodder Group							
Alfalfa	60,820.0	0.0	61,509.8	61,158.7	0.0	35,506.5	0.0
Other Fodder	33,511.2	0.0	34,987.5	17,746.8	0.0	34,987.5	303.0

Fruits Group							
Dates	42,419.6	0.0	42,419.6	42,419.6	0.0	42,419.6	0.0
Citrus	3,374.4	0.0	3,374.4	3,374.4	0.0	3,374.4	0.0
Groups	2,806.8	0.0	2,806.8	2,806.8	0.0	2,806.8	0.0
Other Fruits	4,234.4	0.0	4,234.4	4,234.4	0.0	4,234.4	0.0
Qassem							
Total Revenue (Billion SAR)	3.751		3.665		3.300	3.793	
Profit (Billion SAR)	2.419		2.238		2.350	2.367	
Total irrigation water used (BCM)	2.470		2.158		2.158	2.158	
Total Cropland (ha)	101,254.4		101,254.4		75,433.3	101,254.4	
Crops	Cropland	Subsidies (+/-)	Leader Cropland (ha)	Follower Cropland (ha)	Subsidies (+/-)	Cropland	Subsidies (+/-)
Cereal Group							
Wheat	20,308.6	656.0	30,761.3	0.0	656.0	30,761.3	980.0
Barley	68.2	755.0	277.7	0.0	755.0	277.7	985.0
Sorghum	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maize	1,355.0	713.0	0.0	0.0	713.0	0.0	713.0
Millet	-	-	-	-	-	-	-
Sesame	-	-	-	-	-	-	-
Other Cereal	21.4	0.0	0.0	0.0	0.0	0.0	42.0
Vegetables Group							
Tomato	112.4	0.0	119.1	119.1	0.0	119.1	0.0
Tomato (GH)	588.4	0.0	780.0	0.0	680	780.0	523.0
Eggplant	159.4	0.0	183.7	183.7	0.0	183.7	0.0
Squash	892.5	0.0	872.1	872.1	0.0	872.1	0.0
Squash (GH)	42.5	0.0	34.0	0.0	0.0	34.0	300.0
Cucumber	44.5	0.0	41.6	41.6	0.0	41.6	0.0
Cucumber (GH)	308.9	0.0	605.0	0.0	0.0	605.0	496.0
Okra	135.6	0.0	178.5	178.5	0.0	178.5	0.0
Carrots	1,389.0	0.0	1,422.3	1,422.3	0.0	1,422.3	0.0
Potato	3,737.4	0.0	3,585.2	3,585.2	0.0	3,585.2	0.0
Dry Onion	277.4	0.0	302.8	302.8	0.0	302.8	0.0
Melon	672.2	0.0	714.8	714.8	0.0	714.8	0.0
Watermelon	981.6	0.0	988.5	988.5	0.0	988.5	0.0
Other Vegetable	2,466.0	0.0	2,738.9	2,738.9	0.0	2,738.9	0.0
Other Vegetable (GH)	66.8	0.0	29.0	95.0	0.0	29.0	0.0
Fodder Group							
Alfalfa	19,104.8	0.0	9,430.2	16,001.1	0.0	9,430.2	0.0
Other Fodder	4,683.6	0.0	4,351.4	4,351.3	0.0	4,351.4	0.0

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Fruits Group							
Dates	39,140.0	0.0	39,140.0	39,140.0	0.0	39,140.0	0.0
Citrus	1,584.6	0.0	1,584.6	1,584.6	0.0	1,584.6	0.0
Groups	1,662.2	0.0	1,662.2	1,662.2	0.0	1,662.2	0.0
Other Fruits	1,451.4	0.0	1,451.4	1,451.4	0.0	1,451.4	0.0
Eastern Province							
Total Revenue (Billion SAR)	2.795		3.186		3.094	3.246	
Profit (Billion SAR)	1.837		2.079		2.138	2.139	
Total irrigation water used (BCM)	0.991		0.891		0.891	0.891	
Total Cropland (ha)	53,762.2		53,762.1		53,423.5	53,762.2	
Crops	Cropland	Subsidies (+/-)	Leader Cropland (ha)	Follower Cropland (ha)	Subsidies (+/-)	Cropland	Subsidies (+/-)
Cereal Group							
Wheat	25,853.4	656.0	26,989.3	26,989.3	656.0	26,989.3	656.0
Barley	113.2	755.0	181.2	181.2	755.0	181.2	755.0
Sorghum	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maize	120.0	713.0	120.9	186.6	713.0	120.9	713.0
Millet	-	-	-	-	-	-	-
Sesame	-	-	-	-	-	-	-
Other Cereal	182.6	0.0	189.0	189.0	0.0	189.0	0.0
Vegetables Group							
Tomato	533.5	0.0	616.2	616.2	0.0	616.2	0.0
Tomato (GH)	598.9	0.0	618.0	618.0	680.0	618.0	0.0
Eggplant	105.6	0.0	137.5	137.5	0.0	137.5	0.0
Squash	157.1	0.0	177.2	177.2	0.0	177.2	0.0
Squash (GH)	43.1	0.0	44.0	44.0	0.0	44.0	0.0
Cucumber	9.0	0.0	12.8	12.8	0.0	12.8	0.0
Cucumber GH	192.6	0.0	390.0	0.0	0.0	390.0	1,746.0
Okra	183.0	0.0	211.8	211.8	0.0	211.8	0.0
Carrots	12.2	0.0	12.2	12.2	0.0	12.2	0.0
Potato	40.8	0.0	77.4	77.4	0.0	77.4	0.0
Dry Onion	126.0	0.0	170.5	170.5	0.0	170.5	0.0
Melon	150.0	0.0	139.8	139.8	0.0	139.8	0.0
Watermelon	59.6	0.0	111.8	0.0	0.0	111.8	20.0
Other Vegetable	1,358.8	0.0	1,976.6	1,976.6	0.0	1,976.6	0.0
Other Vegetable (GH)	220.0	0.0	592.0	562.0	0.0	592.0	0.0
Fodder Group							
Alfalfa	2,695.0	0.0	0.0	97.4	0.0	0.0	-246.0
Other Fodder	2,476.6	0.0	2,462.6	2,462.6	0.0	2,462.6	0.0

