Water Trading: Irrigation Technology Adoption and Economic Impact of Transboundary Water Reallocation

by

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Abstract

The overall purpose of the study is to evaluate how water trading could improve water use efficiency in southern Alberta, Canada and how benefits of water reallocation could be achieved in the Nile River basin in Africa. The impact of water scarcity has become more prominent in these areas in recent years because of increasing population growth, urbanization rates, and unexpected changes in climate patterns. The ability to supply water to meet the needs of multiple sectors of the society is a compelling challenge to policy makers in the developed and in the developing world.

In the first paper, the gain of adopting efficient irrigation technologies as a major water conservation strategy is assessed in southern Alberta, Canada. Water trading is modeled with a choice of irrigation technology adoption. Simulation results show that farmers will be willing to use efficient irrigation technologies when the net gains from adoption are higher than the cost of adoption. However, the adoption of most efficient irrigation technologies is more likely to occur when water conservation-induced polices are provided in the South Saskatchewan River Basin (SSRB).

In the second paper, the economic impact of altering the current agreement governing the Nile River Basin is assessed. The Nile River basin is still governed by the 1959 agreement signed between Egypt and Sudan, without the upstream countries. With this agreement, of the annual average 84 billion cubic meters (BCM) of Nile River water, 66 percent is allocated to Egypt and 22 percent to Sudan with the remaining 12 percent going to surface evaporation and seepage at the Aswan High Dam in Egypt. The simulation results show that under certainty conditions, reallocation of water to Ethiopia would have minimal impact on the economies of Egypt and

Sudan. However, under stochastic conditions, a greater negative impact is observed in the agricultural sector while in both countries the industrial and services sectors improve. Overall, there is a net welfare gain of 3.1 percent of Gross Domestic Product (GDP) of all the three countries under certainty conditions of water reallocation. Under stochastic conditions, however, there is a 0.53 percent net welfare loss of GDP to the three countries with water reallocation. These results tend to suggest that if these countries could cooperate, it would be possible to mitigate the negative impacts of water reallocation on Egypt and Sudan.

Dedication

To my family, wife and children

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction to the Research Papers

1.1 Introduction

Water is a highly valuable resource with a large number of competing demands, which include water for households, irrigation, hydropower generation and ecosystem services (Rosegrant et al., 2002; Saleth and Dinar, 2004). The ability to supply water to meet the needs of the multiple sectors of the society is a compelling challenge to policy makers in the developed and in the developing world. Concurrently, due to spatially uneven distribution of precipitation and rapidly increasing water demands driven by the world population, climate changes, as well as degradation of freshwater resources, there is an increasing scarcity of water resources in many countries. By 2025, 1.8 billion people are estimated to be living in areas with absolute water scarcity, and approximately half of the global population could be under water-stress conditions (Rosegrant et al., 2002). In fact, the consequences of water scarcity are already evident in 80 countries which constitute 40 percent of the world population (Gleick, 1993; Hamdy et al., 2003).

Many overpopulated countries are nearing or presently exceeding their sustainable water resource utilization levels and cannot meet the basic water needs of their rapidly growing populations because of water shortages (Gleick, 1993). Also, water scarcity has led most of these countries to increase food imports because the local agriculture sector is not able to produce sufficient food to support the existing food supply within acceptable levels (Saleth and Dinar, 2004). These increasing food supply gaps are posing serious challenges beyond the economic and political resources needed for the necessary developments concerning the allocation and use of water in all sectors, particularly in agriculture. Often, the effects of water scarcity also spill over the social and political arenas, causing severe water conflicts among competing users, regions, and countries (Gleick, 1993; Wolf et al., 2003).

The economic burden of water scarcity is one of the most pervasive natural resource allocation problems faced by policy makers in arid and semiarid countries. It is also recognized that water scarcity results not only from decreasing levels of water, but also from inefficient water use and mismanagement, institutional weakness and ineffective policies (Livingston, 1995; Dinar et al., 1997; Bruns and Meinzen-Dick, 2005). Consequently, water resource management has become a social and economic issue of the present century and policy makers face new challenges of growing societal demands but with fewer water supplies (Bruns and Meinzen-Dick, 2005). Over the years, engineering approaches (e.g., development of dam and irrigation canal systems) have been used to achieve more reliable water supply. In recent years, however, demand management approaches (e.g., water markets, water pricing) are proving to be effective and appropriate in many countries (e.g., Australia, United States, and Chile). The challenge is how to develop policies to encourage efficient use of water for current and future generations. Many studies have been carried out in this domain (Dinar et al., 1997; Livingston, 1995; Saleth and Dinar, 2004; Bruns and Meinzen-Dick, 2005), but there are still many obstacles to reaching efficient, equitable and sustainable water allocation levels. For instance, existing water agreements such as the Nile treaty and Water Act in Alberta are lagging far behind current development needs of rapidly growing populations. These agreements usually lack adequate support systems and efficient mechanisms necessary to provide guidelines for sustainable water management. As a result of these factors (i.e., debate and lack of understanding) they have not been used as extensively as would be indicated.

1.2 Economic Problem

The economic problem this thesis seeks to address relates to the implications of water scarcity; that is, when the demand for water is high relative to supply. This issue is further aggravated due to increasing population growth and climate changes in arid and semiarid countries. Presently, in most countries suffering from water shortages, and at the heart of this issue, is the question of whether a water crisis can be averted or whether water can be more productive. Increasing the productivity of water is central to producing food, to fighting poverty, to reducing competition for water and to ensuring that there is enough water to support ecosystem services (Gleick, 1993). The more we produce with less water, the lesser the need for water storage development, and the fewer the conflicts among many competing users. Essentially, this provides a greater opportunity to achieve local food security and ensures that more water is available for alternative sectors such as household and industrial uses (Rosegrant et al., 2002; Hamdy et al., 2003). However, to achieve such goals, major improvements are still required in water resource use and irrigation technology management. Meeting such challenges will require a far greater effort and significant changes in how water is managed.

Traditionally, water shortages in arid and semi-arid regions have been addressed through developing more reliable supplies. But as the uses of water have changed and expanded and as more accessible resources have been fully exploited, so the costs for further supply-side options have increased dramatically. This pressure on the supply-side management of water is further aggravated with unexpected climatic conditions in many arid and semiarid countries. Floods and droughts are expected to occur faster and be more intense because of changing precipitation and atmospheric circulation patterns and increasing temperatures. The overall effect of climate change on fresh water resources is a change in the mean runoff, an increase in runoff variability, both between seasons and between years, and an increase in the frequency of extreme events (IPCC, 2007). Many areas, especially in arid and semi-arid climates, will see an overall decrease in water availability. This result adds to the already existing uncertainty in the availability of water resources.

This growing scarcity, rising cost of water and climate change impacts have led to the realization that water has to be allocated and used more efficiently. In achieving efficiency of water use, demand management approaches provide feasible options for policy-makers. This approach is appropriate because it targets the water user rather than the supply of water to achieve more desirable allocations and sustainable use of water. Effective policies designed with demand management approaches are required in these countries to deal with the scarcity problem. It is pertinent to investigate the potential economic benefits associated with various demand management principles. In this thesis, demand management approaches, such as water trading are applied to assess efficiency of water use in southern Alberta while economic modeling approaches are used to assess the impact of possible water reallocation in the Nile River Basin, Africa.

1.3 Study Objectives

The overall goal of this thesis is to investigate policies necessary for efficient and equitable considerations of water management in southern Alberta, Canada and in the Blue Nile River Basin, Africa. Thus, the scope of the study is at the regional and international scales which are consistent with the levels at which policies necessary to achieve efficiency of water use are evaluated. To be specific, given the economic problem on water scarcity, three broad objectives of the thesis are:

1. To examine the gains from water trading, irrigation technology adoption and crop choices in southern Alberta.

2. To analyze the economic impact of water reallocation in Egypt, Sudan and Ethiopia, and to identify potential economy-wide benefits of cooperation among these nations.

3. To examine policies necessary to mitigate impacts associated with water reallocation in Canada and in Africa.

1.4 Thesis Structure

In this thesis, two studies are conducted at the regional and international levels of water management. These studies investigate a range of institutional, microeconomic, and macroeconomic interactions in a competitive market, which affect the behavior of water users in Canada and in Africa. The information generated by this thesis will help: (1) individuals interested in investigating the efficiency of water allocation at different scales; (2) water managers to explore institutions that support efficient and equitable water policies; (3) policy makers in making decisions on the efficient and equitable use of water resources in a trans-boundary context.

The first study of this thesis focuses on modeling the gains from water trading among irrigators in southern Alberta, Canada. Irrigation in Alberta started in the 1800s. A variety of water management policies have been enacted through the 1990s and beyond. Examples of different water management policies are the Natural Resources Transfer Act (1930), and the Water Resources Act (1931) that require water licences for all water uses except for household consumption (Alberta, 1930; Alberta, 1931). A major drawback of the Water Resources Act was that it did not allow for water trading, a mechanism that encourages efficiency of water use. As a result, the Alberta government passed the Water Act in 1999 (Alberta, 2000a: Section 81). The Water Act does allow transfer of water between districts, but under strict conditions. For instance, a district is unable to transfer water licenses out of their jurisdiction except in cases where more than 50 percent of the irrigation district membership agrees after a plebiscite has been held or where the Minister waives the requirement for a plebiscite to be held (Alberta, 2000a: Section 81; Alberta, 2000b: Section 11). However, the Act does allow for the transfer of water within each of the irrigation districts (Viney et al., 1996). In response to the increasing water scarcity in the province and the urgency to develop sustainable measures to manage water in the southern part of the province, Alberta's Water for Life Strategy was formulated in 2003 and renewed in 2008. This strategy was designed to address present and future water-scarcity challenges. A major goal of the strategy is to achieve efficiency and increased productivity of water use in Alberta (Alberta Environment, 2003).

Economic studies have examined various issues related to Alberta's new water law and policy. These issues include pricing systems (Peacey, 1995; Hatch, 1995; Adamowicz and Horbulyk, 1996); value of water rights (Veeman et al., 1997); farm water demand, risk and uncertainty analysis (Hatch, 1995; Viney et al., 1996, Gheblawi, 2004); efficiency gains from water trading (Horbulyk and Lo, 1998; Mahan et al., 2002; Cutlac et al., 2006); and potential benefits of water sharing among irrigation districts (He and Horbulyk, 2010; He et al., 2012). These studies focus on aggregate welfare gains from water reallocation and water trading, and therefore do not capture farm-level incentives for irrigation technology adoption, crop choices and heterogeneous issues. However, in irrigated agriculture, differences in land quality have been shown to be an important factor in determining adoption decisions on both irrigation technologies and crop choices at the farm level (Caswell and Zilberman, 1986).

Previous US studies have applied a farm-level profit model under different water management policy objectives. This model has been applied to examine the gains from irrigation technology adoption (Caswell and Zilberman, 1986); external effects of input use and environmental policies in resources conservation and pollution reduction (Caswell et al., 1990); and diffusion of resource-quality augmenting irrigation technologies under output supply and input demand effects (Caswell et al., 1993). However, the above studies ignore trading of water rights. The ability to trade these rights may encourage greater efficiency of water use.

Burness and Quirk (1980) indicate that without water trading, senior rights holders have an incentive to irrigate all their land, which may leave the junior rights holders with little or no water. The literature on water trading and technology adoption focuses on drainage reduction (Dinar and Latey, 1991), price uncertainty and transaction costs (Carey and Zilberman, 2002; Carey et al., 2002) and imperfect information (Dridi and Khanna, 2005). Little attention has been given to investigating gains from farmers switching among different irrigation technologies after water trading to produce profitable crops and the effects of transaction costs on the gains from water trading. In this thesis, the Caswell and Zilberman (1986) model is applied for the first time to southern Alberta, Canada. Unlike previous studies, the model is expanded to incorporate: (1) six main irrigation technologies and 12 crops, and (2) water trading, irrigation technology adoption and crop choices under future drought conditions in southern Alberta.

The second study explicitly focuses on the economic impact of water reallocation given current agreements in transboundary water management in Africa. Water resources and environmental management problems often engage multiple stakeholders with conflicting interests (Dinar, 2006). For example, the Nile River Basin has ten riparian countries with Egypt and Sudan being the largest users of the Nile waters. These countries have become the major users because of the 1959 Nile River Agreement (Wolf et al., 2003). This agreement was signed only between Egypt and Sudan. In fact, this agreement followed an earlier one signed in 1929 between Egypt and Great Britain who represented its colonies Sudan, Tanzania, Kenya and Uganda. Both treaties shared the flow between the most downstream countries (i.e., Egypt and Sudan) without consulting other riparian countries. Ethiopia, which contributes 86 percent of the annual discharge of the Nile River, has challenged the validity of this treaty and has expressed its disagreement to these countries. Ethiopia, which is upstream from Egypt and Sudan, defends its claim based on the principle of "reasonable and equitable use", a notion introduced by the Helsinki Rules (International Law association, 1996). Egypt and Sudan defend their claims by the principle of historic rights and the United Nations (UN) watercourse convention (United Nation, 1997) as well as the Berlin Rules (International Law Association, 2004).

Given the nature of conflict on water rights within the basin, economic impact analysis may provide insights into gains and losses with possible water reallocation in the basin (Waterbury, 1997). Most studies indicate that water scarcity issues in a transboundary context are more likely to be resolved through cooperation than conflict (Wolf et al., 2003; Sadoff and Grey, 2002). In transboundary settings, efforts to establish clear property rights to contested water could help increase the overall benefits of water use.

There are unresolved questions, however. What are the economic impacts of water reallocation, who are the winners and lossers and what compensation mechanisms are available to internalize the possible effects from reallocation? Also, how can the countries achieve cooperation and sustain any cooperative agreement? How can effective sustainable international water agreements be designed? Besides these questions are the issues of contested property rights to Nile River waters and the design of acceptable water allocation rules.

Previous economic studies have examined various issues related to the impacts of water reallocation and possible benefits from cooperation on the Nile River Basin. These issues include the implications of microdam development in Ethiopia (Guariso and Whittington, 1987; Waterbury and Whittington, 1998), alternative allocation policies in Egypt (Wichelns, 2002), impact of hydropower generation and irrigation supply in the Blue Nile River (Block, 2007), efficiency and water policy uncertainties in Egypt (Mohamed, 2001) and economic value of cooperation on the Nile River Basin (Whittington et al., 2005; Wu and Whittington, 2006). The cited studies suggest that, given the impacts from reallocation, cooperative development projects in the Nile River Basin could create significant economic benefits relative to the *status quo* (i.e., noncooperation). However, these previous studies are based on partial equilibrium modeling approaches. Resulting policy conclusions could be misleading since simultaneous equilibrium changes in several markets are ignored (Ginsburgh and Keyzer, 1997; Bergamn, 2005).

Transboundary water rivalry affects many sectors of the economy. Therefore a computable general equilibrium (CGE) modeling framework is appropriate to assess the impact of water reallocation and possible cooperation among countries within the basin. The strength of CGE models lies in their ability to account for inter-sectoral linkages while satisfying the constraints imposed by economic theory (Ginsburgh and Keyzer, 1997). Thus, it is possible to analyze the implementation of a water policy change as well as the distributive effects within the economies of these countries at different levels of disaggregation. Also, many of these studies have not investigated the impacts of water allocation under uncertainty conditions in the basin. Thus, CGE models can be important in guiding economic policy. They provide a bridge between the realm of economic theory and reality. CGE models have been used to estimate the economic impacts of water reallocation while estimating economic impacts using this approach is not unique in itself, simulating water reallocation in a transboundary context and explicitly capturing uncertainties into the model, until now, are yet to be explored in the water economics literature.

1.5 Contribution of the Thesis

The papers in this thesis seek to develop strategies that could lead to efficiency of water use in Canada and Africa. In particular, the first paper contributes to the literature on water conservation and farmer decision processes during water trading and irrigation technology adoption. Unlike previous studies, this study explores options on how the gains from water trading could be used in the adoption of efficient irrigation technologies to produce profitable crops under the considerations of drought. It is expected that results from the study can inform discussion and development of policies necessary to enhance water trading in southern Alberta during drought periods. The second paper builds on previous studies on the Nile River Basin, but with a focus on multi-country, multi-sectoral water reallocation. This paper seeks to model the aggregate impacts of water reallocation and provide policy options necessary to mitigate these impacts. Results from this paper could inform decision-makers seeking to develop water markets and win-win water allocations among the riparian countries and potentially adopt strategies to implement benefits sharing schemes based on feasible water allocations and equity considerations. Overall, models in all these papers could guide governments in developing more sustainable water policies.

1.6 Plan of the Thesis

The thesis is organized into four chapters followed by appendices. Following the introduction, chapter two is devoted to investigate the economic gains from water trading, irrigation technology adoption and crop choices in southern Alberta. Chapter three examines the economy-wide impacts of water use among three countries in the Nile River Basin. Both welfare and distributive impacts of the current and future water policies are examined. The final chapter provides discussion and policy conclusions of the thesis.

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Chapter 2: Modeling Irrigation Technology Adoption and Crop Choices: Gains from Water Trading with Farmer Heterogeneity in Southern Alberta, Canada

2.1 Background and Justification

Water scarcity is a major concern at both national and global levels. In recent years, the urgency of this issue has become even more pertinent because of increasing populations, urbanization, oil exploration and unexpected droughts. In the southern part of Alberta, Canada, policy makers have recognized this issue and are developing approaches to mitigate water scarcity and ensure efficient water use. Achieving efficiency[1] of water use is a prime target for policy makers in southern Alberta (Alberta Environment, 2002). Irrigation accounts for 71 percent of water allocation in the province (Alberta Environment, 2002). Most of these irrigators are in the southern part of the province, but 80 percent of water lies in the northern part of the province (Alberta Environment, 2002; Nicol and Klein, 2006).

In response to this unequal spatial distribution of water and the challenge of developing sustainable measures to manage water in the southern part of the province, Alberta's Water for Life Strategy was formulated in 2003 and renewed in 2008. This strategy envisions a holistic approach towards managing provincial water by addressing present and future water scarcity challenges. This policy document outlines key water management recommendations, one of which is to achieve efficiency and productivity of water use in Alberta through the application of economic instruments (Alberta Environment, 2003). Previously, the benefits of economic instruments such as water trading had been given policy recognition in the Water Act (Alberta, 2000a: Section 81) and in the Irrigation District Act (Alberta, 2000b: Section 11). Potential benefits from water trading occur when irrigators use the gains from trading to adopt efficient irrigation technologies or shift to crops that require less water.[2] Adopting efficient irrigation technologies such as low-pressure sprinkler or drip technologies lead to a higher proportion of

[1] In general economic efficiency has two components (Yotopoulos and Nugent, 1976; Kopp and Diewert, 1982). These are technical and allocative efficiency. Technical efficiency deals with how farmers produce different quantities of output from a given set of measured inputs of production. Allocative efficiency focuses on how to equate the value of the marginal product of each factor of production to its marginal cost. In other words, an irrigated farm is allocative inefficient if it does not use the inputs in optimal proportions, given the observed input prices, and hence does not produce at the minimum possible cost (Coelli et al., 2002; Abay et al., 2003). The product of these efficiency terms constitutes economic efficiency of resource use (Coelli, 2005).

[2] Also water trading can cause an unintended increase in water use when the licences that are traded were previously unused or underused.

applied water getting to the root zones of crops. This allows a higher level of water consumption for irrigated crops at a given level of water application, and can allow an irrigator to reduce irrigation application rates while meeting the crops' consumptive demands. Essentially, adopting efficient irrigation technologies could improve farm yields and reduce production and energy costs (Schuck et al., 2005). With increasing demand for water in the South Saskatchewan River Basin (SSRB), efficient irrigation technologies will be required to conserve significant quantities of water for alternative uses. In the SSRB, farmers have the consumptive right to most of the water that they are allowed to divert to their farms. Therefore, it is important to understand farmers' decision-making processes in terms of their impacts on the gains from water trading, irrigation technology adoption and crop choices.

If farmers "save" water from their given allocation by adopting a more efficient irrigation technology, it is their choice as to how the saved water is used (Nicol et al., 2008). Previous studies conducted in the SSRB on water trading primarily examined either inter- and intra-district aggregate welfare gains from reallocation of water relative to the "status quo" of no trading, or alternative water sharing scenarios (Horbulyk and Lo, 1998; Mahan et al., 2002; Cutlac et al., 2006; He and Horbulyk, 2010; Cutlac and Horbulyk, 2011; He et al., 2012). These studies principally focus on planning issues regarding water allocation and do not capture farm-based incentives for irrigation technology adoption, crop choices and farmer-heterogeneity issues (i.e., differences in land quality). In irrigated agriculture, differences in land quality in particular are important factors in determining adoption decisions for both crops and irrigation technology choices at the farm level (Caswell and Zilberman, 1986).

2.1.1 Economic Problem

In the SSRB, the application of water for irrigated agriculture is not as efficient as it could be. For instance, about 21 percent of water delivered to the farm may be lost due to on-farm inefficiencies in distribution systems and up to 30 percent of water is also lost through inefficiencies in irrigation practices (Alberta Water Council, 2009). The inefficiency associated with water use in the SSRB has been recognized by the water-related departments in the Alberta provincial government and various policy strategies have been proposed and implemented. A summary of the major policy strategies that could help the province maximize water use is the

Water for Life Strategy. One of the feasible outcomes of the Water for Life Strategy is to obtain by 2015 a 30 percent improvement in water use efficiency from 2005 levels (Alberta Environment, 2003).

In achieving the goals of this policy document, more can be done to improve on-farm irrigation management. This can be done by promoting adoption of irrigation technologies that are more efficient in delivering water to the root zones of the crop. The Alberta Water Act allows transfers of water licenses in whole or in part as a means of reallocating water to various sectors of society. Working within the legal settings, it is possible for farmers in irrigation districts to reallocate their saved water until an efficient allocation system is achieved. Water trading is one option for encouraging water-use efficiency. If farmers trade water and potentially invest their gains in adopting efficient irrigation technologies, it is possible that overall irrigation efficiency will be improved in the SSRB. The pertinent research question is: what incentives can be used to encourage a farmer to adopt an efficient irrigation technology to produce the most profitable crop after trading?

2.1.2 Specific objectives

The purpose of this study is to calibrate a farm-based profit function and use it to simulate farm performance in order to:

1. Measure the gains from farmers adopting efficient irrigation technologies and crop choices.
2. Account for the probability of farmers switching from a less-efficient to a more-efficient irrigation technology to produce profitable crops after trading.
3. Estimate the probabilities of farmers switching from less-valued crops to the high-valued crops after trading.
4. Examine gains of water trading in the presence of alternative water conservation policies.

2.1.3 Organization of the chapter

The next section presents the historical development of water rights in Alberta, and an overview of empirical studies of water trading and irrigation technology adoption. This is followed by the study area description. An overview of the theoretical framework applied is presented in Section 2.3. This section also outlines the empirical methods and data used to estimate the theoretical model. In addition, the section presents the calibration approach used to recover missing parameters of the model. Section 2.4 presents the stylized results of the model with a focus on optimal water use, crop yields and profits under different irrigation technologies. Section 2.5 deals with the potential gains from water trading and simulation results of irrigation technology and crop choices under two scenarios. Section 2.6 presents and discusses simulation results and alternative strategies that could improve the likelihood of farmers adopting efficient irrigation technologies to produce profitable crops in the SSRB. The last section deals with the policy conclusions and limitations of the study. Also, this section presents future research options that could be used to improve the analysis.

2.2 Literature Review

2.2.1 Overview of Water Allocation System in Alberta

Irrigation in Alberta started in the 1800s. A variety of water management policies have been enacted through the 1990s and beyond. Examples of different water management policies are the Natural Resources Transfer Act (1930) and the Water Resources Act (1931) that requires water licenses for all water uses except household consumption (Alberta, 1930; Alberta, 1931). This early legislation was rigid. Some of the policy instruments implemented required modifications to reflect the emerging socio-economic demand conditions and climate changes in the province. For instance, one of the conditions of the Water Resources Act was that licenses were to be used for the specific purpose for which they were acquired. This restriction provided little incentive to save water. Also, this particular Act restored the basic principles of "first-in-time, first-in-right," where water was allocated to senior license holders over junior license holders. A major drawback of this Act was that it did not allow for water trading, a mechanism that could encourage efficient water use. Water trading provides incentives to users to conserve water and sell any excess for higher-valued uses.

In 1991, the Alberta government initiated a review of water legislation due to increased demands for water. The basic idea was to ensure that water is managed effectively for all future generations (Alberta Environment, 2003; Hill, 2006). The recommendations from this review led to the Water Act of 1999 and subsequently the Irrigation District Act of 2000. These new Acts are more flexible than the previous ones because water trading is allowed within irrigation districts. Also, water trading is possible across districts but only under certain conditions. One key condition of any inter-district transfer is such that a plebiscite must be held and 50 percent of district members must agree to the proposed transfer to another district (Alberta, 2000b: Section 11; Alberta, 2000a: Section 81). The Act also states that the proposed transfer should be in the interest of the general public and the public must have been given a 30-day meeting notice that the district intends to transfer the water. In addition, the proposed transfer should be such that it will not have any major impact such as contributing to water shortages and environmental damage in the originating district.

In 2003, in response to managing water scarcity in the province and the urgency to develop sustainable measures to manage water in the southern part of the province, Alberta formulated its Water for Life Strategy. This strategy seeks to provide a better approach to managing provincial water by addressing present and future water scarcity challenges in the province. As mentioned above, one goal of this strategy is to achieve increased efficiency and increased productivity of water use in Alberta (Alberta Environment, 2003). In particular, this strategy has stressed a goal of ensuring that by 2015, overall efficiency and productivity of water use in Alberta improves by 30 percent from 2005 levels (Alberta Environment, 2003). In 2008, the significance of this objective was further stressed in the renewed Water for Life Action Plan that reflected more current realities and issues facing the province (Alberta Water Council, 2008). Both policy documents highlight the roles of economic instruments such as water markets in achieving the efficiency and increasing productivity of water use in the future. These policy documents seek to manage the provincial water resource in more equitable and efficient ways with the aim of achieving sustainable water resources and economic development as well as protecting the ecosystem (Alberta Water Council, 2008).

2.2.2 Empirical Review

This section presents findings of previous studies on the effectiveness of the aforementioned government policies on provincial water use. In water resource management, efficiency is improved when water is put to a higher value use (Kemper, 2001; Dinar et al., 1997). In southern Alberta, water policies that focus on applying economic instruments such as water pricing and water rights trading are perceived to be effective in resolving issues of water allocation (Adamowicz and Horbulyk, 1996).

It appears that policy-makers and irrigated farmers prefer water trading to water pricing even though both encourage efficiency of water use. These users may have a legitimate reason for favoring water trading, because in practice it is difficult to implement water pricing schemes. Some of the major issues associated with implementing effective water pricing schemes are: (1) how to establish an optimal pricing scheme, (2) how to administer this pricing scheme, (3) political feasibility of the pricing scheme, and , (4) how to incorporate multiple values of water. In contrast, implementing water trading is relatively easier and is usually acceptable to both farmers and policy makers (Bjornlund and McKay, 2002; Sawyer et al., 2005; Griffin, 2006; Horbulyk, 2010). In addition, existing studies have shown that effectively introducing water markets in southern Alberta could provide significant benefits to various sectors and subsequently improve overall social welfare (Viney et al.,1996; Adamowicz and Horbulyk, 1996; Nicol and Klein, 2006).