Continue of Table 4-3

Fruits Group							
Dates	14,403.8	0.0	14,403.8	14,403.8	0.0	14,403.8	0.0
Citrus	759.2	0.0	759.2	759.2	0.0	759.2	0.0
Groups	149.0	0.0	149.0	149.0	0.0	149.0	0.0
Other Fruits	3,219.2	0.0	3,219.2	3,219.2	0.0	3,219.2	0.0
Tabuk							
Total Revenue (Billion SAR)	1.197		1.185		1.178	1.154	
Profit (Billion SAR)	0.582		0.570		0.578	0.543	
Total irrigation water used (BCM)	0.746		0.681		0.681	0.618	
Total Cropland (ha)	44,405.8		44,405.7		44,405.8	44,405.8	
Crops	Cropland	Subsidies (+/-)	Leader Cropland (ha)	Follower Cropland (ha)	Subsidies (+/-)	Cropland	Subsidies (+/-)
Cereal Group							
Wheat	19,486.6	656.0	21,144.0	21,815.4	656.0	22,972	656.0
Barley	271.0	755.0	643.9	0.0	755.0	1,225.4	1,675.0
Sorghum	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maize	4.0	713.0	0.0	0.0	713.0	0.0	713.0
Millet	-	-	-	-	-	-	-
Sesame	-	-	-	-	-	-	-
Other Cereal	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vegetables Group							
Tomato	534.9	0.0	588.1	576.6	0.0	632.6	0.0
Tomato (GH)	77.3	812.0	90.0	90.0	680	90.0	812.0
Eggplant	37.2	0.0	40.6	37.9	0.0	45.6	0.0
Squash	24.7	0.0	32.7	28.6	0.0	39.3	0.0
Squash (GH)	41.7	0.0	40.0	0.0	0.0	40.0	2,030.0
Cucumber	18.3	0.0	17.8	17.6	0.0	21.2	0.0
Cucumber (GH)	221.9	0.0	220.0	220.0	0.0	220.0	0.0
Okra	19.8	0.0	18.9	17.4	0.0	22.6	0.0
Carrots	3.6	0.0	5.1	4.4	0.0	5.9	0.0
Potato	1,468.2	0.0	1,248.7	1,262.7	0.0	1,261.9	0.0
Dry Onion	351.0	0.0	381.9	383.7	0.0	366.3	0.0
Melon	164.2	0.0	184.4	187.4	0.0	170.1	0.0
Watermelon	171.0	0.0	207.9	196.9	0.0	222.8	0.0
Other Vegetable	555.6	0.0	761.7	769.4	0.0	636.9	0.0
Other Vegetable (GH)	30.2	0.0	32.0	32.0	0.0	32.0	0.0
Fodder Group							
Alfalfa	9,849.6	0.0	7,153.1	7,347.5	0.0	4,692.9	0.0
Other Fodder	581.6	0.0	1,101.4	924.7	0.0	1,214.7	0.0

Continue of Table 4-3

Fruits Group							
Dates	3,302.6	0.0	3,302.6	3,302.6	0.0	3,302.6	0.0
Citrus	1,187.6	0.0	1,187.6	1,187.6	0.0	1,187.6	0.0
Groups	1,227.4	0.0	1,227.4	1,227.4	0.0	1,227.4	0.0
Other Fruits	4,775.8	0.0	4,775.8	4,775.8	0.0	4,775.8	0.0
Hail							
Total Revenue (Billion SAR)	2.102		1.965		1.782	2.052	
Profit (Billion SAR)	1.346		1.112		1.195	1.198	
Total irrigation water used (BCM)	1.643		1.113		1.113	1.113	
Total Cropland (ha)	81,628.2		81,628.6		74,512.0	81,628.2	
Crops	Cropland	Subsidies (+/-)	Leader Cropland (ha)	Follower Cropland (ha)	Subsidies (+/-)	Cropland	Subsidies (+/-)
Cereal Group							
Wheat	22,721.8	656.0	48,056.7	43,017.4	656.0	48,068.1	656.0
Barley	261.0	755.0	0.0	461.9	755.0	0.0	-115.0
Sorghum	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maize	13,422.4	713.0	0.0	0.0	713.0	0.0	199.0
Millet	-	-	-	-	-	-	-
Sesame	-	-	-	-	-	-	-
Other Cereal	9.0	0.0	0.0	0.0	0.0	0.0	-106.0
Vegetables Group							
Tomato	88.8	0.0	162.7	183.9	0.0	161.2	0.0
Tomato (GH)	486.6	752.0	509.0	509.0	680.0	509.0	752.0
Eggplant	236.2	0.0	274.5	268.4	0.0	272.9	0.0
Squash	380.4	0.0	390.6	401.4	0.0	398.0	0.0
Squash (GH)	4.8	0.0	4.0	4.0	0.0	4.0	0.0
Cucumber	31.8	0.0	49.1	39.0	0.0	51.6	0.0
Cucumber (GH)	49.6	0.0	96.0	96.0	0.0	96.0	0.0
Okra	62.0	0.0	47.1	55.3	0.0	44.7	0.0
Carrots	24.4	0.0	86.8	52.1	0.0	103.7	5,215.0
Potato	4,843.4	0.0	6,366.1	0.0	0.0	6,451.7	385.0
Dry Onion	335.6	0.0	129.0	251.8	0.0	110.3	0.0
Melon	135.4	0.0	193.3	178.5	0.0	193.3	0.0
Watermelon	3,318.4	0.0	2,975.6	3,336.1	0.0	2,870.7	0.0
Other Vegetable	164.5	0.0	217.5	230.5	0.0	222.9	0.0
Other Vegetable (GH)	14.7	0.0	14.0	14.0	0.0	14.0	0.0
Fodder Group							
Alfalfa	8,280.0	0.0	0.0	0.0	0.0	0.0	-946.0
Other Fodder	4,701.4	0.0	0.0	3,356.7	0.0	0.0	-1,032.0