Various studies have focused on estimating the gains associated with introducing water markets in southern Alberta. A study by Horbulyk and Lo (1998) was one of the first to apply a linear programming modeling approach to examine the allocative efficiency of water trading under water-scarcity conditions in Alberta. These authors used the following four scenarios: Scenario one assumed "*status quo*" conditions (i.e., without trading water across districts); Scenario two allowed for intra-regional water trading. Scenario three allowed for interregional trading. Scenarios two and three held water allocation apportionment and in-stream utilisation constant from the first scenario. The final scenario focused on apportionment and the possibility of trading of in-stream flow units. The model results suggested that allowing water to be traded could increase aggregate consumer surplus by more than 56 percent. This static optimization model concluded that all users and regions considered had improved welfare levels when water trading was allowed.

Mahan et al. (2002) expanded on the work of Horbulyk and Lo (1998) and formulated a model for the entire SSRB. The model results showed substantial differences in water values between districts, indicating possible gains from water trading. This model also examined welfare gains under different water reallocation scenarios compared to the baseline allocation, where water trading is not allowed. Similarly, scenario one did not allow for water trading between districts. Scenario two allowed for intra-regional trade, while three assumed intra- and inter-regional trade. The results from the latter scenarios showed improvements over the "*status quo*" allocation in terms of gains in welfare from water trading. This study further showed that in drought years the gain could be substantial. The above studies showed that gains may occur from water trading if water is reallocated from low-value uses to high-value uses in both inter- and intra-regional contexts, but that consequences of trading water under spatial and temporal distributions of water are not considered.

Cutlac et al. (2006) incorporated temporal and spatial dimensions of water reallocation into the Horbulyk and Lo (1998) model and used it for the Bow River Basin, Alberta. Their calibrated model was used to examine several water reallocation scenarios over different temporal and spatial scales. The following two scenarios were simulated in a multi-market setting and compared under short- and long-run demand impacts. The first scenario examined the impacts of a 30 percent reduction in available annual water supply from the base allocation. Scenario two examined the impacts of a 30 percent increase in urban demand for water and compared to the base case (i.e., no reallocation). The model was recalibrated with long-run demand curves for urban and irrigation users while hydropower and recreational demand curves retained their short-run values. These same two scenarios were used to examine three cases to account for the influence of relative long-run elasticity differences across markets. These cases were: (1) both urban and irrigation demands were assumed to be more elastic, (2) irrigation demands were assumed to be relatively more own-price-elastic, and (3) urban water demands were assumed to be relatively more elastic than irrigation demands. Results from the first scenario showed a substantial decrease in water supply and a four-fold increase in market price levels. In comparison to the first scenario, there was a smaller magnitude of change in prices and quantity responses across the four demand regions. Furthermore, the model showed that in equilibrium, the quantity of water demanded by urban users increased by less than 30 percent, though there were variations across the four sets of elasticity values utilized in the study.

Cutlac and Horbulyk (2011) modeled the annual value of water that can be derived from alternative water allocations in the SSRB. The study employed similar scenarios as in Cutlac et al. (2006), but with a basin-wide focus. The Cutlac and Horbulyk results further showed that water reallocation could have substantial benefits for society, and that these benefits could be achieved at a reasonable cost.

The gains from water trading, irrigation technology and crop choices have been examined at the district level in the SSRB. In particular, He and Horbulyk (2010) applied positive mathematical programming (PMP) methods to examine irrigation decisions and crop choices in the Bow River basin, which is a sub-basin of the SSRB. The simulation results show that with a 10 percent reduction in water, the use of economic instruments could increase welfare by 0.5 percent, relative to seniority allocation. Furthermore, as the degree of water scarcity rises to 20 percent and 30 percent, the associated welfare increases by 2.0 percent and 5.8 percent, respectively. Recently, He et al. (2012) extended the PMP approach and used it in the SSRB to examine gains in different proportional sharing scenarios. The simulation results show that there are gains in alternative sharing schemes relative to the current seniority-based allocation system. Results from these mathematical programming models suggest that trading water could improve societal welfare. However, the models focused on aggregate welfare gains from water reallocation in southern Alberta. As a result, these models are unable to provide policy information about how these allocations impact, and are affected by, a farmer behavior, an irrigation technology to be adopted, farmer-heterogeneity issues (i.e., land quality, management skills, etc.) and choice of the most profitable crop that could be cultivated.

As mentioned above, in irrigated agriculture, heterogeneity is an important factor in determining adoption decisions on irrigation technology (Caswell and Zilberman, 1986; Dridi and Khanna, 2005). In this regard, Viney et al. (1995) used a linear programming model for 12 representative farms in the Eastern Irrigation District in southern Alberta and found that specialty[3] crop producing farms have higher marginal water values than other farms. The productive water values for specialty crops were \$100 to \$350 per acre-foot versus \$10 to \$68 per acre-foot for farms growing standard crops such as cereals, oilseeds, and forages. In addition, the authors found that the individual farm marginal water values could translate into capitalized assets values from \$300-700 per acre, but this depended on the specific farm type and associated farm improvements. Their study contributed to the discussion on the opportunities associated with water trading in southern Alberta, but their model still used aggregate farms; considerations of irrigation technology adoption and crop choices were ignored.

In general, a farmer's decision to adopt an irrigation technology is affected by economic variables, environmental characteristics and institutional variables (Hochman and Zilberman, 1978; Schaible et al., 1991). These exogenous factors tend to vary with the individual farmer's decision-making processes and subsequently affect irrigation technology choices at the farm level. In spite of the importance placed on these variables in the literature, most empirical studies

[3] Specialty crops include dry beans, sugar beets, carrots, potatoes, alfalfa seed, canola, dry peas, fresh corn (sweet), faba beans, lentils, mustard seed, sunflower, and canary seed, (Alberta Agriculture and Rural Development, 2009).

rely on the use of regional average data or aggregate district data to compare percentages of adoption among farmers in a given country. Averaging data on a district or regional basis has a similar influence on both farmer behavior and physical characteristics. Using aggregate data may not directly show the influence of farm-level variables on adoption behavior of farmers. Thus, statistical estimates from these data may seriously bias the policy implications of farm-level adoption decision making processes (Green and Sunding, 1997). Unlike empirical studies, theoretical studies are able to capture farmers decision making processes by matching irrigation technology adoption choices to on farm-level variables, such as water-holding capacity, land quality, water price, and water supply sources and also model policy decisions that could lead to improvements for an individual farmer.

The basic irrigation technology adoption problem is well established, and most previous research follows the theoretical model first put forward by Caswell and Zilberman (1986). Their framework makes it possible to analyze the effects of farm characteristics and irrigation technology characteristics on a farmer's choice of adopting irrigation technology. Caswell and Zilberman’s (1986) conceptual model is based on the profit-maximizing behavior of farmers with variations in land quality and water prices. Their results showed that adopting modern irrigation technologies tends to increase crop yields and save water. Caswell et al. (1990) extended this model and generalized it to include external effects of input use and the role of environmental policies in resource conservation and pollution mitigation. The study assessed impacts of water-use efficiency on prices, irrigation technology adoption and the introduction of pollution taxes. Also, Caswell et al. (1993) used this model to examine diffusion of resource-quality-augmenting technologies under output supply and input demand effects. All of the above studies cited showed that, in general, modern irrigation technologies are more likely to be adopted on lower-quality land when crop and input prices are high, in severe environmental conditions and when the cost of switching technologies is low. However, these studies ignored gains that could be achieved from water trading and the conditions under which these gains might be used to adopt efficient or modern irrigation technologies.

Burness and Quirk (1980) indicate that without water trading, senior rights holders have the incentive to irrigate all their land, which leaves the junior rights holders with little or no water.

Carey and Zilberman (2002) further extended the Caswell and Zilberman (1986) model to analyze the implications of water trading and the adoption of different irrigation technologies under price and water uncertainties. These authors argued that it is important when modeling farmer adoption decisions to incorporate uncertainty in water supply and water prices, because decisions under these conditions could provide farmers with an option to observe whether water prices increase or decrease before making any farm investment commitment. When accounting for uncertainties and options to wait, the model showed that farmers require a higher price of water before adopting modern irrigation technologies.

Dinar and Letey (1991) applied the model to determine the implications of water trading under the consideration of drainage reduction. A flexible production function was adopted to capture the relationships between water prices, crop yield and drainage effects on the environment. The production function is flexible in the sense that a decision can be made with regard to the optimal irrigation technology choice and quantity of water to be used. The model results showed that higher farm prices of water lead to a reduction in water use and thereby increase the potential amount of water that could be available for alternative uses. The study's conclusion was that a water market system which provides benefits to the individual farmer to change his irrigation management practices with the aim of conserving water could provide substantial benefits to several sectors of the society.

More recent and closely related to this thesis is the work of Dridi and Khanna (2005), who investigated the incentive-compatible mechanisms of irrigation technology adoption and water trading under imperfect information conditions. These authors applied Caswell and Zilberman's model to examine gains from irrigation technology adoption and water trading under both full information and imperfect information. The model results showed that water trading occurred between farmers who did not adopt modern irrigation technologies, and that minor adjustments occurred among low-quality land farmers who had already adopted modern irrigation technologies. When water trading occurred between farmers, it was possible that gains from trading could have been used to adopt modern irrigation technologies. Finally, the study showed that imperfect information makes it less likely that modern irrigation technologies will be adopted, even though there are still incentives for water trading and gains to all parties for adopting modern irrigation technologies.

These reviewed studies show the benefits of farm-based profit models on farmer's decision-making processes during irrigation technology adoption and water trading in the United States (US). Most of these reviewed studies applied the farm based profit model to examine various water policy considerations, but under either riparian rights or prior appropriation water rights systems. Most of the western US states employ a prior appropriation system where priority is based on the date when water was taken and put to a beneficial use. In times of drought, the oldest users have priority over more junior users. In some states, including California, these rights exist in the form of licenses. Similar to California, Alberta uses a prior allocation system that involves issuing licenses with priority among licenses based on "first-in-time, first-in-right". However, water rights in Alberta are mostly described as a usufructuary right. This is the "right" to use all the benefits that can be derived from a resource that belongs to another entity or agent, as long as the property is not being destroyed or injured (Alberta, 2000a: Section 81).

In addition, these previous studies ignored important components of the profit model by restricting the farmer's choice on irrigation technologies to either one or two options (i.e., more efficient or less efficient), and did not capture the heterogeneity in the adoption of different efficient irrigation technologies relative to the traditionally used irrigation technologies. Finally, none of these studies model a farmer's decision on crop choices after water trading. Farmers cultivating different crops will respond differently to water price changes. Because some crops respond less effectively to changes in water availability, the effect of an increase in the price of water may not affect farmers' decisions. Other crops cope well with the changes in water application methods and farmers could change technologies in response to water price increases. The effectiveness of water prices could serve as an incentive to induce farmers to adopt efficient irrigation technologies to improve crop yields and, possibly, save water (Green and Sunding, 1997).

At this point it is worth mentioning that Nicol and Klein (2006) used a survey method to examine the nature of water market in the St. Mary Irrigation District (SMRID) in the SSRB. The authors found that the nature of water market was thin during the 2001 drought period. With regard to water trading, the study showed that about half of the water sold was transferred from low-valued crops to high-valued crops. Also, the study determined that buyers used their purchased water on lands that were under sprinkler-low pressure irrigation technologies. In a related study, Nicol et al. (2008) conducted a survey in Taber and Raymond Irrigation Districts in SSRB to elicit the factors that farmers take into considerations to adopt improved irrigation technologies. The authors found that those with improved irrigation technologies are full time large scale farmers and specialty crop growers. The study also focused on how subsidies could be used to encourage the adoption of improved irrigation technologies and found that most of the farmers require a substantial level of subsidy before they would be able to switch to an improved irrigation technology. These survey studies provide insights into the nature of water market and the pattern of irrigation technology adoption, but the policy outcomes are based on group decision making and do not provide information on individual farmer decision making process on irrigation technology adoption. Also, the economic decision making on the irrigation technology adoption and crop choices are ignored.

In summary, the relationship between inputs and outputs in a farming activity is defined as efficiency. A farm's performance can be assessed based on different efficiency measures, such as technical, allocative and economic efficiency. In southern Alberta, analysis has focused on the technical efficiency of water use but very little attention has been paid to allocative efficiency of water use. In this regard, current government policies have focused on strategies to improve user irrigation practices and ensure that water distribution systems functions efficiently. Allocative efficiency, on the other hand, occurs when water is allocated to the user with a higher marginal value for it. With water allocation, the concept deals with the allocation of the water required for generating water related products and services. It also focuses on how to allocate the available water among competing users in the agricultural, industrial and domestic sectors of the economy as well as ensuring that environmental needs are met. Thus, improving allocative efficiency means evaluating how water can best be allocated and used to achieve, in equilibrium, a society's many needs. This thesis will shed light on the allocative efficiency of water use in southern Alberta through water trading, irrigation technology adoption and crop choices.

The study is designed on the premise that when allocative efficiency is achieved through water trading, extra water units can be relocated to the user or to the society's highest value uses. In the achieving the study objectives, the model presented here departs from that of Caswell and Zilberman (1986) by: (1) including six main irrigation technologies and 12 crops, (2) accounting for water trading, irrigation technology adoption and crop choices under drought conditions, and (3) applying the model to examine possible future water allocation policies in southern Alberta.

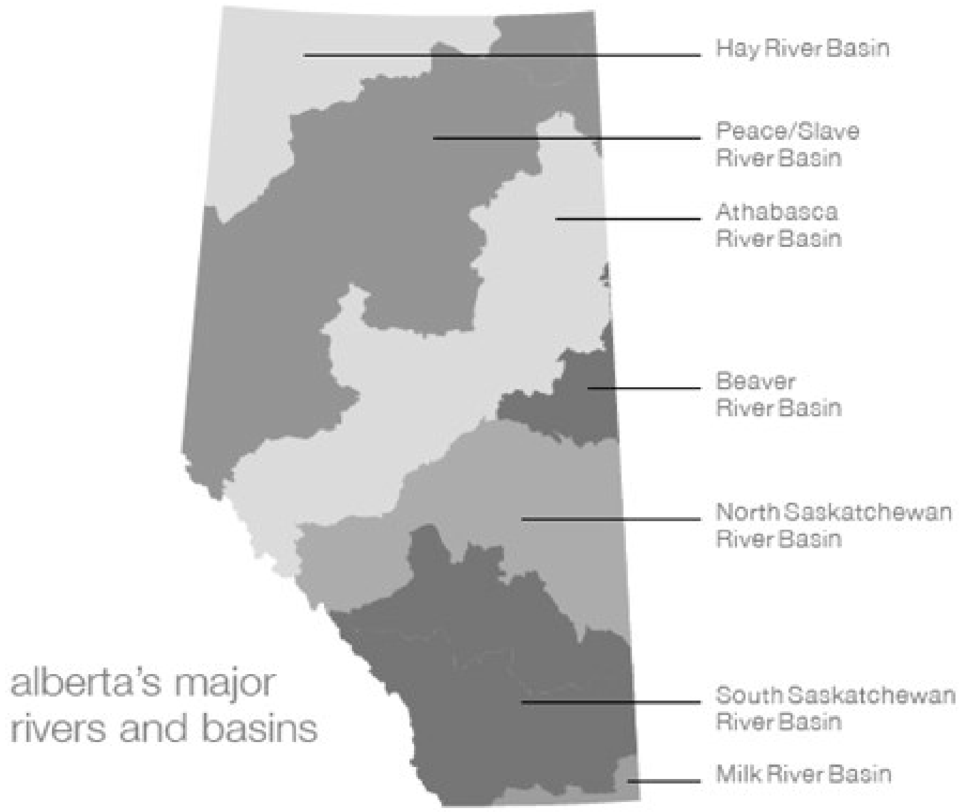
2.3 Methodology

This section describes the theoretical and empirical approaches used in the study. It begins with a brief background description of the study area and the current legislation governing water use in the various irrigation districts. Next, the theoretical model developed to answer the study objectives is presented. Subsequently, the empirical approaches used in estimating key parameters of the model are outlined. The last section deals with the data description of the model and the calibration methodology used to recover a missing parameter of the model.

2.3.1 Study Area

In Alberta, there are seven major river basins (Figure 2.1). These are: (1) Hay River Basin, (2) Peace/Slave River Basin, (3) Athabasca River Basin, (4) Beaver River Basin, (5) North Saskatchewan River Basin, (6) South Saskatchewan River Basin, and (7) Milk River Basin. All of these basins originate from the glacier melt with the exception of Beaver River Basin (AENV, 2002). Most of the irrigated activities in Alberta take place in the SSRB. Water for irrigation mainly comes from rivers such as the Bow River, Oldman River, and the South Saskatchewan River.

Figure 2.1 Major River Basins in Alberta



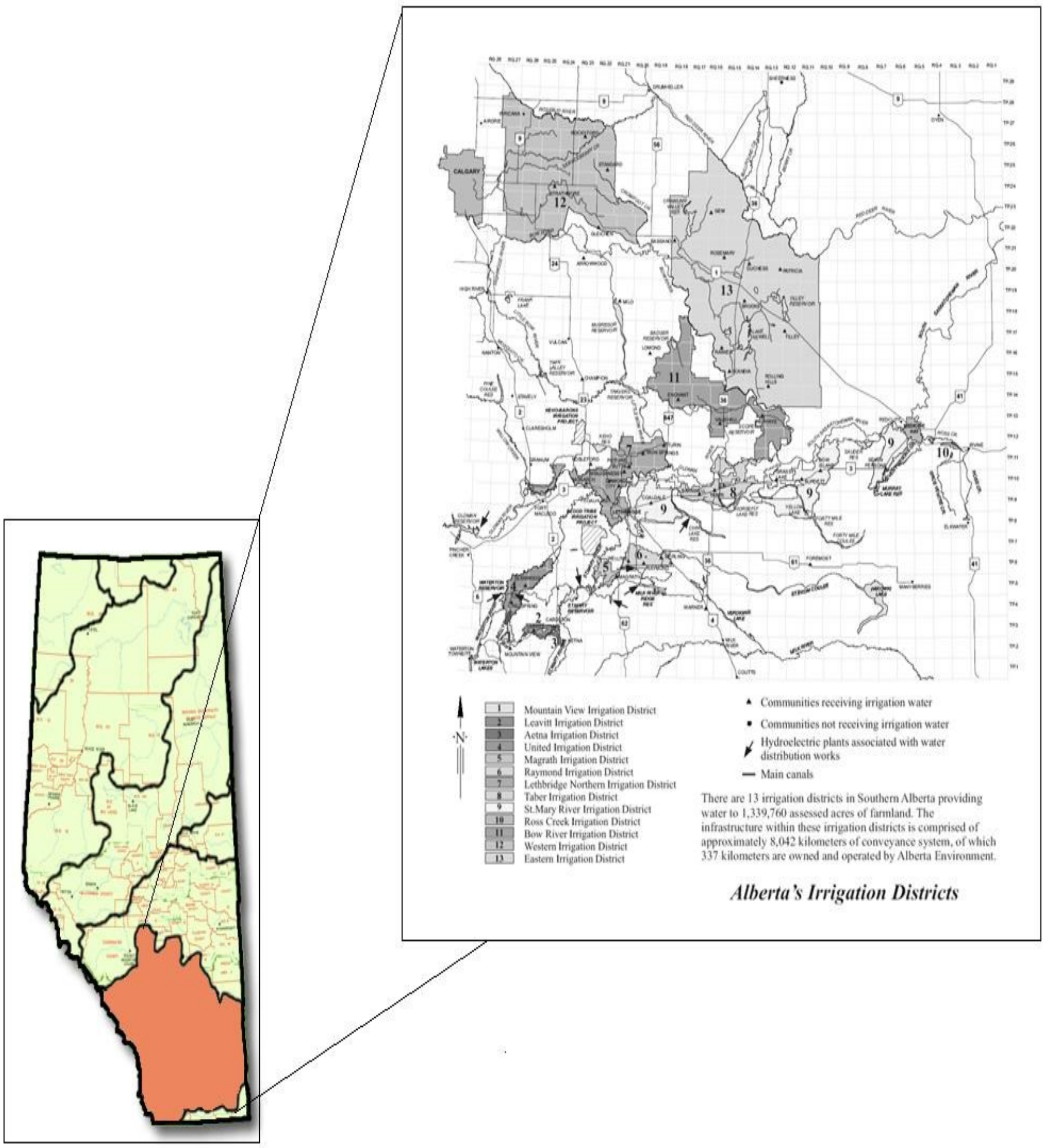
Source: Alberta Environment, 2002. Water for life. Facts and Information on Water in Alberta.

2.3.2.1 Irrigation Districts

There are 13 irrigation districts, all of which are in the SSRB (Figure 2.2). The districts are managed by authorities who set rules on water allocation and who manage 80 percent of the water used to irrigate approximately 1.4 million acres of crops per year in the SSRB (Alberta Agriculture, Food and Rural Development, 2009). Each of the irrigation districts has its own unique history, rules and regulations but these rules and regulations need to fit the overall goal of water management in the province. The districts differ from each other with differences being attributable to factors such as: (1) farm size, (2) climatic conditions, (3) crops, (4) irrigation technologies, and (5) management skills (Irrigation Water Management Study Committee, 2002).

All of these irrigation activities are undertaken on lands classified by the district authorities as suitable for irrigation (Alberta, 2000b: Section 11). These classified lands are incorporated into the district annual development plan for water management and irrigation (Alberta, 2000b: Section 11). These irrigable lands are used to cultivate major crops such as forages (38 percent), cereals (33.6 percent), oil seeds (14.4 percent), and specialty crops (11.3 percent) (Alberta Agriculture, Food and Rural Development, 2009). The variety of crops farmers cultivate across the districts illustrates the heterogeneity in terms of farmer and farm characteristics.

Figure 2.2 Locations of Irrigation Districts in Southern Alberta



Source: Alberta Agriculture, Food and Rural Development, 2009.

The districts vary in size, the largest ones being the St. Mary River Irrigation District (SMRID) and the Eastern Irrigation District (EID). Aetna (AID), Leavitt (LID), Mountain View (MVID), and Raymond Creek (RCID) are the smallest irrigation districts (Figure 2.2). Production and irrigation technology adoption patterns vary across districts as well. For instance, in the RCID, the use of centre pivot irrigation technology is relatively low (i.e., four percent) because of undulating land, while the use of this technology is high in the SMRID (i.e., 82 percent).

In spite of the differences in the use of these irrigation technologies, approximately 70 percent of the farmers in the SSRB use pivot sprinkler irrigation technologies (Alberta Agriculture, Food and Rural Development, 2009). As noted in the introduction, adopting efficient irrigation technologies leads to on-farm efficiency improvement. For instance, in southern Alberta, an increase of about 30 percent in water-use efficiency has been achieved with the gradual adoption of low-pressure pivot irrigation technologies (Irrigation Water Management Study Committee, 2002). Also, return flows across districts have been found to be as high as 56 percent over a five-year period (Irrigation Water Management Study Committee, 2002). Irrigated agriculture generates economic and social benefits that contribute to the livelihood of farmers and other inhabitants of the province (Hart, 2001). Available estimates show that with less than six percent of crop land irrigated, irrigation generates more than 14 percent of the farm cash receipts, about 11 percent of the agricultural value-added products, and 19 percent of direct agricultural employment in Alberta (Hart, 2001). In addition, irrigated agriculture constitutes about 8.3 percent of the producers and contributes 20 percent of the gross agricultural product in Alberta (Hart, 2001; Hill, 2006). A detailed description of the impact of water on the economy of Alberta can be found in Horbulyk and Lo (1998).

2.3.2.2 Irrigation Technologies

Before outlining the theoretical model used in this study, a brief description of the main irrigation technologies in the SSRB is presented. Major irrigation technologies available to farmers in the SSRB can be grouped as gravity irrigation technologies, sprinkler irrigation technologies and micro-drip irrigation technologies. These irrigation technologies have different application efficiencies. Application efficiency of the irrigation technologies provides a general performance measure of the systems in relation to how they transport water through the conveyance systems to the crop. This measure focuses on how the applied water could be stored in the crop root zone to meet the crop water needs. Farmers' understanding of these technologies would help them make irrigation management decisions for optimum crop production.

2.3.2.2.1 Gravity Irrigation Technologies

In these types of irrigation systems, gravity is used to move water from a water source onto the irrigated farm area. Gravity-flood and gravity-developed irrigation are the two common methods under this irrigation system. In a gravity-flood irrigation system, water enters the uncontrolled area and minimal land preparation is needed. Conversely, with gravity-developed, such as border ditch, water enters irrigated areas as a controlled sheet, leading to less water loss than with gravity-flood irrigation. These irrigation technologies are the easiest and least costly methods, but they are usually inefficient.

2.3.2.2.2 Wheel-Move Sprinkler Irrigation Technologies

These irrigation systems consist of several parts including the laterals, wheels, couples and sprinklers. The system has wheels mounted on the lateral line so that the line can be rolled to new areas across the field (Hill, 2000; AIMM, 2007). Flexible hoses are used to connect the laterals to the main water supply line at every new area in the farm. Lateral pipes are usually 0.101 or 0.127 meters in diameter and 9.14 or 12.2 meters in length. Lateral lines are commonly 0.25 mile long (Hill, 2000; AIMM, 2007). The entire system moves with the help of rigid couplers. Typically, a small gasoline engine is attached to the middle of the mainline, which moves the system. The application efficiency of this irrigation system is relatively higher than that of the gravity systems, but less than that for centre-pivot sprinkler irrigation technologies.

2.3.2.2.3 Centre-Pivot Sprinkler Irrigation Technologies

In center-pivot sprinkler technologies, a small amount of water is applied at frequent intervals to a unit area of a crop. The system is composed of a span of pipe which is supported on a wheeled frame-tower and is self-propelled around a central pivot point. The pipe delivers the water to the sprinklers. Water is normally delivered to the pivot point through a main water supply source. The system varies in length, usually from approximately 60 m to 790 m, and is able to irrigate a circular area of about 500 acres (King and Kincald, 1997; Burt et al., 1999). Pressure required at the pivot may vary from approximately 70 kPa (10 psi) when low-pressure spray nozzles are used, to 550 kPa (80 psi) when high-pressure impact sprinklers are used (Burt et al., 1999). These systems are more efficient than the gravity irrigation. However, they are more costly to install and operate because of the need for pressurized water.

2.3.2.2.4 Drip Irrigation Technologies

This type of irrigation system applies water directly to the root zone of the crop through emitters or drippers. The emitters are supplied with water by a network of plastic, main, sub-main, and lateral lines. Each emitter discharges water at a very low rate. The volume of soil dampened by each emitter is relatively small (Burt et al., 1999). The system is well suited for areas of high temperature and limited water resources. It allows for the accurate application of water with minimal loss due to evaporation, poor distribution and seepage, or over-watering. Due to the small diameter of the emitters' openings, water filtration is normally required to reduce potential blockages in these systems. This method is highly efficient because only the immediate root zone of each crop is wetted. Drip irrigation systems are the most efficient, but they can have different levels of complexities and costs. The use of this irrigation system is limited to specific crops in regions with high water prices and poor soil quality.

Drip-and-sprinkler-irrigation technologies are classified as efficient systems because they use energy and equipment to irrigate crops while flood irrigation systems use gravity. This results in the ability of efficient systems to irrigate more frequently. It improves irrigation uniformity and reduces the amount of water lost to deep percolation and runoff. In essence, the output produced with a given amount of water may increase with these efficient irrigation technologies.