Continue of Table 4-3

Fruits Group							
Dates	17,214.0	0.0	17,214.0	17,214.0	0.0	17,214.0	0.0
Citrus	1,441.2	0.0	1,441.2	1,441.2	0.0	1,441.2	0.0
Groups	1,212.2	0.0	1,212.2	1,212.2	0.0	1,212.2	0.0
Other Fruits	2,279.6	0.0	2,279.6	2,279.6	0.0	2,279.6	0.0
Jouf							
Total Revenue (Billion SAR)	2.104		2.100		2.097	1.895	
Profit (Billion SAR)	1.207		1.199		1.196	1.029	
Total irrigation water used (BCM)	1.471		1.431		1.431	1.121	
Total Cropland (ha)	94,481.2		94,480.7		94,481.2	94,481.2	
Crops	Cropland	Subsidies (+/-)	Leader Cropland (ha)	Follower Cropland (ha)	Subsidies (+/-)	Cropland	Subsidies (+/-)
Cereal Group							
Wheat	49,967.0	656.0	51,022.6	51,022.6	656.0	61,956.1	656.0
Barley	646.6	755.0	795.5	795.5	755.0	795.5	755.0
Sorghum	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maize	435.8	713.0	0.0	0.0	713.0	0.0	713.0
Millet	-	-	-	-	-	-	-
Sesame	-	-	-	-	-	-	-
Other Cereal	13.6	0.0	16.9	16.9	0.0	16.9	0.0
Vegetables Group							
Tomato	649.5	0.0	587.8	587.8	0.0	587.8	0.0
Tomato (GH)	114.9	890.0	108.0	108.0	680.0	108.0	890.0
Eggplant	33.2	0.0	42.6	42.6	0.0	42.6	0.0
Squash	102.5	0.0	188.9	188.9	0.0	188.9	0.0
Squash (GH)	22.1	0.0	40.0	40.0	0.0	40.0	0.0
Cucumber	23.5	0.0	27.8	27.8	0.0	27.8	0.0
Cucumber (GH)	61.7	0.0	76.0	76.0	0.0	76.0	0.0
Okra	88.4	0.0	106.4	106.4	0.0	106.4	0.0
Carrots	74.8	0.0	57.1	57.1	0.0	57.1	0.0
Potato	1,282.6	0.0	1,814.7	1,814.7	0.0	1,814.7	0.0
Dry Onion	1,188.8	0.0	809.8	809.8	0.0	809.8	0.0
Melon	31.0	0.0	17.7	17.7	0.0	17.7	0.0
Watermelon	35.8	0.0	62.7	62.7	0.0	62.7	0.0
Other Vegetable	77.1	0.0	173.9	173.9	0.0	173.9	0.0
Other Vegetable (GH)	4.9	0.0	8.0	8.0	0.0	8.0	0.0
Fodder Group							
Alfalfa	12,603.4	0.0	10,933.4	10,933.4	0.0	0.0	0.0
Other Fodder	510.2	0.0	1,077.6	1,077.6	0.0	1,077.6	0.0

Continue of Table 4-3

Fruits Group							
Dates	5,215.0	0.0	5,215.0	5,215.0	0.0	5,215.0	0.0
Citrus	716.8	0.0	716.8	716.8	0.0	716.8	0.0
Groups	1,371.8	0.0	1,371.8	1,371.8	0.0	1,371.8	0.0
Other Fruits	19,210.2	0.0	19,210.2	19,210.2	0.0	19,210.2	0.0

CHAPTER 5. ANALYSIS AND CONCLUSIONS

5.1. Introduction

Initially the chapter provides a synthesis and discussion of the analytical results of the dissertation provided in Chapter 4. The first part of the synthesis examines the extent to which it is possible to achieve the current level of food security while using less irrigation water, while the second part discusses possible trade-offs between the two government objectives of minimizing irrigation water use and maximizing food security. This discusion is extended using the concept of Pareto Optimality to see how the government could apply policies to better achieve a balance between its objectives. The remainder of the chapter provides some conclusions from the analysis, asesses limitaions of the research and suggests opportunities for future research that can extend the modelling approach.

5.1.1. Is it possible to maintain the current level of food security while reducing irrigation water use?

The dissertation aims to find a balance between the goals of minimizing irrigation water use and satisfying a specific level of food security. To do this the dissertation used two algorithms, RIWP and IIWMP to achieve the objective. Results show that with the IIWMP algorithm it is possible to maintain the current level of food security and reduce irrigation water with appropriate government intervention. By government using a combination of policies that: adjust the distribution of irrigation water among regions, and impose crop specific subsidies, and taxes, both of the government's objectives can be achieved. For this to happen, government interventions must take into account farmers' goal of maximizing profit, and policies must be designed so that farmers respond to the government's goals.

Figure 5.1 shows the results of two "status quo" situations with the first one estimated using the current price set, while the second status quo is estimated with the adjusted price set. In each solution the level of food security is held constant while irrigation water is reduced. The figure shows that it is possible to maintain the current level of food security and achieve a greater reduction in irrigation water used by applying the IIWMP algorithm. The optimal solutions show the first status quo reduced irrigation water by 3.718 BCM while the second status quo reduced it 2.87 BCM.

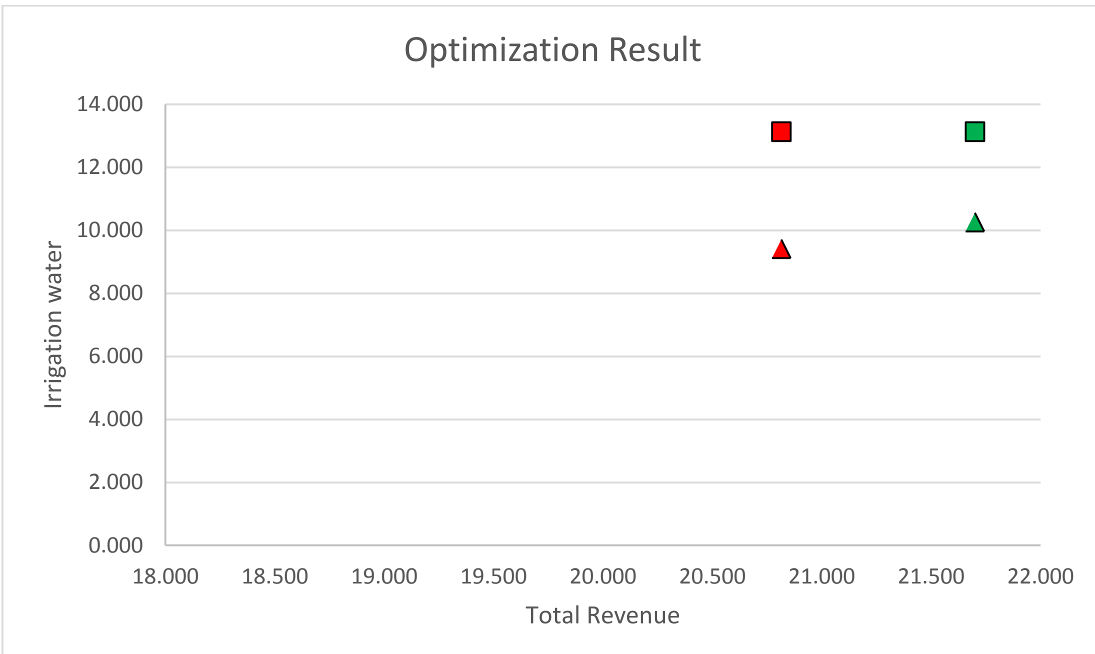

Figure 5-1 Optimal solution of the two status quo points.

- Represents the initial solution of the first status quo
- Represents the optimal solution with Government intervention of the first status quo
- Represents the initial solution of the second status quo
- Represents the optimal solution with g Government intervention of the second status quo

5.1.2. The trade-off between the two objectives

As the dissertation adopted the *a posteriori* preference approach to solving the bi-level multi-objective multi-follower situation, this section provides the results from running a number of different levels of food security (total product revenues) to show the trade-off between the two objectives. This provides a multi-solution option that can allow the leader, decision-maker, or government to select the best solution to maximize its utility. The dissertation also used the ε-constraints method, which provides a different level of solutions to solve the bi-level optimization problem. Thus, the dissertation finds a number of multi-solution options, but not all of these solutions are Pareto Optimal.

Figure 5.2 shows the results from running 23 scenarios using the IIWMP algorithm to minimize irrigation water while satisfy a range of total revenue constraints. The entire solution set meets the bi-level optimization condition, which is that a crop pattern suggested by the leader or government is adopted by the followers or farmers. The multi-solution option starts with a high total revenue target, which is 22.892 billion SAR and moves in steps to a low total revenue target, which is 18.313 billion SAR. The results show that increases in the level of food security require using more of the irrigation water. This result is obvious as irrigation water is one of the main inputs in the agricultural sector.

Figure 5.2 shows the two status quo points as well as the efficient solution points, and initial results for the RIWP and IIWMP algorithms. The result of the RIWP algorithm leads to a reduction of the irrigation water, but does not satisfy the food security target. Meanwhile, the IIWMP algorithm is more efficient, as the government reaches its total revenue target with less irrigation water at both status quo points. Not all of these solutions are Pareto Optimal, but all of them are more efficient solutions than the status quo points.