2.3.3 Theoretical Model[4]

This section deals with the theoretical approach used for the study. A model is calibrated to characterize southern Alberta farmers' decision-making processes on the choice of irrigation technologies and crops, as well as gains from water trading. It is assumed that farmers' decision-making is done on a per hectare basis. A modification of Caswell and Zilberman's (1986) basic model is presented in this section. Their model, as well as that of Dridi and Khanna (2005), focuses on two irrigation technologies (i.e., more efficient and less efficient technologies) and a

[4] Caswell and Zilberman (1986), Dridi and Khanna (2005), Khanna et al. (2002) are the main sources for the discussion in this section.

single crop. In this section, the same basic model is presented, but it is expanded to consider six irrigation technologies and 12 irrigated crops. Also, the production function used in this study is modified to reflect actual crop yields in the study area by incorporating average annual precipitation, spring soil moisture and potential crop evapotranspiration.

2.3.3.1 Farmer Behavior

Consider N farmers, indexed $i = 1,...,N$ producing C different crops, indexed $c = 1,2,...,C$, using different irrigation technologies and water as inputs. Let P^c be the exogenous output price of a particular crop being produced in an irrigation area. Farmers are heterogeneous with respect to land quality, denoted by θ_i. The land-quality parameter which differentiates farmer types is distributed with density $f(\theta_i)$ and a cumulative distribution $F(\theta_i)$ over the support $\left[\underline{\theta},\overline{\theta}\right]$.

For a variety of crops, farmers choose from a menu of M feasible irrigation technologies, indexed $t = 1,2,...,M$, ranging from least to most efficient. The differences in these irrigation technologies are measured based on their application efficiency of water use. The less efficient irrigation technologies such as gravity flood have an application efficiency of about 30 percent because gravity is used to apply the water from the distribution channels at the head across the farm. This often results in a non-uniform application of water (Irrigation Water Management Study Committee, 2002, vol. 5). More efficient irrigation technologies such as micro-drip and pivot sprinklers have an application efficiency of about 80-90 percent, as pressure is used to distribute water uniformly throughout the entire farm (Irrigation Water Management Study Committee, 2002. vol. 5). The amount of water applied and effective water used per crop per hectare under irrigation technology t and crop c are denoted as w_i^{tc} and e_i^{tc} respectively. In this regard, the amount of water applied is the gross irrigation, which is the quantity of water diverted or extracted from the river. Effective irrigation is the water consumed by the crop. Efficiency or irrigation effectiveness can be defined as the ratio of effective water used to the applied water. In this study, it is assumed to be dependent on irrigation technology, crop choice and land quality.

Following the approaches of Caswell and Zilberman (1986) and Dridi and Khanna (2005), and assuming a linear relationship between w_i^{tc} and e_i^{tc} with a multiplicative land quality augmenting function, effective water is defined as $e_i^{tc} = w_i^{tc} h_i^t(\theta_i)$, where the function $h_i^t(\theta_i)$ is the irrigation effectiveness of irrigation technology t for a given farmer. The function h^t is the percentage of water absorbed or effectively used by the crop and takes a value from 0 to 1. To illustrate the effect of land quality and irrigation technology choices, two irrigation technologies are considered at this stage to further simplify the model: an efficient technology for which the technological variable t equals 2, and an inefficient technology for which t equals 1.

The characteristic of the land quality variable is its ability to sustain water under the inefficient irrigation technology. For instance, sandy soils may correspond to a low value of θ_i, while loamy soils may have a high value. The value for land quality variable directly affects the irrigation effectiveness of the technologies. It is assumed that $h^{2'}(\theta_i) > 0,\ h^{2''}(\theta_i) < 0$, implying that the marginal gain in irrigation effectiveness from the technology adoption declines as land quality improves. The efficient irrigation technology increases the efficiency of water use with a given land quality such that $h^2(\theta_i) \geq h^1(\theta_i)$ for $0 < \theta_i < 1$, and it is assumed that $h^2(\underline{\theta}) = 0$ and $h^2(\overline{\theta}) = 1$. The above relationships constitute the land-quality augmenting-effect (Caswell and Zilberman, 1986). These assumptions about h^2 imply that the gap between h^2 and h^1 decreases with improved land quality (i.e., increased θ_i) (Caswell et al., 1993).

2.3.3.2 Production Function

Let y_i^{tc} be the actual yield per crop per hectare. We define $y_i^{tc} = f(Z)$, where Z is defined as ratio of moisture use by crops and moisture availability. The specific relationship of this ratio can be given as (UMA, 1982; Irrigation Water Management Study Committee, 2002. vol. 5):

$$Z = \frac{ETa + w_i^{tc} h_i^t(\theta_i)}{ETp_i^c}, \qquad (2.1)$$

ETp^c is the amount of evaporation from soil and transpiration from crops, which occurs given sufficient moisture availability (UMA, 1982). Moisture availability is comprised of spring soil moisture (SSM), effective precipitation (PRCP), and effective irrigation ($w_i^{tc} h_i^t(\theta_i)$). However, actual evapotranspiration (ETa) is estimated as the sum of SSM and PRCP. PRCP is the effective precipitation used in the growing season in the form of rain or snow with a 10 percent adjustment to account for drainage losses when soil moisture levels are near optimal (UMA, 1982). SSM is further defined as the spring soil moisture available at the start of a growing season, which depends on the amount of moisture stored in the soil at the end of the previous season plus winter precipitation (UMA, 1982).

In applied production economic analysis, selecting a functional form to properly describe the underlying technology is not a simple task. In many empirical studies, Cobb-Douglas production functional form specification is the most preferred function. To avoid the shortcomings inherent in the Cobb-Douglas specification (e.g., unitary elasticity of substitution between inputs), most irrigation technology adoption studies incorporate more flexible functional forms such as a quadratic function. The quadratic function has the ability to model stage III of production; that is, as more water is applied a maximum yield is reached, followed by decreasing yield with respect to water application.

In this study, an augmented quadratic production function which depends only on effectiveness of irrigation water as a function of land quality is selected and specified below. Using equation (2.1), the augmented production function for farmer i can be formulated as;

$$y_i^{tc} = \{a_0 + a_1(Z) + a_2(Z^2)\}Yp^c \qquad (2.2)^5$$

where Yp^c is the potential yield per crop per hectare, and $a_1 > 0, a_2 < 0$ and $a_0 \leq 0$ are crop-specific regression coefficients. Note that the proportion of potential yield per ha that is achieved for a given level of Z is represented by the function in the bracket of equation (2.2). The above production function has the properties of a neoclassical production function; that is, concavity and the marginal productivity of effective water is assumed to be nonnegative, but declining $(i.e., y_i^{tc'}(.) \geq 0, y_i^{tc''}(.) < 0)$.

[5] y_i^{tc} / Yp^c represent the ratio of actual to potential crop yield as estimated from the second-degree polynomial function for an irrigated crop (UMA, 1982). The ratio is an estimate of the relative crop yield for a given level of irrigation.

Although the effects of an increase in irrigation efficiency over the amount of irrigation water applied are not clear-cut, they depend on the specific characteristics of the production technology. Caswell and Zilberman (1986) show that adopting a more efficient irrigation technology could lead to water saving, but this is dependent on the elasticity of marginal productivity of effective water. The elasticity of marginal productivity of effective water (emp^{tc}) with respect to irrigation technology t and crop type c is defined as $emp^{tc} = -Z\frac{\partial^2 y_i^{tc} / \partial Z^2}{\partial y_i^{tc} / \partial Z}$.

The value of elasticity of marginal productivity of water approaches infinity when $y_i^{tc'}(.)$ is zero and it approaches zero when the marginal productivity of effective water approaches its maximum. Thus, in the economic production range of water use, emp^{tc} is positive and increasing with the amount of effective water.

In addition, Caswell and Zilberman (1986) proved that, in cases where emp^{tc} is greater than one, an increase in irrigation effectiveness tends to reduce actual water use; and in cases with low emp^{tc}, an increase in irrigation effectiveness tends to increase water use. Thus, an increase in irrigation effectiveness will result in an increase in yield, but benefits from water are derived only when the emp^{tc} is low and may not be beneficial when the emp^{tc} is high.

2.3.3.3 Irrigation Technology Costs

Let the total irrigation costs per hectare be denoted as $TC_i^{tc} = g^t w_i^{tc} + k^{tc}$ where, k^{tc} is the fixed irrigation cost per dollar per hectare. This is the cost of equipment and set up of an irrigation technology system. It is assumed that this fixed cost does not depend on the energy requirements of the irrigation technology and land quality. To further simplify, it is assumed that the investment costs associated with adopting an efficient irrigation technology are higher than the investment costs of an inefficient irrigation technology $(k^{2c} > k^{1c})$. The term g^t represents variable costs in dollars per millimeter of water applied per hectare.

2.3.3.4 Profit Maximization[6]

In the absence of any market restrictions, a profit-maximizing farmer takes land quality and prices as given and chooses the quantity of water to be applied, irrigation technology and a crop by following a two-stage profit-maximization procedure (Caswell and Zilberman, 1986; Khanna et al., 2002; Dridi and Khanna, 2005). In this study, a farmer has six irrigation technologies and 12 crops. In the first stage, the farmer decides on the optimal amount of water to be applied to the crop for each irrigation technology. Once this decision is made, the choice of selecting the optimal irrigation technology depends on the relative profitability of each technology. The optimal crop and irrigation technology are selected from the combinations of irrigation technologies and irrigation crops during the profit maximization.

Let π_i^{tc} denotes quasi-rent per ha at this stage for irrigation technology t and crop c. Then,

$$\pi_i^{tc} = \max_{w_i^{tc}} (P^c y_i^{tc}(Z) - g^t w_i^{tc} - k^{tc}) \qquad (2.3)$$

The first order condition from equation (2.3) is expressed as[7]:

$$P^c y_i^{tc'}(Z) h_i^t(\theta_i) - g^t = 0, \ \forall \theta \qquad (2.4)$$

This condition indicates that the price of effective water and optimal production occurs when the value of the marginal product of effective water is equal to its price[8]. The concavity of the production function ensures that the second order condition for the profit maximization is obtained (see Appendix F).

From equations (2.1), (2.2) and (2.4), the interior solution to equation (2.3), which is the optimal quantity of water use (w_i^{tc*}) can be derived as:

$$w_i^{tc*} = \frac{a_1 ETp_i^c}{2a_2 h_i^t(\theta_i)} - \frac{ETp_i^{c^2} g^t}{2a_2 P^c h_i^t(\theta_i)^2} - \frac{ETa}{h_i^t(\theta_i)} \qquad (2.5)$$

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[6] Not all costs are considered by the profit function in equation 2.3 because of data availability and mathematical complexities. Therefore the term profit as used in this thesis refers to quasi-rent or short-run profit.

[7] The prime indicates derivative and chain rule is used to obtain equation (2.4) by taking the derivative of profit with respect to water.

[8] This condition may not necessary be valid in situations when the price of water is zero in the absence of water trading.

In the second stage, the farmer compares quasi-rent per ha under the alternative irrigation technologies and crop choices, and decides what technology combinations and crop to use. The farmer will choose the irrigation technology that maximizes profit.

Let $\hat{\pi}_i^{tc}$ denote the second stage quasi-rent for farmer i and $\hat{P}^c$, $\hat{y}_i^{tc}$, $\hat{g}^t$, and $\hat{k}^{tc}$ are the associated output price, yield, variable irrigation costs and fixed costs of irrigation technology. Given optimal quantity of water use in equation (2.5), the optimization decision process at this stage can be formulated as:

$$\hat{\pi}_i^{tc} = \max_{t,c}(\hat{P}^c \hat{y}_i^{tc}(Z) - \hat{g}^t w_i^{tc^*} - \hat{k}^{tc}) \tag{2.6}$$

The adoption of a more efficient irrigation technology occurs when its quasi-rent is positive and larger than that of the less efficient irrigation technology, such that for any given two irrigation technologies and two crops:

$$\hat{\pi}_i^{22} \geq \hat{\pi}_i^{11}, \forall \theta \tag{2.7}$$

Caswell et al. (1993) showed that the profit gap between efficient and less efficient irrigation technologies decreases as land quality improves. Their argument was that, since using an efficient irrigation technology serves as a land quality-augmenting input, such a technology is more likely to be adopted on low quality land. Their final argument was that the optimal choice of irrigation technology will switch at some point on the continuum of land quality. The level of land quality at which the farmer's decision could change about adopting efficient and inefficient irrigation technologies is called the switching point. Caswell et al. (1993) showed that at this level of land quality, both technologies yield the same profit per ha.

On high-quality lands, either technology is profitable although the inefficient irrigation could be more profitable. It is possible that at a higher land quality the efficient irrigation technology may not be adopted. Where the efficient irrigation technology makes a difference is on land of moderate quality. The above profit model provides conditions under which an irrigation technology and irrigation crop could be adopted, given the variations in land quality. The next section discusses how the profit model is extended to capture the conditions necessary to encourage water trading and the subsequent adoption decisions of farmers at post trade.

2.3.3.5 Water Allocation and Bilateral Trading

In southern Alberta, voluntary transfers of water allocations are allowed within the irrigation districts. Water transfers within the districts are governed by the Irrigation District Act of 2000 (Alberta, 2000b), which allows an allocation of water held under a license to be transferred from one parcel of land to another, as long as the transfer does not have a detrimental impact on another water user or on the aquatic environment (Albert Environment, 2003). Transfers of water allocations can be temporary or permanent. Temporary transfer or trade refers to the sale of annual allocation of water while permanent trade refers to the sale of the water license (Alberta Environment, 2003). The model developed here applies to both systems, but the simulation results focus on temporary trading. In reality, there has been very little permanent trading in southern Alberta. Much of the trading in the region has been on temporary trading of water allocation, primarily in 2001, due to a severe drought.

This section provides the theoretical formulation of the gains from water trading under perfect information. Unlike the US situation, in southern Alberta the district authorities allocate an annual quantity of water to the farmers (Alberta, 2000a: Section 81; Alberta, 2000b: Section 11; Nicol and Klein, 2006). Depending on the district, the annual water allocated ranges from 18 to 24 inches per acre in the SSRB (EID, 2002). Water trading occurs when there is a difference between the annual quantity allocated and the amount of water needed to produce a particular crop or during drought conditions. Also, the trade-offs between the cost of water and the value of water has to be considered before trading may occur. Farmers in a given district have permission to trade water. During water trading, some farmers act as buyers and others as sellers. In this model, the decision to be a buyer or a seller depends on the marginal benefits of both parties at the time of trading and the variation in land quality.

In modeling water trading and the potential impact on crop choice and irrigation technology, two alternative theoretical approaches may be considered; simultaneous decision making or sequential decision making. Simultaneous decision making implies that decisions regarding water trading as well as selection of crop and irrigation technology are made at the same time. Sequential decision making assumes that the decisions are made in sequence.

Studies such as Green et al. (1996), Moreno and Sunding (2005) and Schoengold et al. (2006) suggest that a simultaneous modeling approach should be used to examine these types of decisions. However, the simultaneous modeling approach is most useful for problems where uncertainty of future water supplies and prices as well as quasi-irreversible nature of investment in modern irrigation technology are considered (Carey and Zilberman, 2002). Also, Koundouri et al. (2006) and Groom et al. (2008) suggest that the simultaneous modeling is appropriate in cases when water is a scarce farm input. In this situation, expected profit levels become random because they are functions of exogenous climate conditions. Risk-averse farmers might adopt water-efficient irrigation technology so as to reduce the production risk they encounter during water scarce periods (Awudu et al., 2011).

When water scarcity is not involved and the adoption is mainly about different farm choices, the analysis may focus on examining the determinants of irrigation technology adoption, crop choices and potential gains from water trading. The approach is then to identify factors that determine whether irrigators adopt or reject irrigation technology after water trading (Ersado et al., 2004; Moreno and Sunding, 2005; Amsalu and Graaff, 2007). This thesis belongs to the latter group of studies, since the aim is to determine the probability of farmers switching among irrigation technologies after water trading. Under these circumstances, it is appropriate to consider using a sequential decision making modeling approach.

Many of the studies that have used the simultaneous modeling assumption are based on econometric approaches and their focus have been to test for potential endogenity of crop choices in irrigation technology adoption with no consideration for water trading (e.g., Moreno and Sunding, 2005; Awudu et al., 2011). Given the nature of the problem considered in this thesis and the empirical methodology used in the analysis, the simultaneous assumption would be problematic due to the "curse of dimensionality" issue (Chong and Sunding, 2006; Dinar and Zilberman, 1991). The use of simultaneous assumption with irrigation technology adoption, crop choices and water trading may result in a complex optimization problem that would not yield much analytical insight, but would serve to make solving the numerical simulation extremely difficult. As a result, the gains from using such an approach may not justify the cost (Caswell and Zilberman, 1986; Green, 1995; Khanna et al., 2002; Dridi and Khanna, 2005). Since the aim of the study is to examine potential gains from trade, the sequential assumption modeling approach is more tractable and numerically straightforward to implement.

Finally, the methods used to determine optimal water trades and the use of sequential decision making processes in this thesis are consistent with previous studies on irrigation technology adoption and water trading in different geographical areas. Examples of the use of this type of decision making process of selecting an irrigation technology and a crop include Caswell and Zilberman (1986), Caswell et al. (1990), Caswell et al. (1993), Shah et al. (1995), Dinar and Zilberman (1991), Caswell et al. (1990), Khanna et al. (2002), Green (1995), Green et al. (1996), Moreno and Sunding (2005), Negri and Brooks (1990) and Schoengold and Sunding (2011). Previous studies that have looked at water trading and irrigation technology adoption using a similar approach include Carey and Zilberman (2002), Dinar and Letey (1991); Dinar and Zilberman (1991) and Dridi and Khanna (2005).

Suppose farmers i and j own transferrable rights to annual water allocation, given as w_i and w_j, respectively. Using the farm-based profit function for farmer i and farmer j, and their marginal benefit functions, it is possible to examine whether or not there are trading opportunities for these farmers. From equation (2.3), farmer i and j profits maximization decision making processes before water trading can be specified as:

$$\pi_i^{tc}(w_i, h_i^t(\theta_i)) = P_i^c y_i^{tc}(w_i, h_i^t(\theta_i)) - g_i^t w_i - k_i^{tc} \qquad (2.8)$$

$$\pi_j^{tc}(w_j, h_j^t(\theta_j)) = P_j^c y_j^{tc}(w_j, h_j^t(\theta_j)) - g_j^t w_j - k_j^{tc}, \qquad (2.9)$$

The first order conditions from equations (2.8) and (2.9) are:

$$\frac{\partial \pi_i^{tc}}{\partial w_i} = P_i^c \left(\frac{a_{1i}}{ETp_i^c} - 2a_{2i} \left(\frac{ETa + w_i h_i^t(\theta_i)}{ETp_i^c} \right) \frac{1}{ETp_i^c} \right) h_i^t(\theta_i) - g_i^t = 0 \qquad (2.10)$$

$$\frac{\partial \pi_j^{tc}}{\partial w_j} = P_j^c \left(\frac{a_{1j}}{ETp_j^c} - 2a_{2j} \left(\frac{ETa + w_j h_j^t(\theta_j)}{ETp_j^c} \right) \frac{1}{ETp_j^c} \right) h_j^t(\theta_j) - g_j^t = 0 \qquad (2.11)$$

As stated above, water trading encourages efficiency of water use and provides benefits to buyers and sellers within the district (Griffin, 2006). The implicit assumption of this model is that a farmer with a higher marginal benefit for water tends to have a greater incentive to purchase water from a farmer with lower marginal benefit. Thus, water trading rules can be defined as follows[9]:

If $\frac{\partial \pi_i^{t_i c_i}}{\partial w_i} \neq \frac{\partial \pi_j^{t_j c_j}}{\partial w_j}$, there are mutually gainful trade opportunities assuming the transaction cost is zero.[10] Suppose that $\frac{\partial \pi_i^{t_i c_i}}{\partial w_i} \geq \frac{\partial \pi_j^{t_j c_j}}{\partial w_j}$. In this case, farmer i buys water from farmer j and this extra water could be used to increase crop yield. In response to now having less water, farmer j could invest the additional income from selling water to adopt an efficient irrigation technology, all things being equal. If trade occurs between these farmers, we can derive the amount of water traded (w_{ji}) between i and j as[11]:

$$\frac{\partial \pi_i^{t_i c_i}(w_i + w_{ji})}{\partial w_i} = \frac{\partial \pi_j^{t_j c_j}(w_j - w_{ji})}{\partial w_j}, \qquad (2.12)$$

By combining equations (2.1), (2.5), (2.8), (2.9) as well as (2.10), (2.11) and (2.12), the solution for the amount of water traded (w_{ji}) is given in equation (2.13) below (see Appendix F for full derivation of equation (2.13)):

[9] The farmers involved in trading may have different crops. In situations where the crops are the same, the differences between farmers would be captured by the variation in land quality.

[10] It should be noted that it is not necessary for all such derivatives to be unequal, just the two derivatives representing the pre-trade optimal decisions for the two trading farmers.

[11] As these traders contemplate a potential trade of water, they are assumed to each actively consider their optimized (post-trade) choice of crop and technology associated with all possible levels of w_{ji}. The bounds on how much each would be prepared to bid or accept for each marginal unit of water, w_{ji} are defined with reference to all possible crop and irrigation technology choices.

$$w_{ji} = \frac{\dfrac{a_{1i}P_i^{c_i}h_i^{t_i}(\theta_i)}{ETp_i^{c_i}} - \dfrac{a_{1j}P_j^{c_j}h_j^{t_j}(\theta_j)}{ETp_j^{c_j}} - (\beta_1) - 2ETa(\beta_2) + g_j^{t_j} - g_i^{t_i}}{2\left(\dfrac{a_{2i}P_i^{c_i}h_i^{t_i}(\theta_i)}{ETp_i^{c_i^2}} + \dfrac{a_{2j}P_j^{c_j}h_j^{t_j}(\theta_j)}{ETp_j^{c_j^2}}\right)} \tag{2.13}$$

where

$$\beta_1 = \left(\frac{2a_{2j}P_j^{c_j}h_j^{t_j^2}(\theta_j)w_j}{ETp_j^{c_j^2}} - \frac{2a_{2i}P_i^{c_i}h_i^{t_i^2}(\theta_i)w_i}{ETp_i^{c_i^2}}\right)$$

$$\beta_2 = \left(\frac{a_{2j}P_j^{c_j}h_j^{t_j}(\theta_j)}{ETp_j^{c_j^2}} - \frac{a_{2i}P_i^{c_i}h_i^{t_i}(\theta_i)}{ETp_i^{c_i^2}}\right)$$

After water trading and without transaction costs, these farmers can maximize their individual benefits by consuming water to the point where their marginal benefits functions (MB) are equal. At the margin, each unit of water will be worth the same to each farmer at the end of trading. Thus, $MB_i(w_{ji}) = MB_j(w_{ji}) = u_{ij}$ which serves as the price of the water transferred between the farmers (Griffin, 2006; Dinar and Zilberman, 1991; Zilberman et al., 2008; Sunding et al., 1998; Green, 1995). It is further assumed that this transfer is only possible when the water trade is beneficial to both parties. The post-trade profit functions $(\pi_i^{tc*}, \pi_j^{tc*})$ for farmers i and j can be expressed as in equations (2.14) and (2.15) below:

$$\pi_i^{tc*}(w_{ij}, h_i^t(\theta_i)) = P_i^c((-a_0 + a_1(\delta_i) - a_2(\delta_i)^2)Yp_i^c) - g_i^t(w_i^{tc*} + w_{ij}) - k_i^{tc} - u_{ij}w_{ji} \tag{2.14}$$

$$\pi_j^{tc*}(w_{ij,} h_j^t(\theta_j)) = P_j^c((-a_0 + a_1(\delta_j) - a_2(\delta_j)^2)Yp_j^c) - g_i^t(w_j^{tc*} - w_{ij}) - k_j^{tc} + u_{ij}w_{ji} \tag{2.15}$$

where

$$\delta_i = \frac{ETa + (w_i^{tc*} + w_{ij})h_i^t(\theta_i)}{ETp_i^c}$$

$$\delta_j = \frac{ETa + (w_j^{tc} - w_{ij})h_j^t(\theta_j)}{ETp_j^c}$$

Subsequently, the buyer and the seller compare the gains from trading to the value of water traded. The decision making process is done such that both parties compare the differences in their profits with the expected gains from water. To complete the water trading decision making processes for the traders, three additional constraints are required, as follows:

$$\pi_i^{tc*}(w_{ji}(\theta_i,\theta_j),h_i^t(\theta_i)) \geq \pi_i^{tc}(w_i^{tc*},h_i^t(\theta_i)) \quad (2.16)$$
$$\pi_j^{tc*}(w_{ji}(\theta_i,\theta_j),h_j^t(\theta_j)) \geq \pi_j^{tc}(w_j^{tc*},h_j^t(\theta_j)) \quad (2.17)$$
$$0 \leq w_{ji}(\theta_i,\theta_j) \leq \overline{w}_j \quad (2.18)$$

Constraints (2.16) and (2.17) ensure the trading parties a minimum level of profit at least equal to the profit they had before initiating any water trading. At this stage, we adopt ex post individual rationality, which means that a farmer accepts a trade only if the realized profits are at least as large as those in the absence of trade (Dridi and Khanna, 2005). This is a much stricter requirement than the interim individual rationality where constraints (2.16) and (2.17) would be replaced by their expected values as suggested by Gresik (1991). Constraint (2.18) limits the volume of trade to be no greater than the water allocation of the seller.

For the amount of water traded to be feasible, it has to be accompanied by a monetary transfer given by the expressions below (equations 2.19 and 2.20). The final level of monetary transfer will be determined through negotiation between the trading parties:

$$u_{ij}w_{ji} \leq P_i^c((-a_0 + a_1(\delta_i) - a_2(\delta_i)^2)Yp_i^c) - g_i^t(w_i^{tc*} + w_{ji}) - k_i^{tc} - \pi_i^{tc*} \quad (2.19)$$

$$u_{ij}w_{ji} \leq \pi_j^{tc*} - P_j^c((-a_0 + a_1(\delta_j) - a_2(\delta_j)^2)Yp_j^c) + g_j^t(w_j^{tc*} - w_{ji}) + k_j^{tc} \quad (2.20)$$

where w^{tc^*} is the optimal water use and π^{tc^*} is post-trade profit functions as defined previously.

After trading, it is expected that both the buyer and seller would be willing to invest their potential trading gains in farm improvements in the form of irrigation technology. These irrigation technologies can improve both crop yield and farm profits if accompanied by better farm management practices. Since optimal water use for each farmer is hypothesized to decrease with increasing land quality (Caswell and Zilberman,1986; Dinar and Zilberman,1991; Dridi and Khanna, 2005), it is expected that as land quality increases, so does the marginal value for water. This indicates that for trading to be beneficial for water allocation, the farmer with lower land quality must be selling to a farmer with higher land quality. This implies that at post-trade, it is possible that those farmers who sell part of their water allocation may use the gains from trade to adopt efficient irrigation technologies. It is expected that these farmers will adopt efficient irrigation technologies when post-trade incremental net benefits of the efficient irrigation technology exceed its costs such that:

$$P_i^c(w_i^{1c*}+w_{ji})(h_i^2(\theta_i)-h_i^1(\theta_i))[a_1-a_2(w_i^{1c*}+w_{ji})(h_i^2(\theta_i)+h_i^1(\theta_i))]\geq k_i^{t2} \quad (2.21)$$

$$P_j^c(w_j^{1c*}-w_{ji})(h_j^2(\theta_j)-h_j^1(\theta_j))[a-a_2(w_j^{1c*}-w_{ji})(h_j^2(\theta_j)+h_j^1(\theta_j))]\geq k_j^{t2} \quad (2.22)$$

If the above conditions are satisfied, both the seller and buyer are expected to adopt efficient irrigation technologies to produce profitable crops. When trade occurs, positive gains are expected for the seller as well as the buyer. With these gains, both the seller and the buyer will decide whether to switch to an efficient irrigation technology or remain with their current irrigation technology. Also, they have to decide on the choice of a crop that makes the technology profitable, under prevailing market conditions.