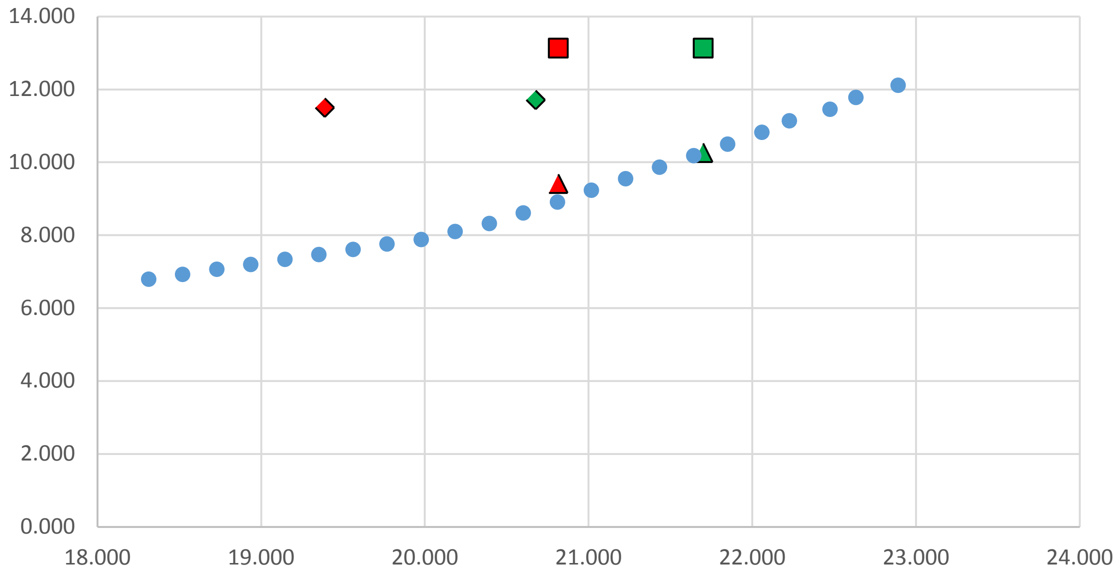

Figure 5-2 Comparing the result between the algorithms and shows the efficient solution of running bi-level multi-objective multi-follower for a different level of total revenue.

- Represent the initial of the first case
- Represent the solution of the first round of the algorithm of the first case
- Represent the optimal solution with g Government intervention of the first case
- Represent the initial of the second case
- Represent the solution of the first round of the algorithm of the second case
- Represent the optimal solution with g Government intervention of the second case

Figure 5.2 also shows the results of running the IIWMP algorithm scenario to optimize the allocation of irrigation water. A subset of these points is Pareto Optimal. As the study has two of the status quo points or levels of total revenues, one of them is Pareto Optimal while the other is not. The study does not find any Pareto Optimal solutions for the second status quo, which is the second level of total revenues, but the alternative solution is more efficient than the status quo point. Therefore, when the government decides to move to one of these solutions, the new optimal solution will minimize the irrigation water use, but some farms/regions will experience less profit. On the other hand, the first status quo point has ten alternative solutions that satisfy the government's objectives and does not harm any of its followers (i.e., farmers).

Figure 5.3 shows the set of optimal solutions and describes the relationship between the irrigation water used objective and the total revenue objective. The relationship between the two objectives is positive, which means the government wants to increase the level of food security, which will require more irrigation water. The model also provides a subset solution that could be more efficient than the two status quo points, as shown in Figure 5.2.

A subset of the solution can be a non-dominated solution (Pareto front), and all these points on this curve are strictly Pareto Optimal, as shown in Figure 5.3. In detail, the second status quo point is not Pareto Optimal, but some points increase the effectiveness of using irrigation water. Thus, if the government decides to develop the observed solution, one region would highly benefit. Using the first status quo point as the initial point, then the government has 10alternative solutions that reduce irrigation water consumption and increase total revenues. However, Figure 5.3 shows the Pareto Optimal front, which involves points that lead to minimizing irrigation water while no regions/farmers experience reduced profits, as observed in Table 5.1. The best Pareto Optimal point occurs when target revenues are 21.019 billion SAR, and optimal irrigation consumption was 9.223 BCM. Under this scenario, all farmers/regions benefit. These scenarios demonstrate that the government has the opportunity to develop irrigation water management policies that reduce irrigation water consumption and increase the total revenues from agricultural production.

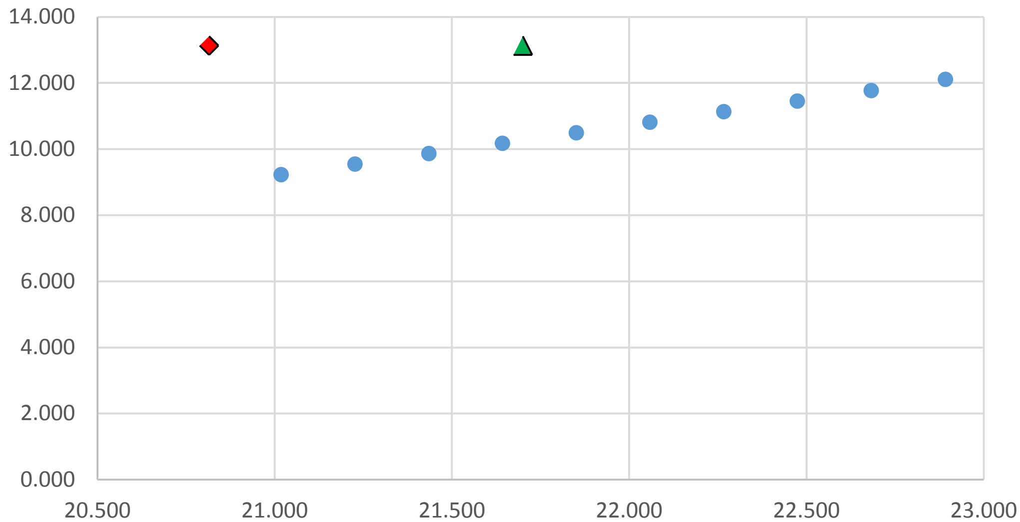

Figure 5-3 Pareto Optimal Front for the first status quo point

Table 5-1 All Pareto Optimal Compare to the status quo point of First Case

	Total Return (Billion SAR)	Water Irrigation Consumption (BCM)	Riyadh	Qassem	Eastern	Tabuk	Hail	Jouf
Current Crop Pattern	20.815	13.131	5.051	2.342	1.755	0.493	1.153	0.958
Scenario 1	22.892	12.103	5.934	2.367	2.139	0.580	1.198	1.211
Scenario 2	22.684	11.770	5.890	2.367	2.139	0.580	1.198	1.211
Scenario 3	22.475	11.447	5.886	2.367	2.139	0.543	1.198	1.088
Scenario 4	22.267	11.129	5.807	2.367	2.139	0.543	1.198	1.029
Scenario 5	22.059	10.811	5.685	2.367	2.139	0.543	1.198	1.029
Scenario 6	21.851	10.493	5.563	2.367	2.139	0.543	1.198	1.029
Scenario 7	21.643	10.176	5.441	2.367	2.139	0.543	1.198	1.029
Scenario 8	21.435	9.858	5.320	2.367	2.139	0.543	1.198	1.029
Scenario 9	21.227	9.540	5.198	2.367	2.139	0.543	1.198	1.029
Scenario 10	21.019	9.223	5.076	2.367	2.139	0.543	1.198	1.029

5.1.3. Policy to balance the government objectives while considering the farm objectives.

Since there is a difference between farms' objectives (maximize profit) and the government's objectives (balance food security and irrigation water use), the government has to find policies that lead farmers to make a decision that satisfies the government objectives. The conflated objectives between the government and farmers present a principal-agent problem. Resolving the principal-agent problem requires supplemental policies, such as taxes and subsidies to alter farmers' behavior. In particular, the IIWMP algorithm suggests the government can control irrigation water use among the regions and impose subsidies and taxes to encourage the farmers to adopt the government's objectives.

Model results show that it is possible to reduce irrigation water use from 2.863 to 3.716 BCM while holding total revenue constant. The model assumes the government has control over irrigation water used in each region and imposes a policy to guide farmers in adopting its objectives. This reduction in water use results from government controlling irrigation water use, as well the government adopting policies that encourage farmers to produce new combinations of quantity and variety of crops to reach a specific level of food security.

Thus, when the government determines the amount of irrigation water for each region, it also imposes policies that encourage farmers to meet government objectives. The policies used are combinations of subsidies and taxes that alter the profitability of different crops on a region by region basis. Thus, the government control irrigation water and used subsidies and taxes to control agricultural production to achieve its objectives.

Each region has unique irrigation water targets and policies. For example, Table 4.2 shows that the solution for Hail region suggests the government impose subsidies for wheat of SAR 480 per ton and potatoes by SAR 968 per ton. On the other hand, the government imposes taxes on barley (SAR 55 per ton), other cereals (SAR 56), alfalfa (866 SAR), and other fodder (SAR 982). These subsidies motivate farmers to increase the production of wheat and potatoes while the taxes drive the farmers to stop growing crops that require a large amount of irrigation water to grow.

However, a remaining question is how should the government apply the subsidies. One suggestion is the use of a price floor. The government provides the price floor for specific crops it would support in each region and then pays the difference between the price floor and market price to farmers. Further while the policies satisfy an national revenue constraint they may not ensure that no region is worse off without additional effort. In other words, are the new policies Pareto Optimal or not?

5.2. Conclusion

Dissertation results shows there is potential to reduce irrigation water use while improving the current level of food security if the government chooses the right policy mix. The IIWMP algorithm suggests a possible policy regime that reduces water use and achieves target total revenues. The IIWMP algorithm solves the bi-level, multi-objective, multi-follower programming problem that characterized the current situation in Saudi Arabia. The algorithm aims to minimize the irrigation water consumption that six regions in Saudi Arabia use while satisfying a total revenue target. The algorithm integrates the reallocation of irrigation water among the region and applies supplemental agricultural policies that fit each region. In other words, the algorithm suggests some policy set for each region to encourage the farmers to adopt the government's plan. For instance, the algorithm suggests imposing a tax on those farmers who grow fodder to motivate farmers to stop growing fodder. Meanwhile, the algorithm also suggests imposing subsidies to encourage farmers to grow specific crops, as was observed in most regions.

The bi-level, multi-objective, multi-follower programming approach provides a means to examine alternative ways to achieve conflicting government objectives, where the government must rely on other agents to actually undertake the actions that will achieve its objectives. The models show that government relying solely on water restrictions can achieve a reductions in water use, but that a consequence of this is a reduction in food security, even though it may be possible to achieve the target level of output in principle. To address the underlying principal-agent problem the model uses taxes and policies to alter famer behavior, but it is possible to adopt other policy mechanisms that could achieve similar results. By explicitly using a regional model the potential for some regions to win or lose from government policy that focuses on national level objectives is made clear.