Implicit in the previous discussions and derivations is an assumption that there exists an interior solution for water demand. Specifically, it is assumed that for $\theta\in[\underline{\theta},\overline{\theta}]$, the interior solution for water demand is $w_i^{tc}\leq\frac{a_1ETp_i^c}{2a_2h_i^t(\theta_i)}$ and that total demand exceeds supply. Furthermore, it is assumed that $w_i^{tc}>\frac{a_1ETp_i^c}{4a_2h_i^t(\theta_i)}$ for all farmers, technology and crop and that water use decreases with respect to the farmer's land quality, $\frac{\partial w_i^{tc}(\theta_i)}{\partial\theta_i}<0$. Also, it is assumed that efficiency of water use must hold when this condition is satisfied, $\frac{a_1ETp_i^c}{4a_2h_i^t(\theta_i)}<w_i^{tc*}\leq\frac{a_1ETp_i^c}{2a_2h_i^t(\theta_i)}$. Lastly, w_{ji} must be greater than zero for a trade to occur.

The above water trading and irrigation technology model is used to examine relationships between irrigation technology adoption, crop choices and land quality. In addition, the model is used to verify another theoretical finding: that is, at a certain level of land quality, both the efficient and inefficient irrigation technologies are equally beneficial and beyond that, the inefficient irrigation technology is more beneficial to the farmers than the efficient one. Thus, the efficient irrigation technology is more likely to be adopted on low-quality lands. Regarding irrigated crop choices and irrigation technology adoption, the existing literature shows that farmers switch to an efficient irrigation technology to increase profit. When this occurs, they tend to cultivate high-valued crops, which require more water. This current model is used to examine which crops farmers are more likely to cultivate when they switch to efficient irrigation after water trading. The next section presents and discusses the economic relationships used in deriving key equations of the model.

2.3.4 Empirical Approach

The preceding section presented a theoretical model that illustrates the decision of a farmer to adopt an efficient irrigation technology to produce a profitable crop at post trade. The empirical analysis in this study focuses on estimating/deriving and solving/simulating the equations and the optimal conditions associated with the theoretical model. The following empirical approach is used to acquire data to determine parameter values to calculate optimal water, crop, technology and water trading decisions using the relationships derived in the preceding section.

In the empirical analysis, equations (2.1), (2.2), and (2.3) are combined to derive equation (2.5), which is the optimal water use by crop and irrigation technology. Optimal water use provides an indication of how much water is necessary for the farmers to maximize their profits. The implication of equation (2.5) in relation to equations (2.3) and (2.2) is that if the value of the marginal product exceeds its cost (equation 2.4), then profits can be increased by increasing water use. Alternatively, if the value of marginal product is less than its costs, then profits can be increased by decreasing the level of water use. From equation (2.3), if the profits of the farm are at a maximum, then profits should not increase when water use is increased or decreased. This implies that at a profit maximizing choice of water and output, the value of marginal product ($P^c y_i^{tc}(Z) h_i^t(\theta_i)$) should be equal to water price (g^t). The profit maximization "problem" specified in equation (2.3) is then to find the combination of adjustable water use and output that can yield the farm the same profit. The data used to derive these equations and the optimal conditions are presented below.

2.3.5 Data

Data were collected to determine the ratio of water available to water used by crops (equation 2.1), the actual crop yield (equation 2.2) and the profit of a given farmer (equation 2.3). These included potential (ETp^c) and actual crop evapotranspiration (ETa), potential crop yield (Yp^c), crop output prices (P^c), variable cost of irrigation (g^t) and fixed costs of irrigation technologies (k^{tc}). These data were combined with parameters such as crop specific regression coefficients, land quality and efficiency of irrigation technologies to determine the optimal conditions of equations (2.5) and (2.6). A detailed description of the data and parameters used to derive the optimal conditions is provided in the next section.

2.3.5.1 Irrigated Crops in the SSRB

In the SSRB, there are four main categories of irrigated crops: cereals, forages, oil seeds and specialty crops (Table 2.1).

Table 2.1 Share of Selected Crops in the Irrigated Areas of the SSRB

Crop Category	Crop types	Total Irrigated Area(Acres)	Percentage Share of Total Irrigated Area
Cereals	Barley	106180	8.76
	HRS Wheat	191818	15.82
	SWS wheat	43161	3.56
Forages	Alfalfa	68819	5.67
	Barley Silage	67764	5.59
	Corn Silage	54215	4.47
	Tame grass	82914	6.84
Oil Seeds	Canola	155691	12.85
	Flaxseed	20740	1.71
Specialty Crops	Dry beans	29910	2.47
	Potatoes	42288	3.49
	Sugar beets	35598	2.94
Total Area(Acres)		899098	74.18
Total Area for All Crops(Acres)		1211997	

Source: Alberta Agriculture and Rural Development (2011)

Based on the total area under cultivation, the most dominant irrigated crops are: (1) barley, HRS wheat, SWS wheat (for cereals); (2) alfalfa, tame grass, barley silage, silage corn (for forages); (3) canola, flaxseed (for oilseeds); and (4) dry beans, potatoes, and sugar beets (for specialty crops). Together these crops represent about 74 percent of the total irrigated area under cultivation in the SSRB (Alberta Agriculture, Food and Rural Development, 2011). Table 2.1 presents the percentage share of the irrigated area that each crop occupies in the SSRB. The detailed calculation of the ratio of the share of each crop to the total irrigated area is presented in Appendix A. Given this cropping pattern, the profit function in equation (2.3) is specified as a function of these crops.

2.3.5.2 Crop Yield Estimation

UMA (1982) estimated crop-specific coefficients for the major irrigated crops (equation 2.2). In southern Alberta, the growing season ETa is about 225 to 300 mm for most irrigated crops (UMA, 1982; Bennett and Harms, 2011). The ETp^c values for the irrigated crops considered for the study were gathered from Alberta Agriculture, Food and Rural Development (2009) and reported in Table 2.2. The production function which represents the water-yield function is expressed in equation (2.2). The production function estimates from UMA (1982) study were used together with data collected on ETa, ETp^c and Yp^c in order to calculate the actual crop yields for this study. UMA (1982) showed that actual yield (y^{tc}) to potential yield (Yp^c) ratio could be estimated by fitting data to a second-degree polynomial function as expressed in equation (2.2).

2.3.5.3 Irrigated Crop Prices

Time series data were gathered for the nominal prices for the 12 crops considered in the analysis (equation 2.3). The prices for these crops (except for corn silage) were taken from reports such as Viney et al. (1996), the Alberta Agriculture Yearbook (2008) and the Irrigation Water Management Study Committee (2002, vol. 5). The average corn silage price (at 60 percent moisture) was taken from the Agriculture Financial Services Corporation Commodity (AFSC) price survey (2011). To reduce price-trend variability, the series is converted to uniform units of dollars per ha. Prices are then expressed in 1997 dollars using the Consumer Price Index. The expected price is then taken as a simple average of prices from 1990-1999 (Table 2.2).

These prices were used in the base model to calculate the gains from water trading and irrigation technology and crop switching, at post trade. Recent prices have been collected from 2000-2010 for crops such as sugar beets, potatoes, dry beans, canola, barley, wheat and flaxseed to verify if there is any significance difference between the two periods (Agriculture Statistics Yearbook, 2010). These prices were converted to constant dollars using 2008 Alberta Consumer Price Index (Appendix B).

Table 2.2 Yield Equation Coefficients for 12 Irrigated Crops in the SSRB[a]

Crop Type	a_0	a_1	a_2	P^c($/t)	Yp^c(t/ha)	ETp^c(mm)
Alfalfa	-0.297	1.272	-0.313	88.00	13.59	604.52
Barley	-0.299	1.696	-0.644	170.00	6.42	401.32
Barley silage	-0.201	2.763	-0.244	39.00	27.18	401.32
Canola	-0.021	1.121	-0.360	415.34	3.46	452.12
Dry beans	-0.650	2.498	-1.038	500.03	2.72	604.52
Tame grass	-0.334	1.781	-0.701	95.00	8.44	550.00
HRS wheat	-0.291	1.628	-0.557	381.03	4.94	401.32
SWS wheat	-0.291	1.628	-0.557	314.16	6.67	452.12
Potatoes	-0.618	2.467	-1.014	194.58	49.42	502.92
Sugar beets	-0.501	2.528	-1.144	43.24	61.78	467.00
Flaxseed	-0.021	1.121	-0.360	338.95	2.96	375.92
Corn silage	-0.364	2.570	-1.335	35.00	22.24	510.00

Sources: Irrigation Water Management Study Committee, 2002. vol. 5; AIMM, 2007; Alberta Agriculture, Food and Rural Development, 2009; UMA, 1982; Kaliel et al.,2008; Kulshreshtha and Tewari, 1991; Alberta Agriculture Statistics Yearbook, 2008. a. a0, a1 and a2 indicate the crop-specific regression coefficients. P^c is the output price per crop, Yp^c indicates potential yield per crop and ETp^c is the evaporation from soil and transpiration from crops, which occurs given sufficient moisture.

A paired t-test is performed in SPSS for the periods 1990-1999 and 2000-2010 to test for statistically significant differences in prices for the two periods. The results suggest that there are significant differences for sugar beets, potatoes, barley, and flaxseed prices while price differences for dry beans, wheat and canola were insignificant at a five percent level (see Appendix C).

The differences in these prices could affect the baseline results of the model; that is, the optimal choice of crop as well as incentives for trading water. However, the actual price levels will not affect the ability to use this model to examine relationships between water trading and incentives to adopt irrigation technology. As well, given the differences over time in crop prices, a sensitivity analysis is performed to observe how changes in crop prices could affect the model results.

2.3.5.4 Variable Cost of Irrigation

As mentioned earlier, g^t is the variable cost in dollars per millimeter of water applied per ha. The variable costs of irrigation for each irrigation technology are obtained from the Irrigation Water Management Study Committee (2002. vol. 5) and are presented in Table 2.3.

Table 2.3 Irrigation Technology Variable Cost of Production

Irrigation Technologies	Variable Cost of Water Use $(g^t)^a$ (\$/mm/ha)
Gravity- flood	0.108
Gravity-developed	0.099
Sprinkler-wheel move	0.319
Sprinkler-high pressure	0.351
Sprinkler-low pressure	0.293
Micro-drip	0.279

Source: Variable cost of water (Irrigation Water Management Study Committee, 2002. vol. 5). a. g^t stands for variable cost of water use for irrigation.

On a per-unit-of-water-applied basis, labor costs are more expensive for the gravity flood irrigation technologies than for the pivot sprinkler technologies. Repair and maintenance costs are more expensive for the micro drip technologies than for the gravity technologies. Sprinkler technologies have higher energy costs than gravity technologies. Since the analysis is short run in nature, fixed costs such as depreciation are excluded and therefore only variable costs are included in the calculation of farm profits. The variable costs are then entered into the total cost function with the amount of applied water (measured in millimeters) and used in estimating profit (equation 2.3).

2.3.6 Calibration Methodology

The data presented above are necessary to estimate the profit function in equation (2.3). However, there are no data for the land quality parameter (θ_i). A literature review resulted in no evidence of any sources that would indicate the relationship between efficiency of irrigation technologies and land quality in the study area. Thus, there is the need to derive this parameter because it is required to estimate equations (2.1), (2.2) and (2.3). The method used in deriving these parameters is called calibration. Calibration is a process used to estimate parameter values so as to replicate a benchmark model. Alternatively, an econometric approach could be used to estimate these missing parameters, but this is very demanding in terms of data requirements. The next section specifies the detailed calibration approach used in the study.

2.3.6.1 Land Quality and Irrigation Technology Application Efficiency

As a first step, the land quality parameter (θ_i) is calibrated to replicate the baseline values of the irrigated areas under each irrigation technology in the SSRB (Table 2.4). The calibrated value is then used to derive a proportional relationship between the efficiency of water use for each irrigation technology and land quality. After this calibration, the irrigation efficiency parameter, which is a function of land quality, is used in the production function specified in equation (2.2). Traditionally, this production function provides the yield of a crop given the variations in the amount of water applied. However, equation (2.2) does not include water use efficiency of an irrigation technology with respect to land quality. In order to capture the relationship between land quality and water use efficiency in the production function, this calibration approach is adopted.

The calibration process focuses on the percentage share of land occupied by each irrigation technology in the SSRB. This process helps to provide information on the dominant irrigation technology in the study area. Also, it shows that a greater percentage of the land will be occupied by that irrigation technology. The land area occupied by each irrigation technology was divided by the total area occupied by all the technologies in the study area. This value was then converted to percentage shares for each irrigation technology (Table 2.4). These values were used in the calibration of the land quality parameter.

The land quality value for each irrigation technology is calibrated using the following procedure. Let α^t denote the elasticity of irrigation technology with respect to land quality. This measures how responsive the land is to further irrigation. Practical interpretation means that an increase in land quality results in a reduction in the price of effective irrigation; and, assuming decreasing marginal productivity, the optimal amount of effective water has increased, leading to an increase in both output and quasi-rent per acre (Caswell and Zilberman,1986; Shah et al.,1995).

The effectiveness of irrigation technology t for a given farmer can be mathematically expressed as:

$$h^t = \theta_i^{\alpha^t} \tag{2.23}$$

From equation (2.23), a log property is used to derive α^t as in equation (2.24) below:

$$\alpha^t = \log h^t / \log \theta_i \tag{2.24}$$

From equation (2.24), the values of h^t are taken from studies such as AIMM (2007) and the Irrigation Water Management Study Committee (2002. vol. 5). These are the standard application efficiency rates for the six irrigation technologies selected for the study and are presented in Table 2.4. As seen in Table 2.4, sprinkler low-pressure pivot-irrigation technology is the most dominant technology in the study area and this indicate a greater percentage of the land will be used by this technology.

In the calibration process, the value of θ_i was 0.5, which corresponds to the proportion of land use by the dominant irrigation technology in the study area. As an example, if the application efficiency of the low-pressure pivot irrigation technology is 0.8, using equation (2.24), the value of the elasticity of irrigation efficiency for this technology will be 0.322. Using this same approach, the values for all the other irrigation technologies were calibrated.

Table 2.4 Land Quality Values for Irrigation Technology Effectiveness[a]

Irrigation technologies	Percentage use by of alternative irrigation technologies	Application efficiency of irrigation technology (h^t)	Elasticity of irrigation technology with respect to land (α^t)
Gravity-flood	6.57	0.30	1.737
Gravity-developed	5.33	0.62	0.689
Sprinkler-wheel move	20.05	0.70	0.514
Sprinkler-high pressure	15.80	0.74	0.434
Sprinkler-low pressure	48.81	0.80	0.322
Micro-drip	0.42	0.87	0.201

Sources: Variable cost of water (Irrigation Water Management Study Committee, 2002. vol. 5); AIMM, 2007. a. The percentages given here do not sum to 100 percent, because the calibration does not include all irrigation technologies used in the study area.

The α^t values are presented in Table 2.4. After obtaining these values, equation (2.23) is then used to derive appropriate values for θ_i to indicate the relationship between irrigation technology and land quality for a given farmer. Similar calibration processes can be found in studies such as Hanemann et al. (1987), Caswell and Zilberman (1986), Shah et al. (1995), and Khanna et al. (2002).

2.3.6.2 Irrigation Technology Costs of Production

After calibrating for land quality parameter, the annualized irrigation technology fixed cost parameter (k^{tc}) is then chosen. Available estimates for this parameter were obtained from the Irrigation Water Management Study Committee (2002. vol. 5). These values were used to parameterize the profit model. However, these values did not yield positive profits for most of the crop considered for the study. The approach used was based on the management practices in the

SSRB. In the SSRB, lands suitable for irrigation are classified and incorporated into the annual district development plan for water management and irrigation purposes (Alberta, 2000b, Section 11). Thus, farmers are more likely to irrigate on land which is classified as suitable for irrigation, to ensure positive profits. After the calibration of land quality values (θ_s), the fixed costs are then chosen to ensure that the profits generated by the actual outcomes are not negative. Similar calibration methods are used in studies such as Howitt (1995), Liang (2010), Roberts (1994) and Cho and Cooley (1994). The lower and upper bounds on selected fixed costs of irrigation technologies values used in the model are presented in Appendix D. After calibrating, the land quality and the fixed costs values are then used to estimate optimal water use (equation 2.3), crop yields (equation 2.2) and profit per ha for six irrigation technologies and 12 crops (equation 2.6). The initial results from these equations are outlined in the next section.

2.4 Stylized Results[12]

This section presents the initial results from the theoretical model. In particular, the results presented here focus on optimal water use, crop yields and the profit per crop per ha. The essence of this section is to examine certain theoretical relationships of the model presented in this study. For instance, the first part of the results discussion focuses on the relationships between optimal water application and the effect of variation in land quality. The aim is to verify the theoretical findings that the quantity of water applied with efficient irrigation technologies decreases with increased land quality. The second part of the discussion deals with estimating the actual yield, given potential yields, to verify if yield increases with increased land quality.

The final results presented and discussed in this section focus on the profit function for the 12 crops under efficient and inefficient irrigation technologies considered in the study. These initial results are presented in two parts. The first part deals with the illustration of sample calculations of optimal values for water use, crop yield and profits from the model. The second part focuses on the effect of land quality on the calculated optimal values.

[12] These results, based on the theoretical model, are calculated to examine relationships between land quality and water use, crop yield and profit level per ha. The term stylized is used because these results are not based on actual farm data from the study area. It should be noted that the values presented here are not meant to represent actual profit levels for farmers in the SSRB. It would be difficult to validate these results because of data limitations and difficulties in obtaining individual farm level profit for farmers in the study area.

2.4.1 Crop Water Use by Irrigation Technologies and Land Quality

In this and following sub-sections, the initial simulation results of the optimal values for alternative irrigation technologies and crops are presented. This is done to illustrate how land quality affects optimal values and to compare these results with existing theoretical and empirical studies on irrigation technology adoption and crop choices. The summary results are presented in Tables 2.5 to 2.7.

The first part of the results deals with optimal water use. Table 2.5 provides sample results for optimal water use for alternative combinations of land quality, crop and irrigation technology. In Table 2.5, the rows indicate different irrigation technologies while the crops are presented in the columns. To reiterate, there are six irrigation technologies and 12 crops. The simulation results are presented under three different land qualities; (a) low land quality (0.25), medium land quality (0.5) and high land quality (0.75). This classification is used to illustrate the impact of land quality on the use of water and irrigation technology efficiencies in order to simplify the presentation.

As expected, for most of these crops the simulation results show that optimal water use decreases with increasing land quality (Table 2.5). For instance, the simulation results show that the amount of water use by barley decreases by 38 percent (from 1018.9 mm to 624.72 mm) from low quality land to medium quality land. With respect to water use by barley under medium and high quality lands, the results show that the amount of water use decreases by 45 percent (from 624.72 mm to 343.09 mm). These trends are consistent for water use under most of the crops considered with the exception of tame grass and corn silage. For tame grass, the amount of water use increases by 17 percent (from 858.71 mm to 1000.5 mm) from low to medium quality land, and decreases by 42 percent (from 1000.5 mm to 578.52 mm) under high quality land. Further, the simulation results for corn silage reveal a slight increase in the amount of water use from low to medium quality land, but an even greater decrease from medium to high quality land (Table 2.5).

It should be noted that the optimal water use values are also dependent on irrigation technology. As a result, the effect of land quality and the efficiency of the various irrigation technologies on the optimal water value is also examined. The simulation results show that water use decreases with increasing efficiency of irrigation technologies under all land quality variations considered

(Table 2.5). In addition, the results indicate that optimal water use is higher for low-efficient irrigation technologies for all crops, under low land quality. Additionally, optimal water use decreases for all irrigation technologies with variation in land quality for all crops (Table 2.5). This indicates that as land quality increases optimal water use eventually decreases for all irrigation technologies and that optimal water use is higher for lower efficiency irrigation technologies. These results reaffirm those from previous studies conducted for irrigation technology adoption in the US (Caswell and Zilberman, 1986; Dridi and Khanna, 2005). Optimal water use levels over the full range of land quality values, by crop and irrigation technology, are illustrated in figures 2.3 to 2.6.

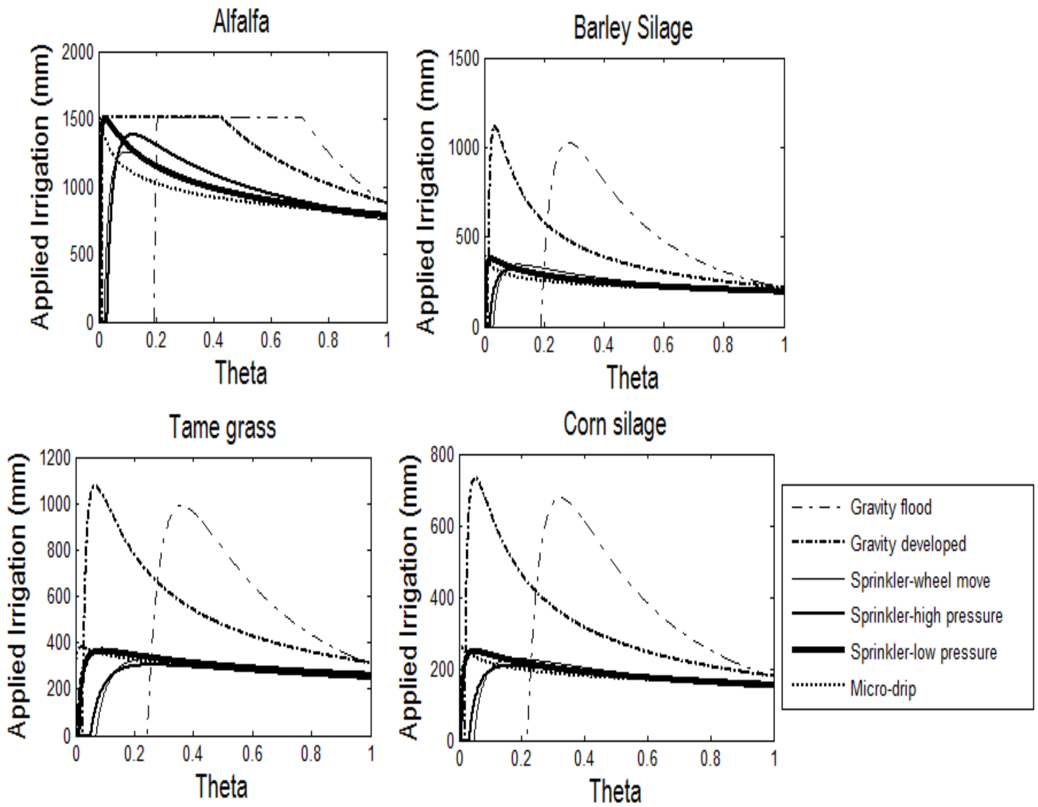
Table 2.5 Stylized Results – Optimal Water Use ($w_i^{tc^*}$, mm) for Alternative Crops (c), Land Quality (θ) and Irrigation Technologies (t) [a,b]

Low Land quality(0.25)												
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	1569.10	1018.90	972.87	1569.10	1569.10	858.71	1569.10	1569.10	1569.10	1569.10	578.39	460.27
tech2	1569.10	517.58	515.25	918.39	1025.20	856.84	693.83	879.74	802.36	537.96	611.31	412.76
tech3	1246.10	314.10	309.49	561.81	700.47	456.10	482.66	619.86	619.00	393.37	322.76	223.31
tech4	1124.00	283.16	279.10	506.34	629.16	413.06	433.30	556.26	554.13	352.65	292.39	202.12
tech5	1101.40	275.05	272.57	489.79	575.33	430.44	392.71	501.01	477.85	311.95	306.07	208.75
tech6	988.80	246.06	244.37	437.43	501.71	395.67	341.11	433.95	405.59	267.97	281.81	191.26
Medium Land Quality(0.5)												
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	1569.10	624.72	620.58	1110.40	1270.20	1007.50	863.23	1097.80	1023.70	677.31	717.69	486.83
tech2	1371.60	338.97	338.08	600.60	656.05	573.72	442.30	559.26	499.52	339.17	409.84	275.67
tech3	1008.40	251.81	249.56	448.40	526.40	394.35	359.28	458.33	436.94	285.32	280.42	191.23
tech4	941.65	235.32	233.10	419.19	494.70	366.27	337.93	431.35	412.99	269.00	260.35	177.75
tech5	936.97	233.14	231.55	414.44	475.06	375.15	322.96	410.83	383.77	253.64	267.20	181.33
tech6	887.14	220.38	219.10	391.45	443.61	359.06	300.99	382.36	353.58	235.10	255.93	173.29
High Land quality(0.75)												
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	1387.60	343.09	342.08	608.05	666.69	578.52	449.77	568.98	510.08	345.57	413.18	278.09
tech2	1060.20	261.72	261.21	463.47	502.16	446.55	338.05	427.00	378.29	258.13	319.14	214.37
tech3	867.11	215.79	214.30	383.62	440.14	346.87	299.27	380.73	355.95	235.14	247.04	167.68
tech4	831.95	207.26	205.69	368.64	426.03	330.47	290.02	369.29	347.42	228.65	235.25	159.91
tech5	846.31	210.24	209.02	373.44	423.28	342.47	287.21	364.86	337.45	224.36	244.11	165.29
tech6	830.71	206.18	205.09	366.07	412.34	338.12	279.49	354.77	326.26	217.66	241.10	163.06

a: crop1(Alfalfa);crop2(Barley);crop3(Barley silage);crop4(Canola);crop5(Dry beans);crop6(Tame grass); crop7(HRS/Durum);crop8(SWS wheat);crop9(Potatoes);crop10(Sugar beets);crop11(Flaxseed); crop8(SWS wheat);crop9(Potatoes);crop10(Sugar beets);crop11(Flaxseed);crop12(corn silage) crop12(silage corn);tech1(gravity flood);tech2(gravity-developed);tech3(sprinkler-move); tech4 (sprinkler-high); tech5 (sprinkler-low); tech6 (micro-drip).