Based on these results, the government should invest in farmers in order to reduce the consumption of irrigation water through the efficient allocation of subsidies. The government has to deal with each region independently and with policies that help the government achieve its goals and farmers' objectives in those regions, whereas agricultural policies in the past were symmetrically directed to all regions while the government neglected the comparative advantage of each region.

5.3. Limitations

The limitation of the study focus on a different parts, such as:

1- Ignores the livestock sector, which has a big impact on current crop choices. The result of the model shows the government would achieve the balance between minimizing the irrigation water used and food security through reduce growing the fodder group and feed grains. This has big implication for the livestock sector that are not considered.

2- Assumes a single farm in each region. To make the model simpler, the study assumes each region represented as a single farm. With multiple farms variability in resources, management ability and objectives will complicate analysis.

3- Assumes average water quality used in each region. In reality water quality varies considerably across regions, and with different levels of water quality crop yield functions are more variable.

4- Does not explicitly consider the impact of the current agricultural policy. AsSaudi Arabia changes its set of policies these provide specific incentives or disincentives to grow particular crops and this in turn alters water use..

5- Use total revenue as a proxy for food security. In reality crop mixes that have equal market value can have very different nutritional content and market scope. Disaggregating the food security target into specific quantities of different crops would resolve this problem but would increase the complexity of the analysis.

6- Government policy is restricted to two objectives of reducing irrigation water use and improving food security. In reality the government may have a larger set of objectives which could increase the potential for additional conflicts among government objectives.

5.4. Future Work

The result of the research helped to open the mind and think on the topic from different cornel and domination. So, the following list shows the ideas could work in the future.

1- Model refinements to address limitations.

2- Expand the number of irrigation technologies because the current dissertation just uses the average irrigation efficiency of an irrigation system.

3- Develop a broader definition of food security and investigate water needs for various level/mixes of crops.

4- The bi-level multi-objective multi-follower optimization model in this study assumed that each region is independent in terms of its objective function, but this is not true. As the primary water source is groundwater and some regions share the aquifer, they share these constraints. Therefore, there is a water availability constraint among these regions. Future studies could explore this constraint, which may give different results than what this study obtained.

REFERENCES

(GAFS), G.A.f.S. 2015. *Detaled result of the Agricultural Census.* General Authority for Statistics.

Abderrahman, W.A. 2005. "Groundwater management for sustainable development of urban and rural areas in extremely arid regions: A case study." *International Journal of Water Resources Development* 21:403-412.

Agriculture, M.o. 2014. *Agricultural Statistical Year Book.* Saudi Arabia - Ministry of Agriculture: Ministry of Agriculture

---. 2005. *Time series of agricultural statistics in the Kingdom of Saudi Arabia during three decades.* Ministry of Agriculture.

Al-Abdulkader, A.M. 2004. "Enterprise budgets of some greenhouse vegetable crops in Saudi Arabia." *Emirates Journal of Food and Agriculture*:39-47.

Al-Ghabari, H.M., F.S. Mohammed, A.M. Al-Omran, and A.R.A. Alazba. "Develop a model for estimating water requirements for the rationalization of irrigation water in the Kingdom of Saudi Arabia." King Abdulaziz City for Science and Technology.

Al-Ghobari, H.M. 2000. "Estimation of reference evapotranspiration for southern region of Saudi Arabia." *Irrigation Science* 19:81-86.

Al-Ibrahim, A.A. 1990. "Water use in Saudi Arabia: problems and policy implications." *Journal of Water Resources Planning and Management* 116:375-388.

Al-Kahtani, S., and S. Ismaiel. 1997. "The Response of Protected Tomato Producers to Market Condition Changes in Riyadh Region in Saudi Arabia." *King Saud University (Agricultural Sciences)* 2:20.

Al-Turki, A.I. (2009) "Evaluation of well water quality in Hael region of central of Saudi Arabia." In *Proceedings of the 13th International Water Technology Conference.* Citeseer, pp. 1121-1132.

Al-Zahrani, K.H. 2003. *Agricultural Developments in Saudi Arabia 1402H-1422H*. Saudi Arabia, Riyadh: King Saud University Press.

Alamoudi, A.I., A.S. AlTokhis, F.S. Awad, A.M. Al Abdalqader, A.m. Al mashaileh, J.M. Al Badri Bushey, Y.Y. Al Dakhil, A.A. Al azba, and S.A. Al Hamed. "A Guide to Estimate Crop Water Requirements in Saudi Arabia." King Abdulaziz City for Science and Technology.

Alghamdi, M.H. 2000. "A Survy of the Situation of Groundwater in Light of the Expansion in the Cultivation of Wheat, Barley, and Fodder Crops in the Kingdom of Saudi Arabia." *Scientific Journal of King Faisal University* 1:24.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. "Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56." *FAO, Rome* 300:D05109.

Alsharhan, A., Z. Rizk, A.E.M. Nairn, D. Bakhit, and S. Alhajari. 2001. *Hydrogeology of an arid region: the Arabian Gulf and adjoining areas*: Elsevier.

Andersson, J. 2000. "A survey of multiobjective optimization in engineering design." *Department of Mechanical Engineering, Linktjping University. Sweden*.

Authorty, C.P. 1970. *the First Five-Year Plan 1970-1974.* Riyadh, Saudi Arabia: Central Planning Authorty.

Bard, J.F. 1988. "Convex two-level optimization." *Mathematical programming* 40:15-27.

Chiandussi, G., M. Codegone, S. Ferrero, and F.E. Varesio. 2012. "Comparison of multi-objective optimization methodologies for engineering applications." *Computers & Mathematics with Applications* 63:912-942.

Cho, J.-H., Y. Wang, R. Chen, K.S. Chan, and A. Swami. 2017. "A Survey on Modeling and Optimizing Multi-Objective Systems." *IEEE Communications Surveys & Tutorials*.

Chowdhury, S., and M. Al-Zahrani. 2015. "Characterizing water resources and trends of sector wise water consumptions in Saudi Arabia." *Journal of King Saud University-Engineering Sciences* 27:68-82.

--- (2012) "Water resources and water consumption pattern in Saudi Arabia." In *The Arab Countries Water Utilities Association (ACWUA), The 10th Gulf Water Conference*. pp. 67-81.

Cohon, J.L., and D.H. Marks. 1975. "A review and evaluation of multiobjective programing techniques." *Water Resources Research* 11:208-220.

Colson, B., P. Marcotte, and G. Savard. 2007. "An overview of bilevel optimization." *Annals of operations research* 153:235-256.

Electricity, M.o.W. 2012. "NOMINATION OF Ministry of Water & Electricity Kingdom of Saudi Arabia, Supporting Documents For King Hassan II Great World Water Prize 2012." Paper presented at KING HASSAN II GREAT WORLD WATER PRIZE. Marseille – France, 2012.

Electricity, M.o.W.a. 2014. *Statistical Report 2014.*

---. 2015. *Statistical Report 2015.*

Falatah, A.M., A.M. Al-Omran, M.S. Nadeem, and M.M. Mursi. 1999. "Chemical composition of irrigation ground water used in some agricultural regions of Saudi Arabia." *Emirates Journal for Agricultural Sciences* 11:23.

FAO. "Groundwater Management in Saudi Arabia

Draft Synthesis Report."

Fernandes, C., J.E. Corá, and J.A.C.d. Araújo. 2003. "Reference evapotranspiration estimation inside greenhouses." *Scientia Agricola* 60:591-594.

Hakanen, J., M. Hartikainen, and K. Sindhya (2013) "Nonlinear Multiobjective Optimization." In.

Kahil, M.T., A. Dinar, and J. Albiac. 2015. "Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions." *Journal of Hydrology* 522:95-109.

Lu, J., C. Shi, and G. Zhang. 2006. "On bilevel multi-follower decision making: General framework and solutions." *Information Sciences* 176:1607-1627.

Lu, J., G. Zhang, J. Montero, and L. Garmendia. 2012. "Multifollower trilevel decision making models and system." *IEEE Transactions on Industrial Informatics* 8:974-985.

Marler, R.T., and J.S. Arora. 2004. "Survey of multi-objective optimization methods for engineering." *Structural and multidisciplinary optimization* 26:369-395.

Mavrotas, G. 2009. "Effective implementation of the ε-constraint method in multi-objective mathematical programming problems." *Applied mathematics and computation* 213:455-465.

Mpusia, P.T.O. (2006) "Comparison of water consumption between greenhouse and outdoor cultivation." In., ITC Enschede.

Nowshirvani, V. 1987. "The Yellow Brick Road: Self-Sufficiency or Self-Enrichment in Saudi Agriculture?" *MERIP Middle East Report*:7-13.

Omran, A. (2008) "Water requirements for irrigation and rationalization." In., King Saud University Press.

Önal, H., and B.A. McCARL. 1989. "Aggregation of heterogeneous firms in mathematical programming models." *European Review of Agricultural Economics* 16:499-513.

---. 1991. "Exact aggregation in mathematical programming sector models." *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie* 39:319-334.

Paranychianakis, N., and K. Chartzoulakis. 2005. "Irrigation of Mediterranean crops with saline water: from physiology to management practices." *Agriculture, ecosystems & environment* 106:171-187.

Qhanim, A.M., and K. Alrwis. 2004. "Current and Suggested Cropping Pattern with Respect to the Water Security in Saudi Arabia." *Journal of Saud University, Agricultural Sciences* 17:26.

Savva, A.P., and K. Frenken. 2002. *Crop water requirements and irrigation scheduling*: FAO Sub-Regional Office for East and Southern Africa Harare.

Sciolino, E. (1985) "Saudis Wring Most of Their Water From The Sea." In *The New York Times*. pp. 001018.

Singh, V., K. Tiwari, and D. Santosh. 2016. "Estimation of Crop Coefficient and Water Requirement of Dutch Roses (Rosa hybrida) under Greenhouse and Open Field Conditions." *Irrigat Drainage Sys Eng* 5:2.

Sinha, A. 2011. *Progressively interactive evolutionary multiobjective optimization*: Aalto University.

Water, M.o.A.a. 1984. *Water Atlas of Saudi Arabia* Riyadh, Saudi Arabia,

: Ministry of Agriculture and Water.

World-Grain.com (2016) "Saudi Arabia ends domestic wheat production program." In., World-Grain.com.

Xu, J., Z. Li, and Z. Tao. 2016. *Random-Like Bi-level Decision Making*: Springer.

Yamashita, A., A. Zanin, and D. Odloak. 2016. "TUNING OF MODEL PREDICTIVE CONTROL WITH MULTI-OBJECTIVE OPTIMIZATION." *Brazilian Journal of Chemical Engineering* 33:333-346.

Youssef, A.M., and N.H. Maerz. 2013. "Overview of some geological hazards in the Saudi Arabia." *Environmental earth sciences* 70:3115-3130.

Zhang, G., J. Lu, and Y. Gao. 2015. *Multi–Level Decision Making*: Springer.

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