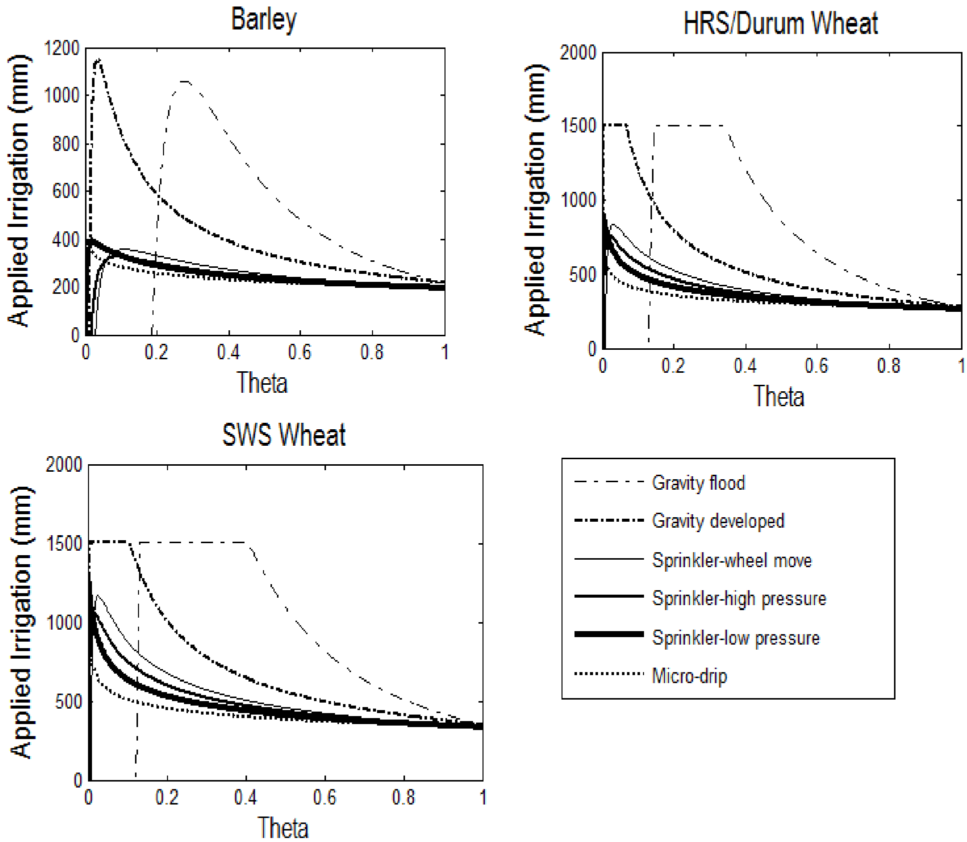
b: The values in this table represent the maximum amount of water that can be allocated for the various irrigation technology and crop combinations.

Figure 2.3 Effect of Land Quality (θ) on Optimal Water Use ($w_i^{tc^*}$) for Forage Crops Under Different Irrigation Technologies[a]



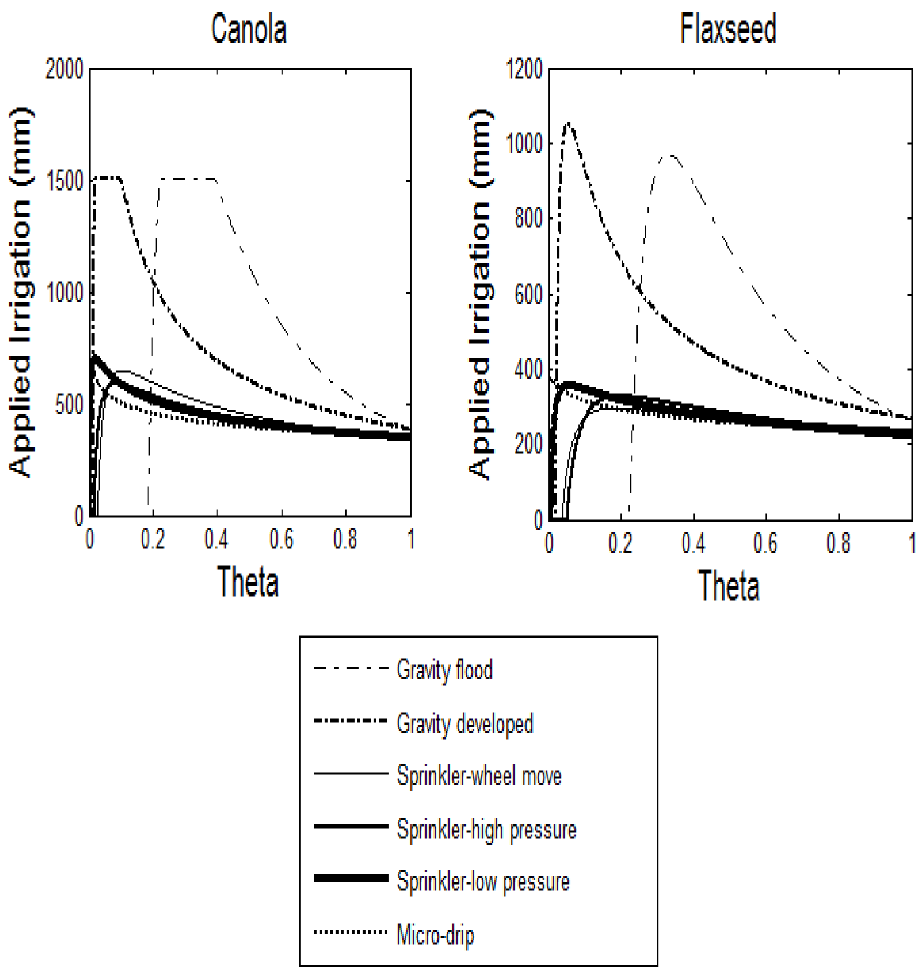
a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Simulation results indicate the amount of water use per crop under each irrigation technology, given land quality.

Figure 2.4 Effect of Land Quality (θ) on Optimal Water Use $(w_i^{tc^*})$ for Cereal Crops Under Different Irrigation Technologies[a]



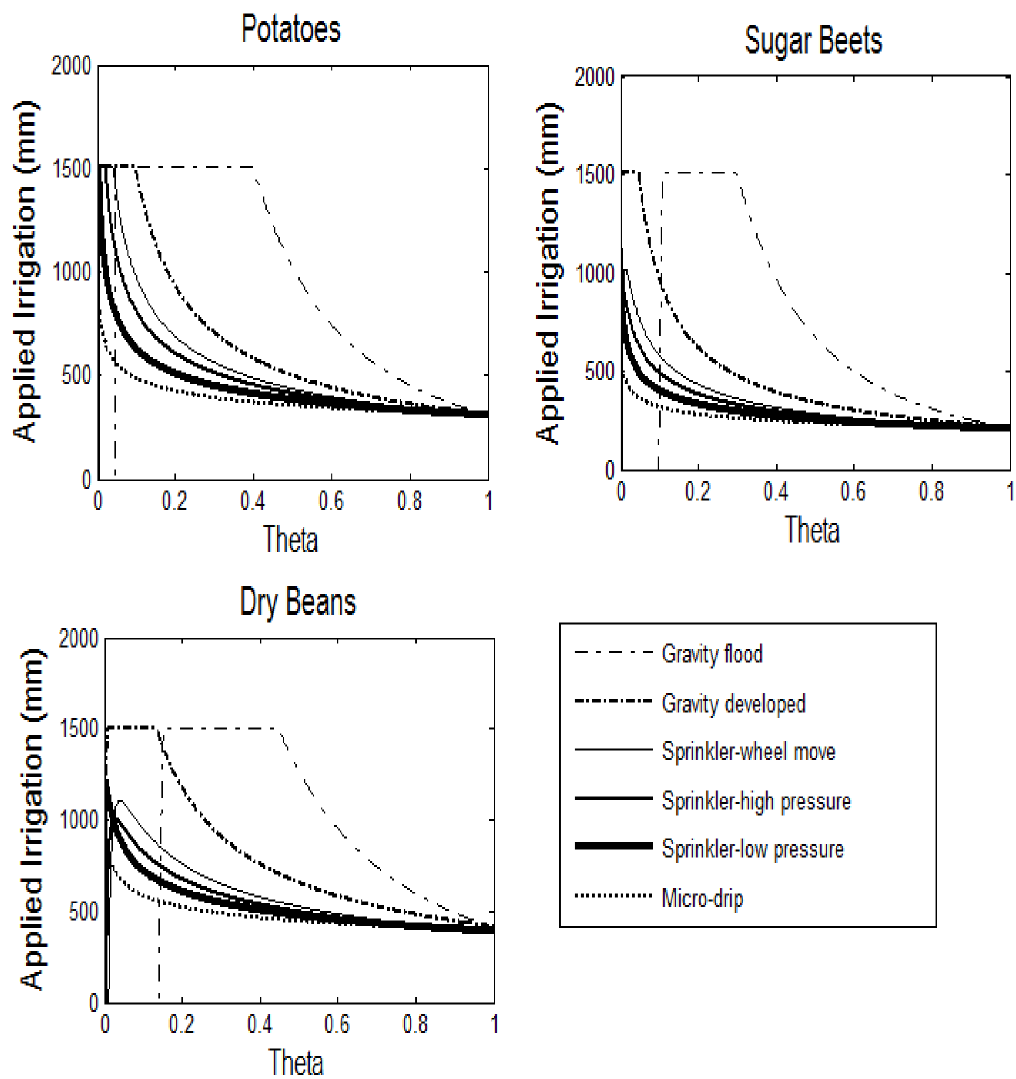
a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Simulation results indicate the amount of water use per crop under each irrigation technology, given land quality.

Figure 2.5 Effect of Land Quality (θ) on Optimal Water Use (w_i^{tc}) for Oil Seed Crops Under Different Irrigation Technologies[a]



a: Theta stands for land quality (θ) *and has a lower value of zero and a higher value of one. Simulation results indicate the amount of water use per crop under each irrigation technology, given land quality.*

Figure 2.6 Effect of Land Quality (θ) on Optimal Water Use $(w_i^{tc^*})$ for Specialty Crops Under Different Irrigation Technologies[a]



a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Simulation results indicate the amount of water use per crop under each irrigation technology, given land quality.

2.4.2 Optimal Crop Yields by Irrigation Technology and land Quality

This section illustrates the relationship between actual optimal crop yield and potential crop yield in the SSRB. Also, the relationships between irrigation technologies, crop yield and variation in land quality are presented. Potential yield (Yp^c), is achieved when the best management practices are applied and major farming inputs including water are not scarce, while actual yield (y_i^{tc}) takes into account growth-reducing factors and considers the farmers' current management practices (Rabbinge, 1993; Evan, 1993). The ratio between potential to actual yields represents the technical level of production.

A major challenge for an irrigated farmer is to adopt a mix of management practices that can minimize on-farm yield gaps. As water is one of the major on-farm limiting factors of a crop yield, it is critical to ensure that an adequate supply reaches the crop's root zones. Equation (2.2) was used to estimate actual crop yields for the 12 main irrigated crops in the SSRB. Given the values of the estimated parameters of the production function for equation (2.2), actual crop yields were obtained. Once optimal water is derived (i.e., equation 2.5), optimal yield (y_i^{tc}) is calculated and calibrated to be 80 percent of potential yield (Yp^c).

Table 2.6 presents results for optimal crop yields, which are dependent on the amount of water use. The results indicate that crop yields increase with increasing land quality. For example, the simulation results for the least efficient irrigation technology show a 0.55 percent increase (from 13.394 t/ha to 13.468 t/ha) in alfalfa yield from low to medium quality land while a 0.22 percent (from 13.468 t/ha to 13.498 t/ha) increase is observed moving from medium to high quality land (Table 2.6). Under SWS wheat, a slight increase is observed from low to medium quality land as well as from medium to high quality land. Similar trends for yield effects under different land qualities are observed for all other crops (Table 2.6). Also, the simulation results reveal that for a given level of land quality, both inefficient and the relatively efficient irrigation technologies would result in the same optimal yield. This result is observed for crops such as potatoes and HRS wheat. With potatoes, when the land quality is 0.5, there is no yield effect between irrigation technologies sprinkler-move and sprinkler-high. This outcome persists for sprinkler-low and micro-drip irrigation technologies as well. This result is evident for HRS wheat only when the land quality is 0.75 and there is no yield effect when moving from gravity flood technologies to gravity developed technologies. These results suggest that at this land quality, both technologies may be beneficial for the farmer. Also, these results suggest that relatively inefficient irrigation technologies may be beneficial to use on high quality lands (Table 2.6).

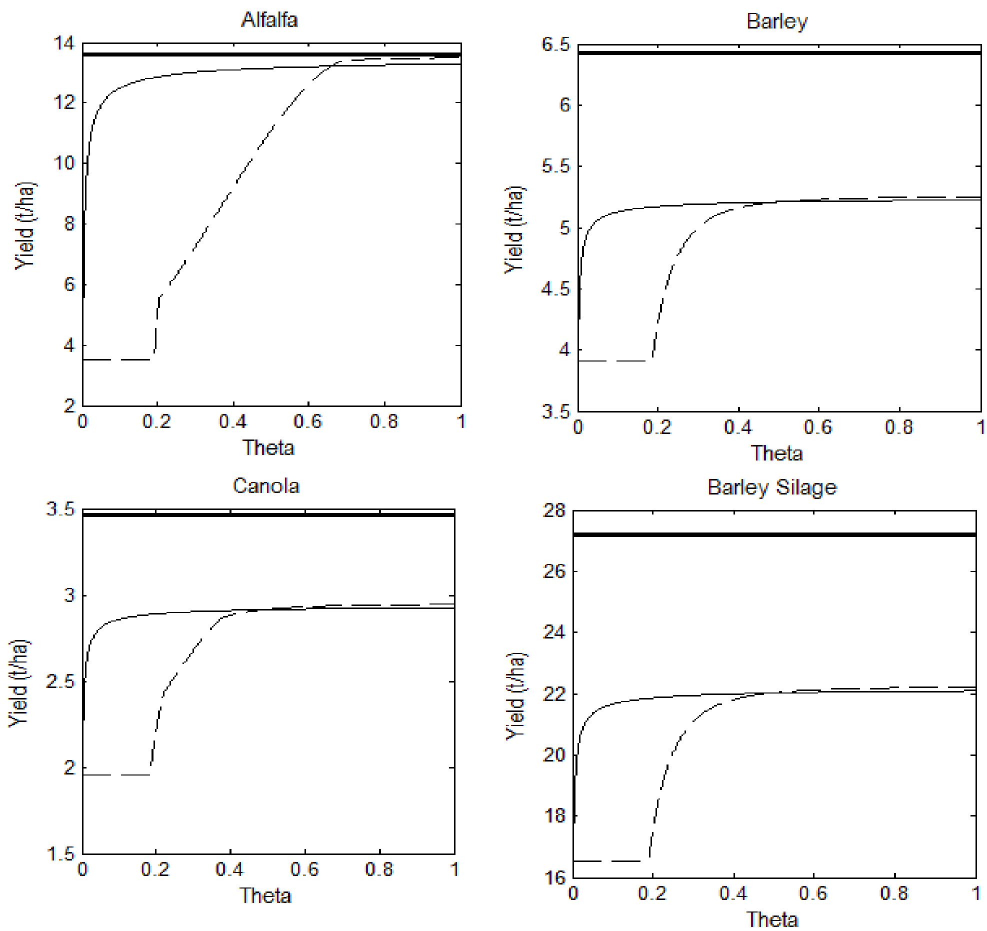
Figure 2.7 illustrates optimal yields for each crop over the full range of land quality values, for two irrigation technologies. As expected, the model results show that (Yp^c) is greater than (y_i^{tc}) for all crops (Figure 2.7). The simulation results also show that crop yield increases as land quality increases, but at a certain land quality both irrigation technologies could produce the same level of yield (Figure 2.7). These results suggest that inefficient irrigation technologies may be beneficial at moderate land quality.

Table 2.6 Stylized Results – Optimal Yield (y_i^{tc}) (t/ha) for Alternative Crops (c), Land Quality (θ) and Irrigation Technologies (t) [a]

	Low Land quality(0.25)											
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	13.394	5.238	22.160	2.936	2.312	6.668	4.436	5.989	43.613	55.309	2.513	19.337
tech2	13.487	5.248	22.202	2.942	2.316	6.708	4.439	5.993	43.614	55.320	2.521	19.386
tech3	13.196	5.212	22.044	2.917	2.302	6.559	4.428	5.979	43.611	55.277	2.491	19.199
tech4	13.172	5.209	22.031	2.915	2.301	6.547	4.428	5.977	43.611	55.273	2.489	19.183
tech5	13.321	5.228	22.112	2.928	2.308	6.623	4.433	5.985	43.612	55.295	2.504	19.279
tech6	13.375	5.234	22.141	2.933	2.311	6.650	4.435	5.988	43.613	55.303	2.510	19.314
	Medium Land Quality(0.5)											
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	13.468	5.246	22.192	2.941	2.316	6.698	4.439	5.992	43.614	55.317	2.519	19.374
tech2	13.503	5.250	22.211	2.944	2.317	6.716	4.440	5.994	43.615	55.322	2.523	19.396
tech3	13.307	5.226	22.104	2.928	2.308	6.616	4.433	5.984	43.612	55.293	2.503	19.271
tech4	13.279	5.223	22.089	2.925	2.307	6.602	4.432	5.983	43.612	55.289	2.500	19.252
tech5	13.371	5.234	22.139	2.933	2.311	6.649	4.435	5.987	43.613	55.303	2.509	19.311
tech6	13.400	5.238	22.155	2.935	2.312	6.664	4.436	5.989	43.613	55.307	2.512	19.330
	High Land Quality(0.75)											
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	13.498	5.249	22.208	2.944	2.317	6.714	4.440	5.994	43.614	55.322	2.522	19.393
tech2	13.510	5.251	22.215	2.945	2.318	6.720	4.440	5.994	43.615	55.324	2.524	19.401
tech3	13.359	5.233	22.133	2.932	2.311	6.643	4.435	5.987	43.613	55.301	2.508	19.304
tech4	13.330	5.229	22.117	2.929	2.309	6.628	4.434	5.985	43.612	55.297	2.505	19.285
tech5	13.396	5.237	22.152	2.935	2.312	6.661	4.436	5.989	43.613	55.307	2.512	19.327
tech6	13.413	5.239	22.162	2.937	2.313	6.671	4.437	5.990	43.613	55.309	2.514	19.339

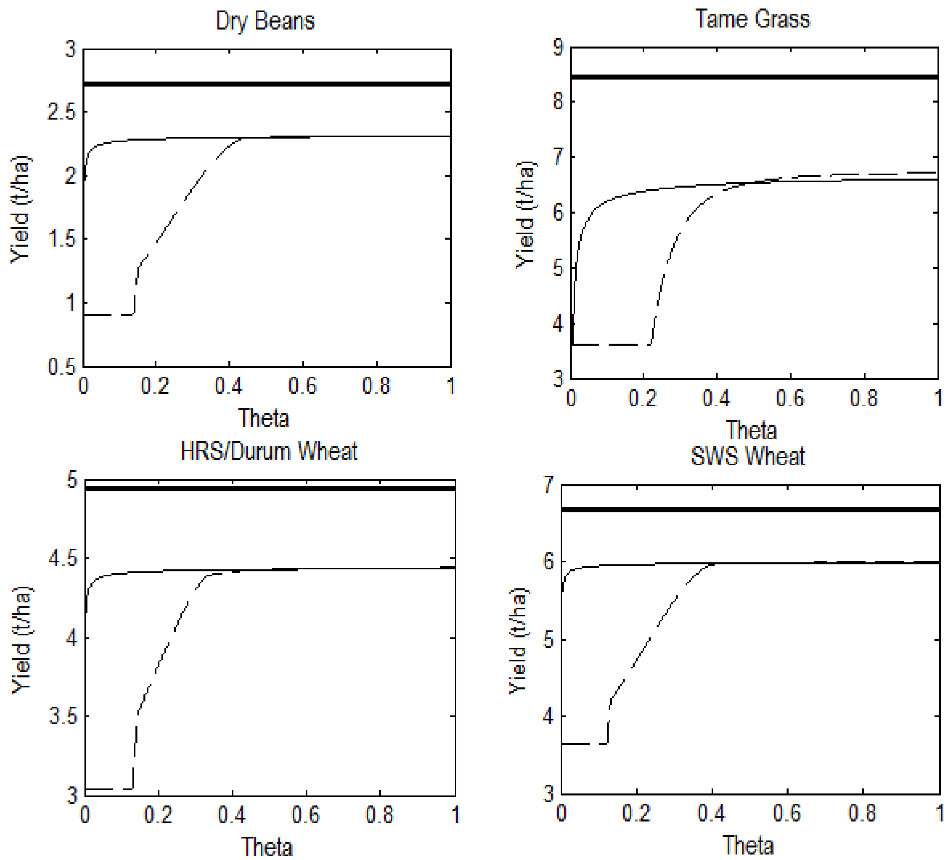
a: crop1(Alfalfa);crop2(Barley);crop3(Barley silage);crop4(Canola);crop5(Dry beans);crop6(Tame grass);crop7(HRS/Durum); crop8(SWS wheat);crop9(Potatoes);crop10(Sugar beets);crop11(Flaxseed);crop12(corn silage)
tech1(gravity flood);tech2(gravity-developed);tech3(sprinkler-move);tech4(sprinkler-high);tech5(sprinkler-low);tech6(micro-drip)

Figure 2.7 Optimal Yield (y_i^{tc}) Per Hectare for 12 Crops (c) under Low and High Efficient Irrigation Technologies (t) [a]



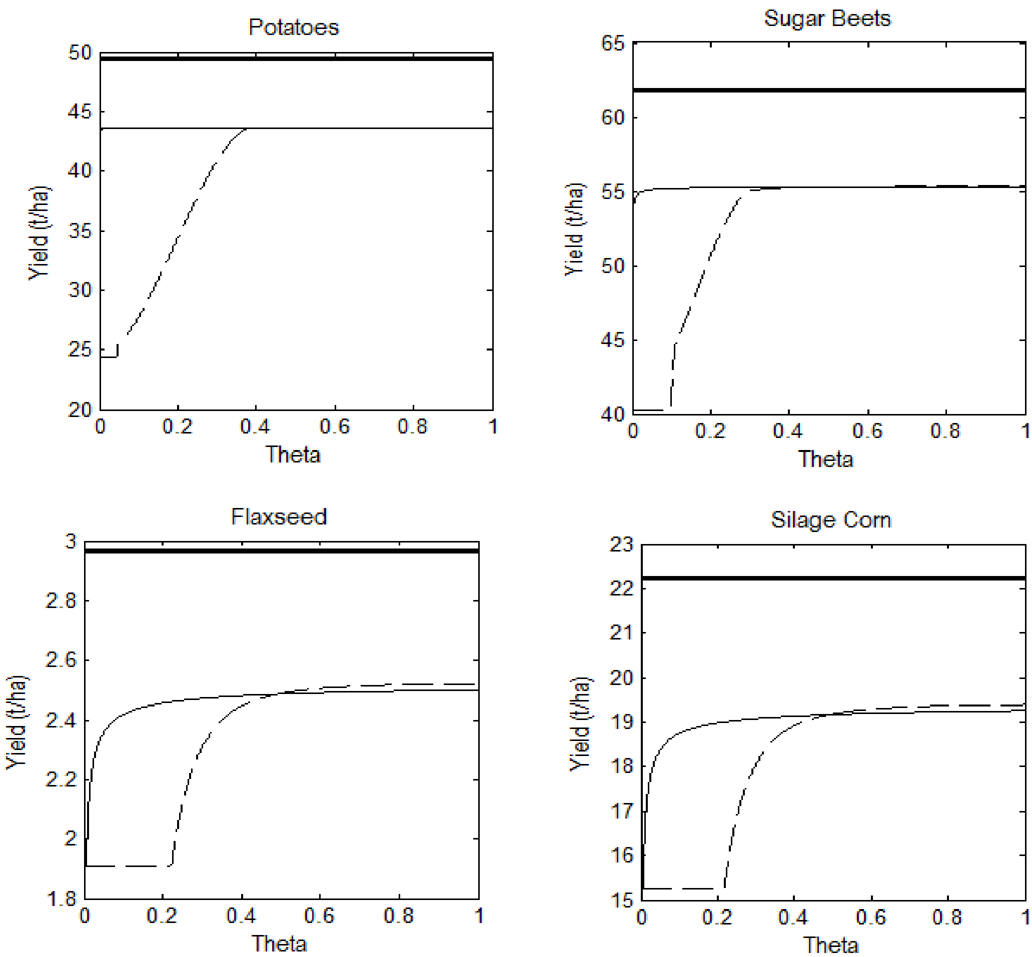
a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Potential Yield (▬); Actual Yield under low efficient irrigation technology (----); Actual Yield under high efficient irrigation technology (——).

Figure 2.7 (Cont'd) Optimal Yield (y_i^{tc}) Per Hectare for 12 Crops (c) under Low and High Efficient Irrigation Technologies (t) [a]



a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Potential Yield (▬); Actual Yield under low efficient irrigation technology (----); Actual Yield under high efficient irrigation technology (——).

Figure 2.7(Cont'd) Optimal Yield (y_i^{tc}) Per Hectare for 12 Crops (c) under Low and High Efficient Irrigation Technologies (t) [a]



a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Potential Yield (▬); Actual Yield under low efficient irrigation technology (----); Actual Yield under high efficient irrigation technology (——).

2.4.3 Optimal Profit under Different Irrigation Technologies and Land Quality

Results for optimal water use are combined with the optimal crop yields, along with irrigation and technology costs, to calculate profits for each combination of irrigation technology and crop. When comparing profits by crop and technology, potatoes, sugar beets and dry beans have the highest profits in all cases. This result is as expected, as these are among the high-value crops, but also require high water use.

Higher profits are also observed for crops such as alfalfa and SWS wheat, under alternative irrigation technologies. Furthermore, the model results show differences in profits across land quality. An important outcome from the simulation analysis is that profit under each technology and crop increases with increasing land quality (Table 2.7). For instance, profit under the least efficient irrigation technology (i.e., gravity flood) for alfalfa increases by 7 percent (from 702.41 $/ha to 752.00 $/ha) moving from low quality to medium quality land and increases by 5 percent (from 752.00 $/ha to 789.49 $/ha) from medium to high quality land. Similar trends of increasing profits as land quality changes are reported for all other crops in Table 2.7. Also, the simulation results show that at a certain land quality, it may be profitable to use a relatively inefficient irrigation technology versus a more efficient one. This result is evident when profit levels of alfalfa for the various irrigation technologies are considered. When the land quality is at 0.75, the simulation results show that gravity-developed technology has the highest profit (811.03$/ha) relative to micro-drip technology, which is the most efficient irrigation technology. This result is consistent for all the crops under gravity-developed technology and micro-drip technology. It is interesting to note that this result is consistent even under low quality lands (Table 2.7). It is possible that beyond this land quality, one would be able to observe that efficient irrigation technologies may be relatively more profitable than inefficient ones. In part, these results are consistent with previous studies showing that the amount of water use decreases with increasing land quality (Caswell and Zilberman, 1986; Khanna et al., 2002; Dinar and Zilberman, 1991; Shah et al., 1995). Under different irrigation crops, however, the simulation results show that the amount of water use may increase or decrease across different land qualities.

Figure 2.8 illustrates optimal profit levels per ha for each crop over the full range of land quality values, for two irrigation technologies. These irrigation technologies are the least efficient and the most efficient irrigation technologies as defined in section 2.3.

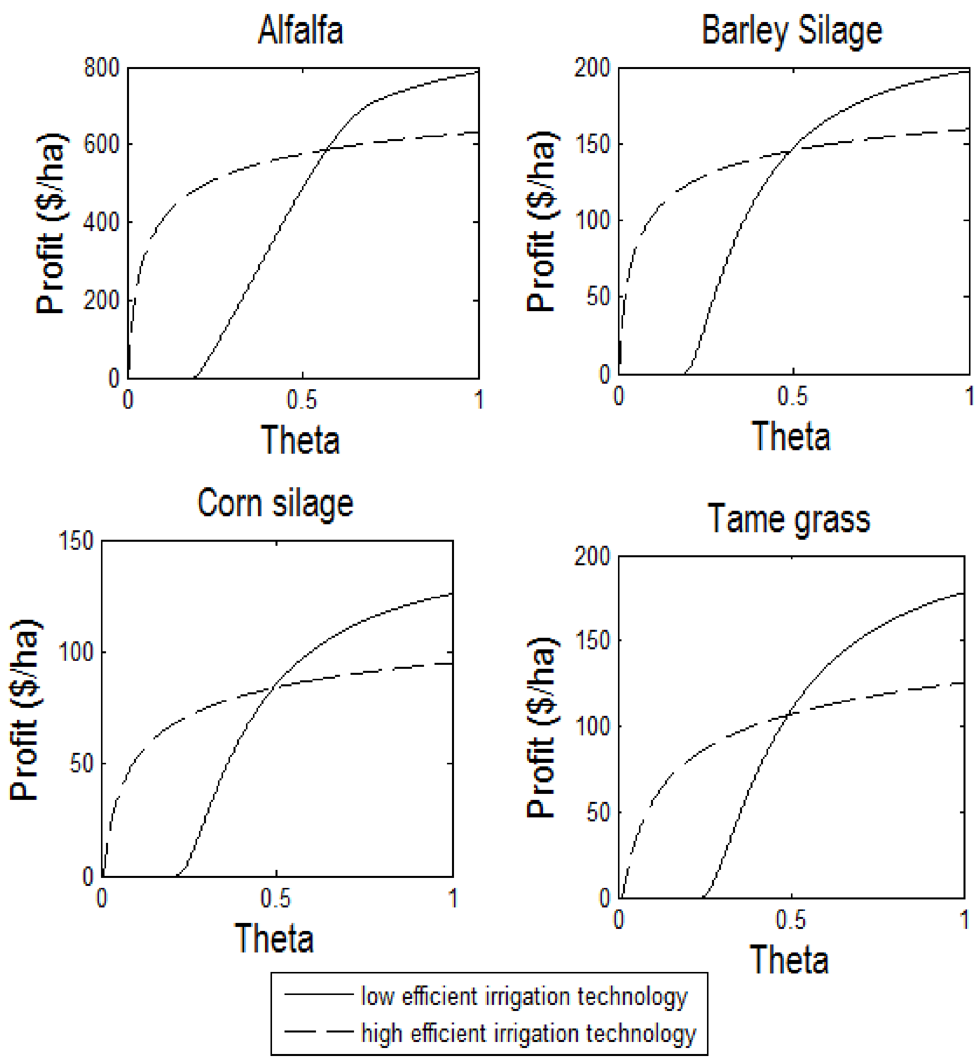
Given the profitability analysis of these crops and the effect of land quality under these irrigation technologies, it is relevant to investigate the potential gains of farmers switching from least efficient irrigation technologies to most efficient after water trading. Many factors could encourage a farmer to switch to an efficient irrigation technology. This study uses water trading as an incentive that can increase profit and conserve water for alternative uses either in the farm or for other sectors of the economy. The next section of this study focuses on this aspect of water trading and the potential gains of switching among irrigation technologies in the SSRB.

Table 2.7 Stylized Results – Optimal Profit (π_i^{tc}) (\$/ha) for Alternative Crops (c), Land Quality (θ) and Irrigation Technologies (θ) [a]

	Low Land Quality (0.25)											
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	702.41	183.41	176.78	334.08	621.42	219.12	477.30	670.96	3672.80	610.05	153.91	109.02
tech2	774.03	201.10	194.42	365.42	655.68	249.04	500.40	700.17	3698.90	627.77	175.28	123.40
tech3	591.25	155.83	149.33	285.12	566.54	173.66	440.13	623.81	3629.60	581.17	121.49	87.11
tech4	581.91	153.51	147.03	280.99	561.83	169.91	436.93	619.74	3625.80	578.66	118.81	85.30
tech5	647.61	169.82	163.25	309.97	594.63	196.53	459.18	648.00	3244.50	596.03	137.79	98.15
tech6	678.64	177.52	170.91	323.62	594.53	209.27	437.52	586.92	1306.50	417.46	146.88	104.29
	Medium Land Quality (0.5)											
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	752.00	195.66	189.00	355.79	645.22	239.78	493.35	691.27	3691.00	622.38	168.67	118.96
tech2	797.74	206.95	200.26	375.78	666.88	259.05	507.93	709.68	3707.30	633.52	182.44	128.20
tech3	640.88	168.15	161.59	307.01	591.30	193.78	456.92	645.14	3649.30	594.28	135.83	96.82
tech4	626.97	164.70	158.16	300.88	584.41	188.11	452.25	639.21	3643.90	590.65	131.79	94.09
tech5	676.07	176.88	170.27	322.49	608.59	208.22	468.63	659.98	3255.40	603.36	146.13	103.78
tech6	695.30	181.64	175.02	330.93	602.64	216.16	443.00	593.86	1312.80	421.69	151.80	107.60
	High Land Quality (0.75)											
Tech	crop1	crop2	crop3	crop4	crop5	crop6	crop7	crop8	crop9	crop10	crop11	crop12
tech1	789.49	204.92	198.23	372.18	662.99	255.56	505.32	706.38	3704.40	631.53	179.95	126.53
tech2	811.03	210.23	203.54	381.58	673.12	264.68	512.13	714.98	3712.00	636.71	186.46	130.91
tech3	669.08	175.15	168.55	319.42	605.17	205.34	466.32	657.05	3660.20	601.57	144.07	102.39
tech4	652.57	171.06	164.48	312.16	597.07	198.56	460.83	650.10	3653.80	597.32	139.24	99.126
tech5	692.17	180.87	174.25	329.56	616.43	214.86	473.93	666.69	3261.50	607.45	150.87	106.98
tech6	704.78	183.99	177.36	335.10	607.23	220.09	446.11	597.79	1316.30	424.08	154.60	109.49

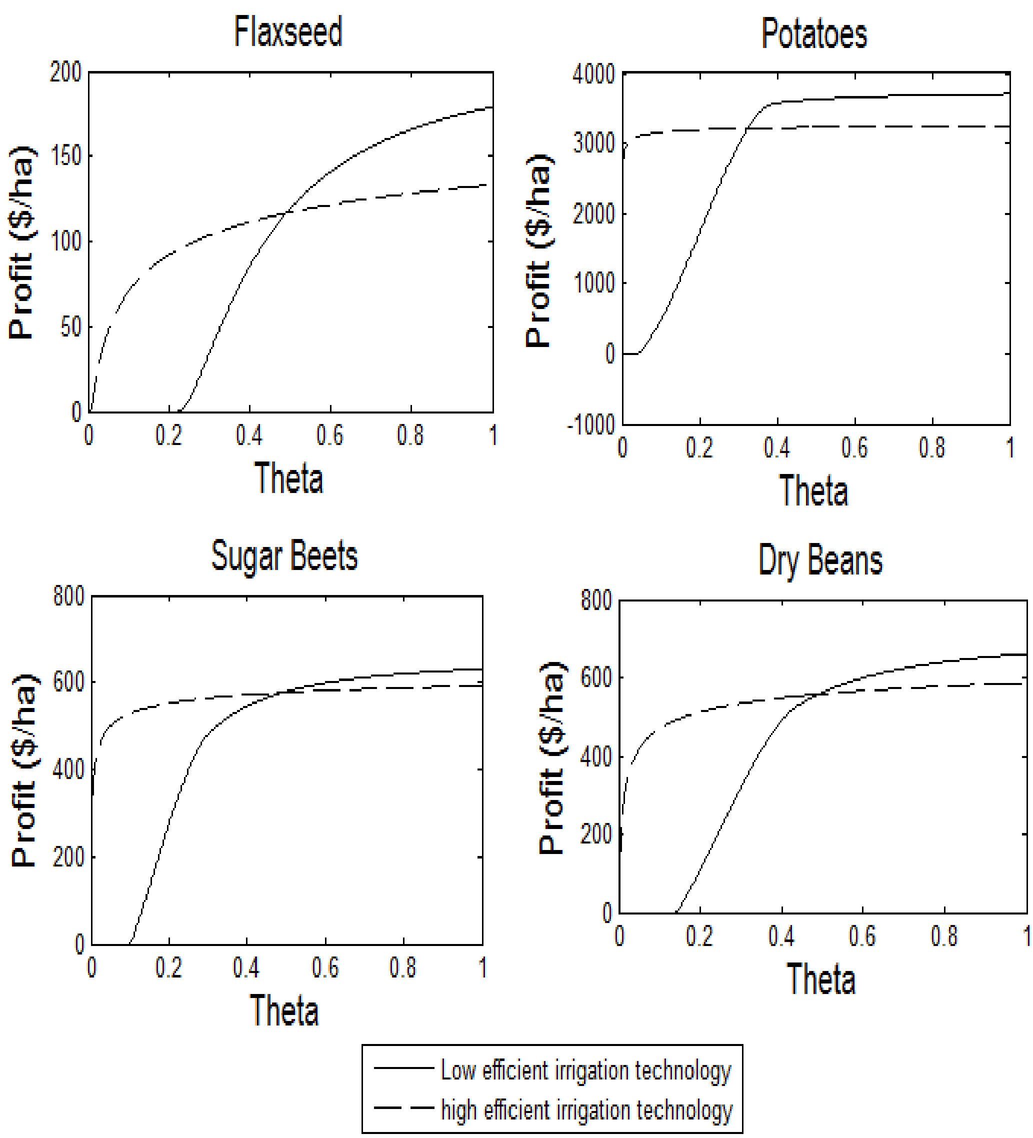
a: crop1(Alfalfa);crop2(Barley);crop3(Barley silage);crop4(Canola);crop5(Dry beans);crop6(Tame grass);crop7(HRS/Durum); crop8(SWS wheat);crop9(Potatoes);crop10(Sugar beets);crop11(Flaxseed);crop12(corn silage)
tech1(gravity flood);tech2(gravity-developed);tech3(sprinkler-move);tech4(sprinkler-high);tech5(sprinkler-low); tech6(micro-drip)

Figure 2.8 Profit (π_i^{tc}) Per Crop (c) under Sprinkler-Low and Flood Irrigation Technologies (t) [a]



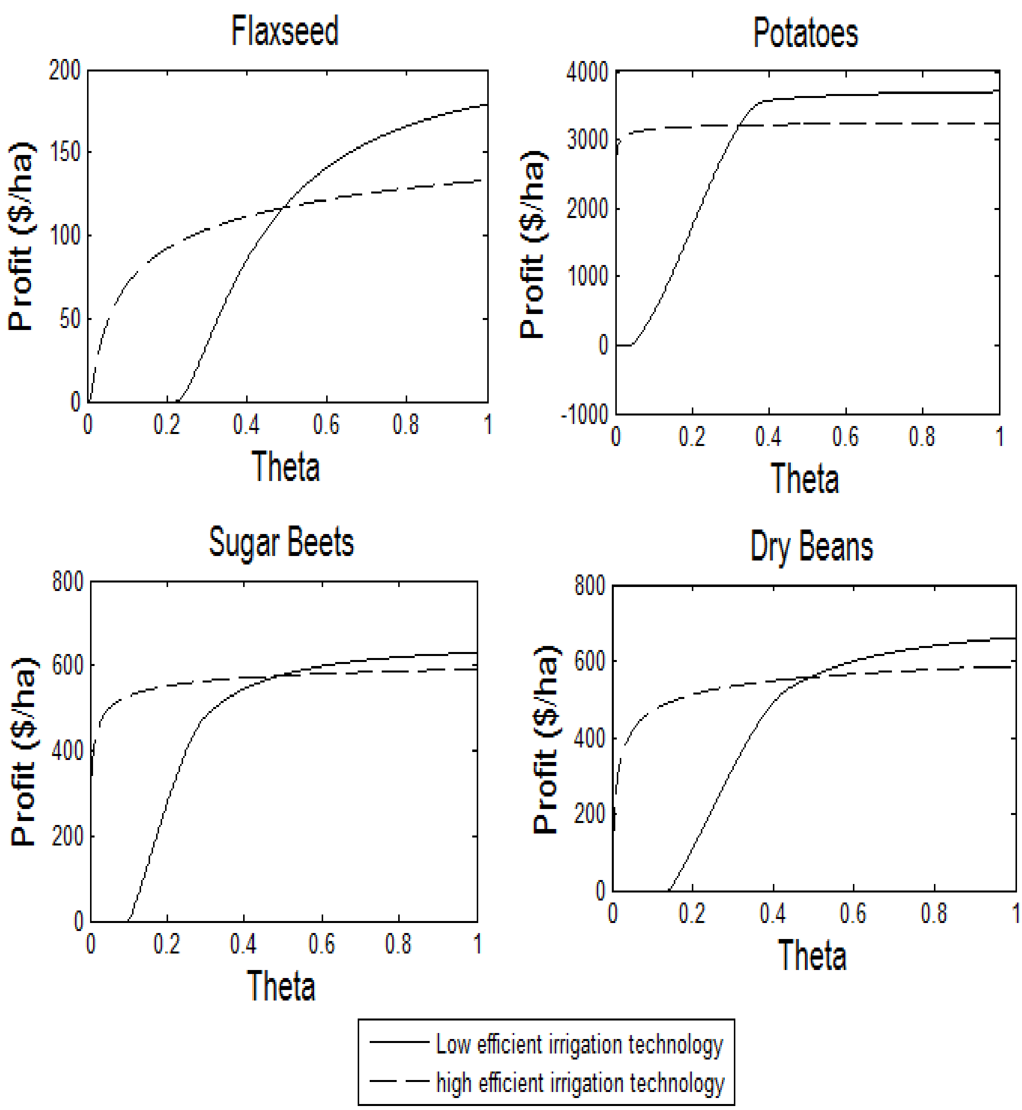
a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Simulation results indicate variation in profits per crop under each irrigation technology, given land quality.

Figure 2.8 (Cont'd) Profit (π_i^{tc}) per Crop (c) under Sprinkler-Low and Flood Irrigation Technologies (t) [a]



a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Simulation results indicate variation in profits per crop under each irrigation technology, given land quality.

Figure 2.8(Cont'd) Profit (π_i^{tc}) Per Crop (c) under Sprinkler-Low and Flood Irrigation Technologies (t) [a]



a: Theta stands for land quality (θ) and has a lower value of zero and a higher value of one. Simulation results indicate variation in profits per crop under each irrigation technology, given land quality.

2.5 Water Trading Simulation

The results presented in the previous section show how the model developed in this study conforms to existing studies on irrigation technology adoption, crop choices and the effects of variation in land quality. This section examines the potential for gains to be derived from water trading and the possibilities of investing those gains in adopting an alternative irrigation technology.

2.5.1 Model Simulation

The water trading simulation is assumed to be between two representative farmers in an irrigation district. As noted earlier, there are six possible irrigation technologies and 12 possible irrigation crops for each farmer. A stochastic simulation is conducted by combining equations (2.3), (2.10), (2.11), (2.16), (2.17), (2.18), (2.19), (2.20) as well as (2.21) and (2.22) to examine the gains from water trading and the probabilities of farmers switching among irrigation technologies and profitable crops after water trading. These equations are functions of the land quality parameters for the buyer (θ_i) and the seller (θ_j).

The simulation is stochastic in that land quality is assumed to be random. The land-quality parameter which differentiates farmer types (θ_i, θ_j) takes a value between zero and one. This parameter is calibrated to reflect the proportional distribution of farmers using different irrigation technologies in the SSRB. Given the range of values for land quality, it is appropriate to use a distribution with bounded support; that is, a distribution defined for the interval $[0,1]$.

In this analysis, land quality is modeled using a beta distribution. The density of a random variable η following a general beta distribution over the interval $[a,b]$ is as follows:

$$f(\eta) = \frac{1}{\beta(a,b)} \eta^{a-1} (1-\eta)^{b-1}, 0 < \eta < 1 \qquad (2.25)$$

where the mean is $(a / a + b)$ and variance is $(ab/(a+b)^2 (a+b+1))$.

The beta distribution is bounded and is flexible in shape. Depending on the values for a and b it can take the appearance of a normal, uniform or skewed distribution (Nadarajah and Kotz, 2004). The beta distribution with a bounded support of zero and one can yield very small numeric values. This could lead to computational challenges and it is appropriate to use large values for a or b in the simulation analysis. A symmetric beta distribution for farmers' land quality is used with parameters $a = 3, b = 3$, which gave a mean of 0.5 and variance 0.013.

One of the key assumptions in the analysis is that land quality is an important determining factor for selection of crops and irrigation technologies (Caswell and Zilberman, 1986; Khanna et al., 2002; Shah et al., 1995; Dridi and Khanna, 2005). The calibration process results in land quality values that are consistent with empirical evidence of irrigation technology decisions made in the region. The resulting calibrated values for land quality were then used as parameters in the profit maximization modeling for both non-trading and trading scenarios. The stochastic simulation entails drawing random land quality values for the buyer and the seller in each period. The detailed simulation steps are explained below.

The simulation steps used to generate the probabilities of irrigation technology switching and irrigation crop switching after water trading are as follows:

Step One: Given an allocation, each farmer derives optimal water use which is a function of land quality, and then uses this optimal water (equation 2.5) to produce crop yield (equation 2.2). The farmer then maximizes profit given land quality, irrigation technologies, irrigation crops and optimal water use. At this stage, the farmer's profit is a function of six irrigation technologies and 12 crops (equation 2.3). The simulation is done to select the irrigation technology and irrigation crop that generate the maximum profit for each farmer. This profit value for each farmer is called the choice function in the simulation. At end of the simulation, depending on the value of land quality, annual allocation, optimal water use, the best combinations of irrigation technology and irrigation crop are selected. The simulation is done in a loop format, where the best combination of irrigation technology and crop are determined for each iteration of the simulation. The simulation is run for 10000 iterations to find the combination of irrigation technology and crop that provide maximum profit for each farmer before water trading.

Step Two: Given the best irrigation technology and irrigation crop, marginal benefit functions (equations 2.10 and 2.11) are derived from equations (2.8) and (2.9) for each farmer from the profit functions in step one (equation 2.3). These marginal benefit functions depend on land quality as well. In the simulation, a water trading condition is imposed such that: (a) when the marginal benefits of the farmers are equal, water trading would not occur, (b) when the marginal benefits are not equal water trading would occur. When water trading occurs, the farmer with the higher marginal benefit for water becomes the buyer (i) and the other becomes a seller (j). At the end of each run of the simulations, the amount of water traded (equation 2.13) and it equivalent price (u_{ij}) are then recorded and saved in a temporary folder for the buyer and the seller.

Step Three: After water trading, a new profit is calculated for the buyer (equation 2.14) and the seller (equation 2.15). These profits are functions of the amounts of water exchanged and the price of traded water. The after trade profits are also functions of the best irrigation technology and irrigation crop from step one. Equations (2.16) and (2.17) are used to ensure that a farmer accepts a trade only if the realized profits are at least as large as those in the absence of trade. A function is programmed in Matlab called jump-trade, which ensures that these conditions are satisfied before trade. Finally, equation (2.18) is used to limit the volume of trade to be no greater than the water allocation for the seller. The gains from water trading are then calculated based on the differences in the profits before and after water trading (equations 2.19 and 2.20).

Step Four: At the end of water trading, both the buyer and the seller have an option to switch irrigation technologies or remain with their current irrigation technologies. Initially, buyers and sellers are allowed to switch "up" to more efficient technology or to switch "down" to less efficient irrigation technology. They also have an option to switch to another irrigation crop or remain with the current crop. It is possible to switch to another irrigation technology, but still keep growing the current crop. Likewise, it is possible to keep the current irrigation technology but switch to another irrigation crop. The simulation is done to examine all these possible combinations (equations 2.21 and 2.22). At this stage, the decision to switch is affected by gains from water trading and the cost of switching to another irrigation technology. If the expected gains are more than the cost of switching, it is worth for the farmer to switch or still remain with the current farming practices.

2.5.2 Computation and simulation implementation

When water trading occurs between the farmers, the amount of water exchanged depends on the irrigation technologies and crops of both farmers. This means that w_{ji} is a matrix with 144 possible combinations of irrigation technologies and crops. In Matlab, all equations and the optimal conditions are defined as functions (Appendix G). The programming is done in such a manner that all the equations and optimal conditions are linked and nested together as functions (i.e., spiral coding). This is done to save time in computation of optimal values. The approach used to implement the computation of w_{ji} is based on Kronecker product of matrices. Matlab has a built-in function "kron" that can be used as K=kron(A,B). Alternatively, sizes can be created for the individual matrices before performing the matrix multiplication. The second approach of creating different sizes for the matrices was adopted because the kron(A,B) syntax was not sufficient when the size of matrices are more than 50 by 50, which was the case in this thesis. The Matlab code for the computation of w_{ji}, which is subsequently used in the computation of all the equations and optimal conditions, is provided in Appendix G.

At the end of trading, the price of water (u_{ij}) is determined as defined and explained earlier. Similarly, the marginal benefit functions of the parties before trade are used to set the upper bound on the price of water. This condition defines the upper bound on the price of water, above which trading is not beneficial to both parties. The upper bound on the price of water is denoted as $\bar{u}$. Furthermore, it is assumed that the probability of u_{ij} being greater than $\bar{u}$ is insignificant and therefore the analysis is restricted to the range of prices for which the farm produces maximum output with any technology and crop combinations (Carey and Zilberman, 2002). Subsequently, equations (2.16) and (2.17) are used to ensure that profits from producing must be greater than or equal to the profit without water trading. Thus, for each technology and crop, the farm's decision to produce is determined by the total profit condition (equations 2.19 and 2.20). In each case, the cutoff is the same for buyers and seller but varies with irrigation technology and crops as well as land quality.

Both the price of water and the amount of water exchanged depend on the random variable of land quality. Given all the other parameters of the model, there is a unique price (u_{ij}) and quantity of water (w_{ji}) exchanged that maximizes both traders' profits so that equation (2.16) and (2.17) are satisfied. In Matlab, two functions were created to search for the price of water and the amount of water exchanged (u_{ij}^*, w_{ji}^*) that satisfied profit maximizing conditions specified earlier and subsequently conditions (2.16) and (2.17). The simulation finds the price and quantity of water exchanged that generate post-trade profit for both parties that is equal to or greater than pre-trade profit (equations 2.16 and 2.17). The theoretical foundation of this approach is based on the irrigation technology adoption literature such as Caswell and Zilberman (1986), Dinar and Zilberman (1991), Khanna et al. (2002), Dridi and Khanna (2005), Shah et al. (1995), Green (1995), Dinar and Letey (1991), Carey and Zilberman (2002) and as outlined in section 2.3.3.4.

Traditionally, historical market prices would be used to estimate the water price. However, reliable farm level water prices are not available. In many informal water trading areas, the sale price of water is the private information of the buyers and the sellers. In many situations, the water agencies have full information about the traders, amount of water exchanged, but very little or no information about the price of water exchanged. Also, the price of water varies significantly from period to period depending on the scarcity of water. Hence, the approach used here is appropriate for modeling informal water trading. It is pertinent to mention that in developing this model, only static games were considered, that is, the analysis excluded dynamic dimensions. In the context of water rights, this assumption is not restrictive since water rights usually span a long period; therefore, each time the contract is designed past information is of little relevance. This approach has been used to model water trading in the US by Dridi and Khanna (2005), Carey and Zilberman (2002), and Griffin (2006).

After the computations of water price and the amount of water exchanged, the simulation analysis is used to estimate the potential gains from trade and to generate probability estimates of the frequency with which water trading results in sufficient producer gains for changes to occur in optimal irrigation technology or crop choice. The results from the simulation are summarized as transition probabilities to show the likelihood of a buyer or seller moving from one irrigation technology to another, post trade (Collins, 1973; Anderson and Goodman, 1957). Results for gains from water trading and technology, crop switching were generated based on 10000 iterations. The simulation was conducted in Matlab 7.4 under two scenarios: (1) full water allocation (i.e., 18-24 inches per acre), and (2) drought allocation conditions (i.e., 9-12 inches per acre). Details of these scenarios are provided below.

2.5.2.1 Scenario One: Full Water Allocation[13]

In the SSRB, the districts have established the maximum amount of water that may be supplied to each acre for irrigation activities. These amounts of water differ across districts, but in general, the annual allocation is in the range of 18-24[14] inches per acre (EID, 2002). When the water is allocated, it is the farmers' responsibility to decide on how to efficiently use their water for crop production. If farmers adopt efficient irrigation technologies or change their farm management practices to save water, they can sell the extra water to other farmers within the same district. The implicit assumption is that when farmers sell water, they have the opportunity to use the extra income to improve farm yields. Given their current irrigation technology, it is possible that these farmers will use their extra income to invest in a different irrigation technology. This scenario examines the probability of farmers switching irrigation technology, after trading.

This is the base scenario and it assumes that farmers have their full annual allocation of water and that farmers have an opportunity to sell any "saved" water. The decision is made based on the minimum of allocation and the optimal water quantity derived in equation (2.5).

2.5.2.2 Scenario Two: Water Scarcity Conditions

The second scenario deals with the situation in which farmers are not able to receive the required annual water entitlement. This situation may occur when there is a drought. For instance, in 2001, there was a drought in the SSRB and the allocations within the districts were reduced to nine inches per acre and in some districts 12 inches per acre. The limit set by the districts during drought years is used in this second scenario. Similarly, the decision is made based on the minimum of allocation and the optimal water quantity derived in equation (2.5). The aim is to examine the gains from water trading and the likelihood of farmers switching irrigation technology under drought conditions. This scenario is selected not only to represent future water scarcity situations in the study area, but to also verify previous findings that farmers are more

[13] Note that this allocation can be more or less depending on several factors such as availability of water in a given year, size of the farm, and district diversions from the source of the water.

[14] The actual amount used to generate the results under full allocation is 19.6 inches, while 10.86 inches is used for the results under scarcity conditions.

likely to switch to an efficient irrigation technology when water is a limiting factor in their production activities (Schuck et al., 2005; Schaible et al., 1991). The next section presents the results of the water trading simulation analysis.

2.6 Simulation Results and Discussion

This section shows the potential gains from water trading and the possibilities of farmers investing the gains in adopting an efficient irrigation technology to produce profitable crops. Scenarios one and two were used to examine the potential gains of farmers adopting efficient irrigation technologies to produce profitable crops. Before presenting the simulation results for the two main scenarios described above, we will present illustrations of potential gains from water trading. The section initially discusses the alternative incentives that could promote the adoption of efficient irrigation technologies in situations where water scarcity is not imminent. Thereafter, the results under conditions of water scarcity are presented. The policy implications of the results from this study are then discussed. Finally, the limitations of the model and gaps for future research are outlined.

2.6.1 Illustrations of Potential Gains from Water Trading

In this section, we present the illustrations of potential gains from water trading between the seller and the buyer. These results are presented to show potential gains pre-trade and post-trade. Ideally, potential gains from trade for each combination of irrigation technology and crop should be provided. However, there are computational issues associated with this since the simulation of gains is done using stochastic methods. Thus for simplicity, potential gains are presented as the mean differences of pre-trade and post-trade profits. These results are presented for three levels of land quality; low (0.25), medium (0.5) and high (0.75). These are provided in Table 2.8.

The simulation results show that pre-trade profits for both the seller and the buyer increase with increasing land quality. For the seller, pre-trade profits increase by 3.6 percent (595.93$/ha to 618.29$/ha) from low to medium quality land, with an increase of 2 percent (618.29$/ha to 629.27$/ha) observed for medium to high quality land. For the buyer, the simulation results show a slight increase in pre-trade profits under the different land qualities considered (Table 2.8).

At post-trade, the simulation results reveal that the seller profit increases by 34 percent (1652.9$/ha to 2222.3$/ha) from low to medium quality land. A higher increase is observed for the seller when the post-trade profits under medium and high land qualities are compared (Table 2.8). At post-trade, the buyer profits also increase under different land qualities. In particular, the post-trade profit under medium land quality increases by 75 percent (1713$/ha to 3000$/ha) when compared with the low quality land. Also, the buyer's post-trade profit increases by 67 percent (3000$/ha to 5033.1$/ha) when medium and high quality lands are compared. The simulation results show that in both pre-trade and post-trade, the buyer obtains relatively higher gains than the seller. These results are consistent with the intuition that buyers have a higher marginal valuation for water, and this increases with increasing land quality.

As expected, the potential gains from trade increase for both traders with increasing land quality. These results suggest that under high land quality, both traders find water trading to be profitable. It is possible these potential gains could lead to additional efficient irrigation technology adoption when the net gains of irrigation technology are higher than the cost of adoption.

The results presented in Table 2.8 provide an indication of the potential gains from trade that farmers under different land qualities may obtain and their implications for irrigation technology adoption and crop choices. The final level of monetary exchange is obtained through negotiation between the traders, and cannot be determined within the framework presented in this thesis. Nevertheless, for various potential water trade levels that induce efficient irrigation technology adoption, the potential monetary exchange is shown in Table 2.8, which indicates that there are positive gains from trade.

The potential gains estimated from the simulation are dependent on the price of water, amount of water exchanged and the irrigation technologies, as well as crop choices. All these values also depend on the level of land quality. For simplicity, we present the summary statistics of the mean values of price and amount of water exchanged during water trading. The simulation results reveal a mean price of water as $4.11/ha/mm and the mean amount of water exchanged to be 236.73 mm. The distribution of mean price of water and the amount of water exchanged during water trading is presented in Appendix E. The next section of the thesis deals with the results under the two main simulation scenarios.

Table 2.8 Stylized Results of Potential Gains from Water Trading

Land quality values(mean)	Land quality[a]					
	Low	Low	Medium	Medium	High	High
1000 Iterations	Seller	Buyer	Seller	Buyer	Seller	Buyer
Mean profit before trade($/ha)	595.93	615.51	618.29	623.26	629.27	631.60
Median profit before trade($/ha)	377.74	394.53	395.01	400.36	406.77	409.90
Mean profit post-trade($/ha)	1652.90	1713.80	2222.30	3005.00	4315.00	5033.10
Median profit post-trade($/ha)	851.25	852.88	732.13	851.11	2461.40	3522.50
Gain from trade(differences in mean profits($/ha))	1056.97	1098.29	1604.01	2381.74	3685.73	4401.50

a: These means are dependent on land quality, irrigation technologies and crops.

2.6.2 Results from Scenarios One and Two: Potential Gains from Irrigation Technology Adoption

This section provides a discussion of results associated with water trading where there may be potential gains for farmers from switching to different irrigation technologies, post trade. The results in this first section deal with scenarios in which farmers may maintain their current irrigation technology or switch to either a more efficient or less efficient irrigation technology, after water trading.

Table 2.9 presents the transition probabilities of the seller and buyer switching to different irrigation technologies after water trading.[15] In the transition probability matrix, the columns refer to the current irrigation technology being used while the rows identify irrigation technology adopted at the end of trading. In this analysis, the diagonal elements of the transition matrix

[15] Transition probabilities are derived based on the likelihood of a buyer or a seller switching to other irrigation technologies, at post trade. They are derived by dividing the number of times a given farmer with a technology or a crop switch from current technology to any other technology by the total number of occurrences of that technology or crop (Anderson and Goodman, 1957). This normalizes each row so that it sums to one, and the value represents the gains of a farmer switching from one irrigation technology to another.

represent the probabilities of retaining the same irrigation technology. Off-diagonal elements represent probabilities of switching from the technology used initially (column) to a different technology (row).

The simulation results show that under no scarcity conditions, there are limited opportunities for both traders to switch to a more efficient irrigation technology. The simulation results indicate that both water buyers and sellers are more likely to remain with sprinkler-wheel move irrigation technology, gravity flood irrigation technology, sprinkler-low pressure irrigation technology and micro-drip irrigation technology after water trading, than to make any change at all. However, if the initial technology is gravity developed, both traders are more likely to switch "back" to gravity flood technology than any other option; that is, shift to a less efficient technology (Table 2.9). Similarly, in the case when the initial technology is sprinkler-high pressure, there is a significant probability for both the seller (75 percent) and buyer (100 percent) to change to gravity flood irrigation technology.

Under scarcity conditions, both water trading parties are more likely to switch to other irrigation technologies (Table 2.10). However, there is no consistent pattern in terms of the direction of the switch. For producers initially using gravity developed technology (both buyers and sellers), there is approximately a 50 percent probability of switching to a more efficient technology. Similarly, for buyers who are initially using sprinkler-wheel move technology, there is approximately a 55 percent probability of switching to more efficient technology. However, for the other scenarios, both buyers and sellers have greater probability of either switching to less efficient irrigation technology or staying with the same irrigation technology (Table 2.10).

These simulation results are contrary to prior expectations. It was expected that with water trading, farmers are likely to adopt efficient irrigation technology to increase yield, increase profits and conserve water for alternative uses (Dinar and Letey, 1991). These simulation results may indicate that, at post trade, the benefits of increased irrigation efficiency do not outweigh the higher investment costs (as represented by the fixed costs) (King and Kincaid, 2005; Seo et al., 2008; Schaible et al., 1991). One possible conclusion is that the gains from water trading do not serve as incentives for water traders to switch to efficient irrigation technologies, post trade.

Feng and Segarra (1992) found that about 11 percent of all the farmers in Southern High Plains of Texas are likely to switch from conventional sprinkler system to gravity systems and concluded that the low transition probability of farmers to efficient irrigation technologies may be due to economic and marginal gains in water efficiency. Also, these results tend to support the survey evidence of private irrigators in southern Alberta. Private irrigators are not willing to adopt efficient irrigation technologies unless the benefits are greater than the costs of adoption. These farmers also believed that they already used all the water saving irrigation technologies that are practical for their farming purposes (Nicol et al., 2010).

Results presented in this section are also consistent with previous theoretical and empirical studies on irrigation technology adoption. Dridi and Khanna (2005) found that water trading occurs between traders with high land quality, thus the gains from trading may be more beneficial if less efficient irrigation technologies are adopted instead of efficient technologies. There is a strong evidence to support this empirically (Green, 1995; Caswell and Zilberman, 1986; Lichtenberg, 1989). For high quality land the gain from adopting efficient irrigation technologies cannot offset the higher level of fixed costs, and thus, less efficient irrigation technology may be profitable at high quality land. These results are consistent with previous study on irrigation technology adoption and investment options in the US by Carey and Zilberman (2002), who found that with water trading, farmers have the option to wait and invest in efficient irrigation technologies at a later stage. They also found that farmers are more likely to use the additional water to augment their current water supplies and not necessary adopt efficient irrigation technologies.

While it is possible that, with water trading, there are not sufficient economic incentives to encourage producers to switch to more efficient irrigation technology, there are other reasons why these results could be occurring. In particular, the results may be at least partly a function of assumptions and the calibration approach used to implement the profit maximization model. For example, one factor contributing to the pattern of simulation results for the water trading models is the level of fixed costs for each technology. As discussed earlier (2.3.3.3), these costs were determined based on a calibration procedure designed to ensure that the base model generated non-negative profit levels. This was due to a lack of reliable data on fixed costs for irrigation technologies. As a result, it is possible that the calibrated values do not reflect the true fixed costs, particularly in terms of relative levels of those costs between different irrigation technologies.

A related issue is that of investment requirements to switch technologies. The fixed costs per ha used in the analysis should reflect the cost of investing in alternative technologies. However, actually changing technologies represents a “lumpy” investment, requiring a significant initial cash outlay. This change also involves disinvesting in the current technology being used by the producer. It is conceivable that simply substituting one fixed cost for another does not accurately capture the economics of making that type of investment/disinvestment decision.

Lastly, the analysis does not incorporate risk in comprehensive fashion. The modeling of full allocation and scarcity scenarios does represent recognition of the variability in water availability. However, a complete risk analysis would incorporate the level of risk endogenously in the modeling of water trading and technology adoption. This is not done in the current analysis. If the alternative technologies affect the implication of uncertain water availability for buyers and sellers of water, it is possible that incorporating this into the analysis (along with risk preferences of producers) would influence the simulation results.

It is possible that these factors could limit the ability of the simulation modeling to accurately represent the potential for producers to switch to more efficient irrigation technologies after water trading. Given this, combined with policy interests in encouraging producers to adopt more efficient irrigation technology, it may be appropriate to consider undertaking analysis whereby farmers are more likely to switch to efficient irrigation technology, post trade to conserve water. In the following sections, results for modified, or “restricted” scenarios are presented. These are the same two scenarios, with full water allocation and then with water scarcity. In these modified scenarios, however, producers are restricted to either changing to a more efficient irrigation or staying with the same technology.

Table 2.9 Gains from Irrigation Technology Adoption under Full Allocation Conditions[a]

Seller Technology Choices							Buyer Technology Choices						
S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip	S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip
Gravity flood	1.000	0.000	0.000	0.000	0.000	0.000	Gravity flood	1.000	0.000	0.000	0.000	0.000	0.000
Gravity developed	0.827	0.063	0.011	0.081	0.001	0.001	Gravity developed	0.879	0.061	0.022	0.009	0.014	0.014
Sprinkler-wheel move			1.000	0.000	0.000	0.000	Sprinkler-wheel move			1.000	0.000	0.000	0.000
Sprinkler-high pressure	0.750				0.250	0.000	Sprinkler-high pressure	1.000				0.000	0.000
Sprinkler-low pressure					1.000	0.000	Sprinkler-low pressure					1.000	0.000
Micro-drip						1.000	Micro-drip						1.000

Source: Author's Simulation Results. a. Reported results pertain to the probabilities of farmers switching from either less efficient to a more efficient, switch from efficient to less efficient or remain with the current technology, post-trade. S_i and S_j indicate irrigation technology under a profit before and after water trading. In essence, a positive probability indicates the existence of gains from switching among the irrigation technologies after water trading. Note that application efficiency of these irrigation technologies increases from gravity flood irrigation to micro-drip irrigation technology.

Table 2.10 Gains from Irrigation Technologies Adoption under Drought Conditions[a]

Seller Technology Choices						
S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip
Gravity flood	1.000	0.000	0.000	0.000	0.000	0.000
Gravity developed	0.275	0.218	0.175	0.153	0.118	0.061
Sprinkler-wheel move	0.368	0.105	0.105	0.105	0.263	0.053
Sprinkler-high pressure	0.384	0.267	0.122	0.046	0.093	0.087
Sprinkler-low pressure	0.407	0.221	0.128	0.081	0.081	0.081
Micro-drip			1.000			

Buyer Technology Choices						
S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip
Gravity flood	1.000	0.000	0.000	0.000	0.000	0.000
Gravity developed	0.399	0.105	0.131	0.125	0.116	0.122
Sprinkler-wheel move	0.250	0.100	0.100	0.200	0.300	0.050
Sprinkler-high pressure	0.310	0.062	0.147	0.171	0.155	0.155
Sprinkler-low pressure	0.600	0.067	0.000	0.133	0.133	0.067
Micro-drip						1.000

Source: Author's Simulation Results. a. Reported results pertain to the probabilities of farmers switching from either less efficient to a more efficient, switch from efficient to less efficient or remain with the current technology, post-trade. S_i and S_j indicate irrigation technology under a profit before and after water trading. In essence, a positive probability indicates the existence of gains from switching among the irrigation technologies after water trading. Note that application efficiency of these irrigation technologies increases from gravity flood irrigation to micro-drip irrigation technology.

2.6.3 Modified Water Trading Model: Restricted Opportunity to change Irrigation Technology

As discussed in the previous section, there are limitations associated with the water trading analysis that may influence the results. As a result, a revised water trading simulation model is solved. The same two water allocation scenarios (full allocation and water scarcity scenarios) are modeled. However, the revised model is restricted in the sense that the only opportunities for producers to switch irrigation technology are to move to more efficient technologies than are used initially. It should be noted that the revised model does suffer from the same limitations in terms of modeling fixed costs and investment requirements (as discussed in the last section). The purpose of the revised analysis is to examine whether there are incentives to adopt more efficient irrigation technology, in cases where water is traded between producers.

2.6.3.1 Simulation Results for Restricted Scenario One: Potential Gains from Irrigation Technology Adoption

Table 2.11 presents the restricted transition probabilities of both the seller and the buyer (henceforth called parties) switching to different irrigation technologies after water trading under no-scarcity conditions. The simulation results show that post-trade, a seller initially using gravity-developed technology has a 33 percent probability of retaining the same technology, a 15 percent chance of switching from this technology to the sprinkler-wheel-move irrigation technology, a 7 percent chance of using the sprinkler-high-pressure irrigation technology, and a 14 percent chance of using sprinkler-low pressure irrigation technology. For gravity-developed irrigation technology, the seller still has a 32 percent chance of switching to the micro-drip irrigation technology, all things being equal. On the sprinkler-high pressure irrigation technology, the seller has a 25 percent chance of using sprinkler-low and a 75 percent chance of retaining the existing irrigation technology at post trade (Table 2.11). In all other cases, there is 100 percent retention of the initial irrigation technology. These results indicate that the seller has a higher probability of retaining the current irrigation technology after water trading. These results are not surprising, as farmers are not necessarily going to replace their ageing or existing irrigation technologies with efficient irrigation technologies, because of high initial investments. For the buyer, there is a positive probability of movement from gravity-developed irrigation technology to other irrigation technologies after water trading. Specifically, there is a chance of switching to irrigation technologies such as wheel-move, sprinkler-high and drip irrigation technology (Table 2.11). This result is unexpected. With current high energy prices, it could be more beneficial for the buyer to switch to the sprinkler-low irrigation technologies than sprinkler-high, which uses more energy. This result suggests that the gain from water trading does not induce the adoption of efficient irrigation technology for the buyer after water trading. Alternatively, the model may not be accurately capturing all cost impacts of the potential switch.

Concerning wheel-move irrigation technologies, the simulation results show that neither the seller nor the buyer would be willing to switch to any other irrigation technology after water trading. The lack of opportunities to switch from wheel-move to sprinkler-low or sprinkler-high is not surprising and this may be explained by the high cost of switching among these technologies, or because of differences in land quality. In addition, the transition probability matrix estimated in this study shows that both the seller and the buyer are not likely to switch from sprinkler-low irrigation technology to any other irrigation technology after trading (Table 2.11). This result is as expected. Since current energy prices are high, it may be beneficial to keep this irrigation technology which is efficient and requires less energy relative to the sprinkler-high irrigation technology.

Among the irrigation technologies considered, drip irrigation is the most efficient (Table 2.11). It is expected that both the buyer and the seller would be willing to switch from this irrigation technology after water trading. Contrary to expectations, the simulation results show that both parties are likely to remain with this irrigation technology after water trading. This result could be due to the type of crops grown and land characteristics. In the study area, drip irrigation technologies are used to cultivate Saskatoon orchards, small fruits, and nursery stocks, where water transporting tubes can be laid on the irrigated farms and keep in-place for the life of the crop. Also, for about 99 percent of the irrigation taking place in this area, drip irrigation is impractical to use because of high density drip lines required for field crops, high investments and the high annual operational and maintenance costs (Alberta Water Council, 2009).

Gravity flood irrigation technologies are the least efficient irrigation technologies and it is expected that both the seller and the buyer would be more likely to switch to an efficient irrigation technology after water trading. At post trade, the simulation results reveal that both the seller and the buyer are likely to remain with the gravity flood irrigation technology. This result is surprising because a move to any of the efficient irrigation technologies appears to be beneficial for both parties and also provide an opportunity to conserve water in an irrigation area. This result can be explained as being caused by the gain from water trading likely being insufficient to induce the parties to switch to efficient irrigation technologies. Also, this suggests that the gains from trading are limited and both parties seem to avoid additional financial burden which come with a switch to an efficient irrigation technology.

These results appear to suggest that there are limited incentives for either party to switch from current technologies to the most efficient technologies after trading. This is despite the fact that there are gains in terms of increased yield and the possibility of using the saved water to irrigate other farm lands. The results tend to confirm previous studies examining adoption of improved irrigation technologies in southern Alberta (Nicol et al., 2008), and other irrigation areas such the Pacific Northwest (Schaible et al., 1999) and Colorado (Bauder et al., 1997). These studies reveal that unconstrained water supply leads to less adoption of improved irrigation technologies for water conservation, and that an improved technology is more likely to be adopted when it is practical, economically feasible, and during drought conditions (Marques et al., 2005).

Table 2.11 Restricted Transition Probability of Irrigation Technologies under Full Water Allocation [a]

Seller Technology Choices							Buyer Technology Choices						
S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip	S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip
Gravity flood	1.000	0.000	0.000	0.000	0.000	0.000	Gravity flood	1.000	0.000	0.000	0.000	0.000	0.000
Gravity developed		0.331	0.146	0.069	0.139	0.315	Gravity developed		0.520	0.160	0.240	0.000	0.080
Sprinkler-wheel move			1.000	0.000	0.000	0.000	Sprinkler-wheel move			1.000	0.000	0.000	0.000
Sprinkler-high pressure				0.750	0.250	0.000	Sprinkler-high pressure				1.000	0.000	0.000
Sprinkler-low pressure					1.000	0.000	Sprinkler-low pressure					1.000	0.000
Micro-drip						1.000	Micro-drip						1.000

Source: Author's Simulation Results. a. Reported results pertain to the probabilities of farmers switching from an inefficient irrigation technology to an efficient one at post-trade. S_i and S_j indicate irrigation technology under a profit before and after water trading. In essence, a positive probability indicates the existence of gains from switching among the irrigation technologies after water trading. Note that application efficiency of these irrigation technologies increases from gravity flood irrigation to micro-drip irrigation technology.

2.6.3.2 Simulation Results for Restricted Scenario Two: Potential Gains from Irrigation Technology Adoption

As stated earlier, experiences from the US and southern Alberta show that irrigators are more likely to switch to an improved irrigation technology when the price of water is high, as this encourages them to switch because of high expected yields and the possibilities of increasing farm profits. In most cases, a high price of water signals water scarcity in the area or in the country, which serves as an incentive for irrigators to adopt more efficient irrigation technology (Schuck et al., 2005). In this scenario, the annual quantity of water allocated per acre is reduced from 18 to 24 inches per acre to 9 to 12 inches per acre to analyze the behavior of both the seller and the buyer after water trading. The aim is to examine if either the buyer or the seller would have incentives after trading to switch to an improved irrigation technology to produce a profitable crop.

Under scarcity conditions there is more movement from a lower irrigation technology to a higher irrigation technology post-trade (Table 2.12). For a seller who initially uses gravity irrigation technology, there is an 18 percent chance to switch to wheel-move irrigation technology, a 9 percent chance to switch to sprinkler-high, a 32 percent chance to switch to sprinkler-low, a 12 percent chance to switch to drip, and about a 30 percent chance of retaining the initial technology (Table 2.12). For sellers using wheel-move technology, there is a 7 percent chance of switching to sprinkler-high irrigation technology, while a high percentage is seen for the probability of switching to sprinkler-low technology (49 percent). Sellers who initiall use springler-high-pressure technology have a higher likelihood (60 percent) of converting to sprinkler-low-pressure irrigation technology, but have a 20 percent chance to switch to micro-drip irrigation technology (Table 2.12).

At post trade, the transition probabilities reported in Table 2.12 show that the seller is likely to remain with the sprinkler-low irrigation technology. This result is as expected because this irrigation technology is efficient and requires less energy relative to sprinkler-high irrigation technology. Also, this irrigation technology is less expensive and more suitable for the study area than drip irrigation technology.

Based on the results for the transition matrix in Table 2.12, there is a significant likelihood of the buyer switching to other irrigation technologies. For example, the buyer has a positive probability of switching from gravity-developed irrigation technology to sprinkler irrigation technologies as well as drip irrigation technology (Table 2.12). With regard to wheel-move irrigation technology, the simulation results reveal that the buyer is more likely to switch to sprinkler-low irrigation technology than to the other irrigation technologies. As can be seen in Table 2.12, the buyer has an 8 percent chance of switching to sprinkler-high-pressure irrigation technology, a 55 percent chance of switching to sprinkler-low-pressure irrigation technology and about a 25 percent chance of keeping the existing technology after trading. A higher movement is observed among the sprinkler-high and sprinkler-low irrigation technologies after trading. There is an 80 percent chance of the buyer switching from sprinkler-high to sprinkler-low irrigation technology and about a 9 percent chance of the buyer switching to micro-drip irrigation technology after trading.

In comparing the transition matrix for the buyer and the seller, the simulation results reveal interesting differences. The simulation results show that the conversion from sprinkler-high to sprinkler-low irrigation technology is 82 percent for the buyer and about 66 percent for the seller. This result is as expected, because during scarcity conditions, it is possible for buyers to have higher value for water because they tend to cultivate high-valued crops, and that the price of water serves as an incentive to switch to an improved irrigation technology to increase crop yields and improve profits. Contrary to expectations, the seller is more likely to switch from gravity-developed to sprinkler-low than the buyer. This result occurs because of the influence of variation in land quality in the model. It is possible that at the time of trading, the seller has a lower quality land and with the gains from trading, the seller is likely to switch to an efficient irrigation technology to improve yield.

Similar to the simulation results reported under no-scarcity conditions, at post trade, both the seller and the buyer are unlikely to switch from flood gravity irrigation technology to any other irrigation technology. These results occur because there are limited incentives to induce a switch from this technology to an efficient irrigation technology. Also, the simulation results reveal that both parties are unlikely to switch from drip irrigation technology to any other irrigation technology after water trading. A possible explanation could be that due to limited opportunity to use this irrigation technology to cultivate crops in the study area and its high cost requirements, gains from trading cannot induce a switch to other irrigation technologies.

The above results are consistent with the behavior of buyers and sellers during water scarcity situations, when buyers tend to use more efficient irrigation technologies than sellers. Nicol and Klein (2006) found that about 50 percent of sellers surveyed in the SMRID used less efficient irrigation technologies while 75 percent of the buyers utilized their purchased water with efficient irrigation technologies. Survey studies conducted in Lower Murray and Riverland in Australia show that 83 percent of the water sold moved from farmers with less efficient irrigation technologies to those with the most efficient irrigation technologies (Bjornlund and McKay, 1998).

Table 2.12 Restricted Transition Probability of Irrigation Technologies under Scarcity Conditions [a]

Seller Technology Choices						
S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip
Gravity flood	1.000	0.000	0.000	0.000	0.000	0.000
Gravity developed		0.296	0.181	0.089	0.315	0.117
Sprinkler-wheel move			0.351	0.067	0.486	0.094
Sprinkler-high pressure				0.138	0.656	0.205
Sprinkler-low pressure					0.967	0.032
Micro-drip						1.000

Buyer Technology Choices						
S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip
Gravity flood	1.000	0.000	0.000	0.000	0.000	0.000
Gravity developed		0.351	0.226	0.182	0.193	0.047
Sprinkler-wheel move			0.250	0.083	0.555	0.111
Sprinkler-high pressure				0.089	0.820	0.089
Sprinkler-low pressure					0.739	0.260
Micro-drip						1.000

Source: Author's Simulation Results. a. Reported results pertain to the probabilities of farmers switching from an inefficient irrigation technology to an efficient one at post-trade. S_i and S_j indicate irrigation technology under a profit before and after water trading. In essence, a positive probability indicates the existence of gains from switching among the irrigation technologies after water trading. Note that application efficiency of these irrigation technologies increases from gravity flood irrigation to micro-drip irrigation technology.

2.6.3.3 Results from Restricted Scenarios One and Two: Potential Gains from Crop Switching after Water Trading

In this section, simulation results are presented and discussed for the two water trading scenarios (full allocation and water scarcity), allowing producers to both switch from their current irrigation technology and to choose another crop, post trade. As with the previous simulation model scenarios, buyers and sellers are restricted to either keep their current irrigation technology or switch to a more efficient technology. Post trade, the decision to switch to another crop or remain with the current crop is made concurrently with the decision on irrigation technology switching. Thus, it is possible for a farmer to switch to an efficient irrigation technology and switch to cultivate a high-valued crop or remain with the existing irrigation crop at post trade[16]. It is expected that a buyer is more likely to remain with the current crop while the seller is likely to switch to another crop after trading. This result is expected because buyers tend to cultivate high-valued crops, which also require more water.

The simulation results indicate that both the seller and the buyer have potatoes as the most profitable crops before water trading (Table 2.13). With regard to no-scarcity conditions, the simulation results reveal that both parties are likely to remain with these crops after water trading[17]. However, under scarcity conditions, the simulation results indicate that both parties are likely to switch from potatoes to other crops. The simulation results show that the buyer has 80 percent chance of still growing potatoes, a 5 percent chance to switch to alfalfa, a 13 percent chance to switch to dry beans and sugar beets while a 2 percent chance of switching to some other crop. The seller has a 57 percent chance of still growing potatoes, a 23 percent chance of switching from potatoes to sugar beets or dry beans, a 12 percent chance of switching to alfalfa, and 8 percent of still growing

[16] The model does not capture situations whereby sellers use their land to cultivate non-irrigated crops. Although modeling this possibility could provide useful insights, it would not have any effect on the empirical results because of the aim of the study is to investigate efficiency of water use and the possibilities of seller and buyers switching to improved irrigation technologies to conserve water.

[17] As a result, these results are not presented.

Table 2.13 Transition Probability of Crop Adoption under Scarcity Conditions [a]

Seller Crop Choices	Alfalfa	Barley	Barley Silage	Canola	Dry beans	Tame Grass	HRS/Durum	SWS Wheat	Potatoes	Sugar Beets	Flaxseed	Corn Silage
Alfalfa	1.000											
Barley		1.000										
Barley Silage			1.000									
Canola				1.000								
Dry beans					1.000							
Tame Grass						1.000						
HRS/Durum							1.000					
SWS Wheat								1.000				
Potatoes	0.1254	0.0008			0.132		0.0206	0.0275	0.5705	0.1116	0.0116	
Sugar Beets										1.000		
Flaxseed											1.000	
Corn Silage												1.000
Buyer Crop Choices	Alfalfa	Barley	Barley Silage	Canola	Dry beans	Tame Grass	HRS/Durum	SWS Wheat	Potatoes	Sugar Beets	Flaxseed	Corn Silage
Alfalfa	1.000											
Barley		1.000										
Barley Silage			1.000									
Canola				1.000								
Dry beans					1.000							
Tame Grass						1.000						
HRS/Durum							1.000					
SWS Wheat								1.000				
Potatoes	0.0516	0.0005	0.0015		0.069		0.012	0.0004	0.8008	0.063	0.0007	0.0005
Sugar Beets										1.000		
Flaxseed											1.000	
Corn Silage												1.000

a: Reported results pertain to the probabilities of farmers switching from one crop to another at post-trade. First column indicate the state before water trading and first row indicate the state at post-trade. There are 12 crop choices before and after water trading for the seller and the buyer. In essence, a positive probability indicates the existence of gains to switch from one crop to another after water trading. Note that the differences in the crops are based on the profit per crop under the irrigation technologies and land quality.

crops such as wheat, barley and flaxseed. These results are as expected. Since buyers tend to grow high-valued crops such as potatoes and sugar beets it is not surprising to observe that they are likely to remain with current crop after water trading. Specialty crops such as potatoes and sugar beets require more water for optimal production and higher profits. These conditions are necessary for both parties to ensure that there is adequate water to produce these crops. In the SMRID, 64 percent of water sold was used to cultivate potatoes and alfalfa and 26 percent for other crops (Nicol and Klein, 2006).The diagonal probabilities in the transition matrix reported in Table 2.13, indicate that both the buyer and the seller are likely to remain with their current crop.

2.6.4 Strategies to Stimulate Irrigation Technology Adoption

The analysis carried out so far shows that under the restricted scarcity scenario, while there are some incentives to switch to an efficient technology, there are significant probabilities for producers not switching as well. When water is not a limiting factor for production, however, water trading provides limited incentives for farmers to make a post-trade switch to efficient irrigation technology. According to a previous study (Nicol and Klein, 2006), water trading has not been very active in the study area, primarily because water is not a significant constraint to irrigated agriculture. This is consistent with the behavior of famers, as most adopt improved irrigation technologies to increase yield and improve profits, but not necessarily to save water for alternatives uses in other sectors. Also, water trading usually occurs when there is scarcity or an opportunity for farmers to gain from it (Caswell and Zilberman, 1986).

Therefore, it is important to examine alternative strategies that could induce farmers to adopt efficient irrigation technologies to produce profitable crops during periods where water scarcity is not imminent. This analysis would provide policy makers with options on how to design effective policies to mitigate the impact of future water scarcity in the province. The two main strategies selected to stimulate the adoption of efficient irrigation technologies are: (1) a subsidy on the cost of adopting efficient irrigation technology, and (2) an increase in crop prices, if processing facilities are available. These strategies were selected because they are the main economic factors that are likely to influence a farmer who is considering adopting an efficient irrigation technology (Scheierling et al., 2006). Moreover, irrigators in the study area reported these factors as the main constraints to adopting an efficient irrigation technology (Nicol et al., 2008). The effects of these strategies on a farmer's decision-making process regarding post-trade irrigation technology and crop choices are presented and discussed below.

2.6.4.1 Subsidy on Irrigation Technology Adoption

In assessing the possibility subsidizing irrigation technology adoption, the implicit assumption regarding farmers' adoption behavior is that they will switch to an improved irrigation technology when the expected net return under the subsidy approach is greater than the net return to be gained from continuing with the existing irrigation practice. In order to encourage the farmer to adopt an efficient irrigation technology, a minimum public cost-share would be needed to subsidize adoption costs. To examine the effect of different cost-sharing arrangements for irrigation technology adoption, a sensitivity analysis is conducted on the annualized irrigation technology set-up cost paid by the farmer and a potential public agency responsible for providing the subsidy. The sensitivity analysis was conducted to determine the level of subsidy that could encourage a farmer to adopt an efficient irrigation technology to produce high-valued crops. Specifically, the percentage of capital cost paid by the public agency is parametrically increased from zero to 80 percent in 20 percent increments, for the restricted technology adoption scenarios.

The sensitivity analysis shows that from 20 percent up to 40 percent, both the seller and buyer are likely to remain with their current level of irrigation technology adoption. However, the sensitivity analysis indicates a significant variation in the adoption of efficient irrigation technologies when the subsidy level is at 60 percent as reported in Table 2.14.

Table 2.14 Restricted Transition Probability of Irrigation Technology Adoption under Cost Subsidy [a]

Seller Technology Choices							Buyer Technology Choices						
S_i \ S_j	Gravity flood	Gravity developed	Sprinkler-wheel move	Sprinkler-high pressure	Sprinkler-low pressure	Micro-drip	S_i \ S_j	Gravity flood	Gravity developed	Sprinkler -wheel move	Sprinkler -high pressure	Sprinkler -low pressure	Micro-drip
Gravity flood	0.823	0.029	0.043	0.019	0.047	0.038	Gravity flood	0.875	0.027	0.038	0.022	0.033	0.005
Gravity developed		1.000	0.000	0.000	0.000	0.000	Gravity developed		1.000	0.000	0.000	0.000	0.000
Sprinkler-wheel move			0.035	0.357	0.107	0.179	Sprinkler-wheel move			0.500	0.154	0.192	0.153
Sprinkler-high pressure				1.000	0.000	0.000	Sprinkler-high pressure				1.000	0.000	0.000
Sprinkler-low pressure					1.000	0.000	Sprinkler-low pressure					0.571	0.429
Micro-drip						1.000	Micro-drip						1.000

Source: Author's Simulation Results. a. Reported results pertain to the probabilities of farmers switching from a less efficient irrigation technology to a more efficient one at post-trade. S_i and S_j indicate irrigation technology before and after water trading, respectively. In essence, a positive probability indicates the existence of gains from switching among the irrigation technologies after water trading. Note that application efficiency of these irrigation technologies increases from gravity flood irrigation to micro-drip irrigation technology.

At this level of subsidy, both the seller and the buyer are more likely to switch from wheel-move irrigation technology to the sprinkler irrigation technologies. The buyer is more likely to switch from wheel-move irrigation technology to sprinkler-low irrigation than the seller (Table 2.14). In all scenarios considered, both the seller and buyer are likely to remain with gravity-developed irrigation technology. It appears that the level of subsidy is still limited in terms of the ability to induce adoption of these irrigation technologies. The above simulation results suggest that with the provision of a sufficient leve of subsidy, farmers would have incentives to switch to an improved irrigation technology under no-scarcity conditions. This result is consistent with previous studies on irrigation technology adoption, which reported that cost-sharing is effective as long as the percentage of subsidy provision is set high enough to induce a technology switch (Scheierling et al., 2006; Nicol et al., 2008).

2.6.4.2 Crop Output Price Increase

The theoretical model is used to examine whether increased crop prices, over the 1997 base reference prices, could encourage farmers in the SSRB to adopt an efficient irrigation technology. The initial simulation analysis assumes constant real prices for the crops considered in the study. The implicit assumption is that when a farmer decides to switch to an efficient irrigation technology to cultivate a high-valued crop such as potatoes, there will be a processing facility nearby to absorb the produce or a better marketing system to support the delivery of the produce to the consumers. In reality, high-valued crops such as potatoes are produced on a contract basis with processing companies in the study, and given the limits on capacity not all producers would be able to grow this crop.

As a first step, the restricted version of the water trading profit model is solved to establish the base case with no price increase. The sensitivity analysis performed on crop price variable increased crop prices by 30 percent, in 10 percent increments. The analysis shows that increasing crop prices by 30 percent, given the base-year prices, could lead to a 42 percent probability of conversion from gravity-developed to sprinkler-high and sprinkler-low irrigation technologies for the buyer, while the seller has a 32 percent chance of switching to these irrigation technologies.[18] The analysis shows that the buyer is more likely to remain with crops such as potatoes and sugar

[18] The results are not changed for 10 and 20 percent increases in crop prices. The results for the price change scenarios are not provided in tabular form.

beets than the seller. Potatoes and sugar beets are among the highest valued crops in the SSRB, and it would be beneficial for farmers with poor-quality land to adopt efficient technologies for these crops with the assurance of a better marketing system.

This result is consistent with previous findings from the US (Schaible et al., 1999) and southern Alberta (Nicol et al., 2008), which showed that farmers are more likely to adopt efficient irrigation technologies when there is a substantial crop price increase of about 30 to 40 percent. This implies that farmers could afford to own and operate more expensive and physically efficient irrigation technologies if crop prices increased.

2.6.5 Summary

The simulation results for the restricted model show that under scarcity conditions farmers are more likely to switch to improved irrigation technology to produce high-valued crops. The gains derived from irrigation technology adoption and crop production under these conditions indicate that farmers place a high value on water. However, under no-scarcity conditions, both the restricted and unrestricted model results suggest that water trading is much less of an incentive for farmers to invest their gains in adopting efficient irrigation technologies. In order to stimulate the adoption of efficient irrigation technologies under no-scarcity conditions, the restricted model shows that under a possible subsidy consideration on the cost of adopting irrigation technologies, farmers could switch to an improved technology to produce a high-valued crop. Also, a high crop price regime could stimulate the adoption of efficient irrigation technologies under no-scarcity conditions. Policy insights from these results are discussed in the next section.

2.6.6 Policy Implications

The research findings presented in this study have implications for policy makers, farmers and irrigation districts in the SSRB. One objective of this research is to understand how potential gains from water trading could serve as an incentive for farmers to adopt improved irrigation technologies to produce profitable crops. Ultimately, the aim is to examine how farmers could adopt improved irrigation technology to increase yield and profits.

The simulation results show that under restricted model with full water allocation, both traders are likely to remain with their current irrigation technologies. The simulation results from the second scenario under the restricted model with scarcity conditions show that there are some opportunities to switch to an improved irrigation technology after water trading. In situations where there is a switch to an improved irrigation technology, farmers are likely to remain with a high-valued crop. Under scarcity conditions of the restricted model, institutional supports are necessary to facilitate water trading in the irrigation districts. Experience could be gathered from Australia and United States on how such a water trading could be developed and function properly to avoid the effects on transaction costs and other barriers to trade.

In planning for the future, it may be necessary to provide policies that could encourage the adoption of improved irrigation technologies during periods where water scarcity is not imminent. Policy makers would need to consider policy instruments that could encourage the adoption of improved irrigation technologies to increase yield and profits for the farmers, but also to conserve water which could be used in alternative sectors of the economy.

The model developed in this study is used to examine the likelihood of farmers adopting improved irrigation technologies to produce profitable crops under considerations of a subsidy provision on the cost of adoption and crop output price increase over the base year prices. The simulation results suggest that under subsidy considerations, it is possible for farmers to adopt improved irrigation technologies. It should be stressed that a subsidy as an economic instrument could encourage farmers to adopt efficient irrigation technologies to increase crop yields and improve farm profits, but the adoption of these irrigation technologies does not necessarily lead to reduction in water use. This can occur because when farmers adopt efficient irrigation technologies, there is the possibility to increase farm lands under irrigation and cultivate water intensive crops. Also, a subsidy program requires income redistribution from a public sector agency to the irrigated agriculture sector, and may not be possible in the long run and on a large scale in times of severe public budget constraints.

In this thesis, the potential gains from water trading and subsequent post-trade irrigation technology and crop choices are modeled in the frame of private gains to respective farmers in a given irrigation district. The approach used in this thesis implies that attainment of efficient outcomes on the basis of private benefits. Allocative efficiency occurs when benefits are optimal to both trading parties. These outcomes are attained under key assumptions including zero transaction costs.

The potential efficient outcomes notwithstanding, water utilization and allocation have a number of important social implications necessitating social policy interventions. Due to the public nature of water resource and pollution costs, farmers often do not internalize all costs. In essence, all these costs may require public monitoring and enforcement policy. The divergence in these social and private outcomes may result in situations where allocation may not be done based on the most efficient outcomes. For example, although allocating water to the most efficient or highest value crop may be the most efficient private outcome, social policy may dictate otherwise after the internalization of benefits and costs often not considered by private end users such as farmers. The design of optimal water use policy may need to consider a combination of both private and socially relevant factors. It is important to stress that though there are some private gains to adopt efficient irrigation technologies, these gains may be insufficient to induce socially desirable levels of adoption. From public policy perspectives, if it is socially desirable to increase the irrigation effectiveness in order to reduce water use or improve the environment, it may be relevant for the government to encourage efficient irrigation technology adoption. In this regard, the government can support policies that promote adoption by subsidizing all or part of the fixed costs of efficient irrigation technologies.

2.7 Summary and Conclusions

This paper applies a microeconomic model framework to quantitatively analyze the gains from water trading and the opportunities of adopting an efficient irrigation technology to produce the most profitable crops post trade. The model's implicit assumption is that gains from water trading could encourage the adoption of efficient irrigation technologies and these irrigation technologies could be used to cultivate high-valued crops, thus increasing farmers' profits. Also, water trading encourages the use of saved water to be applied in other farm lands, or could be used in alternative sectors of the economy.

To achieve the aims of the study, a short-run profit model was calibrated and simulated for two main policy scenarios of water allocation conditions under restricted and unrestricted models. For the unrestricted model, producers are allowed to switch to irrigation technologies that are more or less efficient than the initial technology being utilized. Due to limiting assumptions associated with the analysis, a second restricted version of the model is also run. In the restricted model, producers are only allowed to switch to more efficient technologies. In both versions, producers do have the option of not changing irrigation technology.

Simulation results of the unrestricted model under no-scarcity conditions show that both traders are likely to remain with their current irrigation technologies. Under scarcity conditions, the simulation results show that water traders are more likely to switch to less efficient irrigation technologies after water trading. These results suggest that water trading provides relatively limited incentive for a farmer to switch, post-trade, to an improved irrigation system. This could be due to the high cost of switching from an inefficient to an efficient irrigation technology. However, there are concerns with respect to assumptions about risk and fixed costs in this analysis.

Under the restricted model considerations, farmers are more likely to switch to an improved irrigation technology to produce a high-valued crop when water is a limiting factor in their production activities. Furthermore, results from strategies necessary to stimulate the adoption of improved irrigation technologies under no-scarcity conditions of the restricted model show that farmers are more likely to switch to an improved irrigation technology under subsidy considerations and higher crop price regimes change. The simulation results of the restricted model reveal that farmers are more likely to use their improved irrigation technologies to cultivate high-valued crops.

This is the first study that has examined farm level gains from water trading and the possibilities of farmers using the gains to invest in improved irrigation technologies to produce a range of profitable crops in the SSRB. However, the results on the factors likely to encourage farmers to adopt improved irrigation technologies, at post trade, are consistent with previous studies. For instance, Caswell and Zilberman (1996) showed that improved irrigation technologies are more likely to be adopted on lower-quality land, when prices of crops, water and labor inputs are high and when the cost of switching technologies is low. Dridi and Khanna (2005) found that when water prices are high, farmers tend to have incentives to trade water and possibly use the gains to adopt improved irrigation technology. Sheierling et al. (2006) found that subsidies encourage a shift to more water-efficient irrigation technologies. By covering a share of the capital cost, they could lower farmers' irrigation costs. Nicol et al. (2008) found from survey results that a substantial level of subsidy may be needed to induce farmers to adopt improved irrigation technologies.

In conclusion, water trading, high crop price regimes and provision of subsidies could encourage farmers to adopt improved irrigation technologies to produce profitable crops. Consequently, adopting improved irrigation technologies allows farmers to cultivate high-valued crops (which require more water) and increase irrigated areas in order to improve profits. However, implementing these strategies would not necessarily conserve water because they are unlikely to reduce consumptive water use. This is because they do not provide economic incentive to reduce the acreage irrigated, reduce water use or encourage farmers to switch to less water consuming crops. Thus, policies necessary to provide incentives to farmers to adopt efficient irrigation technologies and to improve crop yields may be required in the study area. In addition, policies to promote water use efficiency in the study area should focus not only on improving on-farm efficiencies, but also develop strategies to conserve water for alternative uses while maintaining crop yield levels with little or no loss of revenue and avoiding adverse economic impacts on diverse users.

In retrospect, there are some limitations associated with this research which should be addressed as a means of improvement or potential strategies for further study. Some of these (i.e., risk, treatment of fixed costs and investment requirements) have been discussed earlier. An additional limitation is with respect to the effect of transaction costs and water trading. Unlike markets for various commodities, most local water markets have no centralized trading locations and no publicly posted market prices. Due to lack of public and private institutions supporting these markets, potential traders often spend considerable resources gathering market information, finding potential trading partners, negotiating deals, and legally effecting transfers; that is, trading in water markets can be subjected to large transaction costs (Carey et al., 2002; Livingston, 1995; Colby, 1990). Transaction costs have been cited as a reason that more water transfers do not take place, even when large price differences exist among alternative users (Young, 1986; Nicol and Klein, 2006; Nicol et al., 2007; Nicol et al., 2008; Bauer, 1997; Bjornlund, 2003). It would be beneficial if this model could be adapted to capture this aspect. Transaction costs were not included in the current model due to data limitations.

Another limitation is that the current model is a representative for the SSRB and does not capture heterogeneity (i.e., land quality, irrigation technologies and crop choices) among the 13 irrigation districts. It would be beneficial if future studies could apply the model to evaluate specific strategies in the various districts that could stimulate the adoption of irrigation technologies and crop choices. Again, this part was not included in the current model due to considerable data requirements and the time required to debug the input files, sort outputs and interprets the results for the various districts.

The model assumed that a farmer would select an efficient irrigation technology to produce the most profitable crop. In practice, a farmer is likely to cultivate a range of crops on his farm. Future studies could extend this model to capture the adoption decisions of a farmer to cultivate a mixture of crops. Finally, the study focused on water efficiency in the context of irrigation technologies and water trading. However, efficient irrigation technologies also consume a significant amount of energy. Analysis of the trade-offs between water efficiency and energy efficiency in irrigated agriculture is relevant to achieving the economic efficiency of agricultural production in the SSRB while reducing the environmental damages. In this regard, future government policies and research could focus on promoting efficient irrigation technologies that require less energy.

2.8 References

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Chapter 3: Estimating the Economic Wide Impact of Water Reallocation in the Blue Nile River Basin, Africa

3.1 Introduction

Approximately 60 percent of the total annual flow of the Nile River originates from the Blue Nile River Basin (BNRB) of the Ethiopian Highlands (Mohamed, 2001; Timmerman, 2005). Despite this potential, Ethiopia has been able to develop only three percent of the total water resources and about five percent of its irrigable land for food production (Block, 2007). Approximately 83 percent of Ethiopians currently lack access to electricity, and 94 percent still depend on fuel wood for domestic purposes (Block, 2007). The Government of Ethiopia is, therefore, developing one of the largest dams in Africa for hydropower production and irrigation projects in an effort to alleviate poverty and enhance economic growth (Hammond, 2013; Ferrari et al., 2013). The development of irrigation in Ethiopia could influence water use in the two downstream countries. Similarly, the construction of dams will help generate benefits to Ethiopia, but could pose other challenges to water use in the two downstream countries - Egypt and Sudan (Mohamed, 2001; Timmerman, 2005). The Nile River is used to generate about 80 percent of Sudan's electricity production and provides 96 percent of water for irrigation, hydropower, industrial and domestic purposes in Egypt (Mason, 2004; Timmerman, 2005).

Attempts in the past to resolve this water use rivalry have resulted in political tensions among these countries. Downstream countries with significant political power (e.g., Egypt) have threatened to go to war if the upstream countries restrict the flow of the Nile River (Mason, 2003; Küng, 2003). In the past, one proposed strategy has been to motivate riparian countries to adopt cooperative approaches to manage Nile River water resources. If cooperative principles are agreed upon and developed, these countries could achieve economy-wide benefits from the BNRB and the entire Nile River Basin (Whittington et al., 2005). Over time, however, voluntary cooperation has not been successful (Küng, 2003).

There is no agreement on water allocation that is accepted by all these countries. Egypt and Sudan, for example, uphold the principle of “acquired rights” and the validity of the 1959 Nile River Water Agreement (Arsano, 2011). According to this agreement, of the annual average of 84 billion cubic meters (BCM) of Nile River water, 66 percent is allocated to Egypt and 22 percent to Sudan with the remaining 12 percent going to surface evaporation and seepage at the Aswan High Dam (Guariso and Whittington, 1987; Waterbury and Whittington, 1998; Küng, 2003; Block, 2007). Under this agreement, any upstream country must obtain Egypt's approval for irrigation or hydropower projects to ensure that those projects do not reduce water availability for the downstream countries. However, the decisions of Egypt and Sudan may not take into account efficiency and equity considerations of international water use.

Conversely, Ethiopia and other riparian countries do not agree to this treaty "governing" the use of the Nile River. They perceive this allocation as an agreement solely between Egypt and Sudan, since this allocation does not allow the other countries to derive benefits from the Nile River water. The 1959 agreement states that reallocating water for economic development is important for all the countries within the Nile River Basin. Thus it is important that these countries recognize current economic development patterns, demographic and environmental changes and develop sustainable water management policies for poverty reduction in the basin.

Given this background, along with pressure from the international community and the media, coupled with the fact that most upstream countries are constantly facing erratic rainfall patterns for irrigation, the riparian countries need to resolve this historical conflict. Since the economies of Egypt and Sudan are highly dependent on this water, they are more likely to benefit from a basin-wide cooperative development that seeks to enhance the economic value of water. As a first step in resolving this water dispute, the Nile Basin Initiative (NBI) was created in 1998. Ultimately, the aim of this initiative was to develop efficient water use and equitable transboundary water management options. In addition, the NBI has a mandate of achieving cooperation between the riparian countries as well as seeking win-win gains among them. However, this political initiative has not resulted in any alternative feasible allocation rules that seem to be optimal for the full set of riparian countries, especially for Ethiopia, which still has no clear water allocation rights. In order to allow for more equitable use of the Nile water, the Cooperative Framework Agreement (CFA) was signed in 2010 without Egypt and Sudan (IWLP, 2011). This agreement seeks to provide upstream countries with flexibility to use the Nile water for irrigation and hydropower developments (Arsano, 2011; Conniff et al., 2012).

3.1.1 Economic Problem

Presently, policy makers in the Nile River Basin have realized that there are potential benefits to cooperation. Six[19] out of 10[20] countries have already signed the new CFA (IWLP, 2011; NBI, 2011; Arsano, 2011). In spite of the potential benefits from cooperation, Egypt and Sudan still resist to the idea of having new water related projects in the basin. These countries do not fully support such prospects unless they can benefit by acting cooperatively and their water security concerns are adequately addressed in any cooperative agreement. Also, they require that the magnitudes of the impact of water reallocation are available for policy makers to make informed decisions about the use of the Nile River. Therefore, the 1959 Nile Basin Treaty, which is a revised version of an early 1929 treaty, is still the legal treaty for regulating the use of Nile River Basin.

Ethiopia has been deprived of water use for many years. After unsuccessful attempts to pursue Egypt and Sudan to agree to the current cooperative framework agreement[21] on the Nile, Ethiopia decided to adopt unilateral decision making toward the use of the Nile waters. In April 2011, Ethiopia launched the construction of the Grand Ethiopian Renaissance Dam (GERD). This dam has a water storage capacity of 63 billion cubic meters and could generate electricity up to a capacity of 6,000MW (Conniff et al., 2012). The Ethiopian Government claimed that the dam will not only provide electricity to Ethiopians, but it would generate surplus energy for export to neighboring countries, benefiting Egypt and Sudan as well. The concern for Egypt and Sudan is that their available water resources will be reduced as a result of the construction of the dam. Egypt, in particular claimed that there is limited understanding of how the dam would affect downstream flows (Hammond, 2013; Ferrari et al., 2013)[22]. The challenge for these Nile riparian

[19] The countries are Ethiopia, Kenya, Rwanda, Tanzania, Uganda and Burundi.

[20] In this thesis, Sudan is considered as one country and not divided into Sudan and South Sudan. This is because of data issues. Presently, there is no Social Accounting Matrix (SAM) for South Sudan and also the annual average allocation allotted to Sudan has not been shared between the two countries.

[21] The leadership of the Council of Water Ministers of the Nile Basin negotiated for the Cooperative Framework Agreement (CFA), with the hope of overcoming the colonial treaties of the 1929 and 1959 agreements and assumptions that legitimize the power of downstream hegemony that persists in the Nile basin. However, Egypt and Sudan are concerned about the wording of Article 14(b). Article 14(b) states "not to significantly affect the water security of any other Nile Basin State". In particular, Egypt proposed that Article 14(b) should be replaced by the following wording: "not to adversely affect the water security and current uses and rights of any other Nile Basin State" (Arsano, 2011; Mekonnen, 2010).

[22] As mentioned already, Egypt's stand on the use of the Nile for hydropower development remains the same. In June 2013, the immediate past president (i.e., Mohamed Morsi) claimed that all options are open, and that Egypt is

countries becomes how to find a balance between the upstream countries' cooperation for the "principle of equitable use," and the downstream countries' cooperation for the "principle of no appreciable harm" (Waterbury and Whittington, 1987). Therefore, it is relevant to investigate the impacts of upstream water project development policies on downstream countries.

Policy makers in the basin are constantly challenged with the erratic rainfall patterns due to climate variability in the upstream countries. In order to reduce water supply variability in the Nile River Basin, policy makers need to develop strategies to efficiently and equitably apportion available water under uncertain conditions. As water is an input to all economic and social activities and decision-makers need planning tools which reflect the wider consequences of their decisions over the long term, it is of particular interest to examine the impacts of a highly variable water supply on the water allocation in the Nile River Basin.

Previous studies have examined various issues related to the current treaty on the Nile River Basin. These include the implications of microdam development in Ethiopia (Guariso and Whittington, 1987; Waterbury and Whittington, 1998); alternative allocation policies in Egypt (Wichelns, 2002); impacts of hydropower generation and irrigation supply in the BNRB (Block, 2007); and economic value of cooperation on the Nile River Basin (Whittington et al., 2005; Wu and Whittington, 2006). However, these studies ignore the economy-wide impacts of water reallocation for a country within the basin. Transboundary water rivalry affects many sectors of the economy. It is relevant to investigate the impacts of water reallocation and the ripple effects on the various sectors of a country within the basin. Also, many of these studies have not investigated the impacts of water allocation under uncertainty conditions in the basin.

The supply of water is stochastic, and is becoming more so due to climate change. Water allocation planning must be a more effective process under uncertainty conditions because the outcome must be robust for alternative states of nature. This can improve the ability of riparian countries to plan and therefore decreases the impacts of uncertain water allocation. As increased uncertainty reduces investment and therefore decreases productivity of water use relative to what

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not demanding war, but their water security cannot be violated. Finally, Morsi stressed that Egypt had no objection to development projects in the Nile Basin, as long as those developments do not impact Egypt's legal and historical rights (Reuters, 2013).

it could be, it is important to develop models that are able to provide reliable estimates of water for policy makers in the basin. Key research questions which could help to answer some of the grey areas in this topic are given below.

3.1.2 Research Questions

The key research questions to be addressed in this study are as follows:

1. What are the economic-wide impacts of changing the current treaty governing the Nile River Basin?
2. To what extent are uncertainties regarding water supply into the basin affecting the economies of selected countries in the Nile River Basin during water reallocation?
3. What can decision makers in the basin do to mitigate the impact of uncertain water reallocation in the basin?

3.1.3 Objectives of the Study

The main goal of this study is to estimate the economic impact of potential water reallocation on the Gross Domestic Product (GDP) for countries in the Nile basin that are subject to the 1959 water treaty. These aggregate impacts are further decomposed to capture the effects of water reallocation at the sectoral level in a multi-country setting. Reallocation of water under certainty conditions assumes that decision makers are rational and the economic impacts of risks associated with water reallocation are ignored. In this regard, this study also seeks to examine the cost of not factoring risks into water reallocation in the basin. It is important to investigate the impact of risk and uncertainties associated with water as a factor of production, and evaluate policies necessary to mitigate them. Overall, the scope of this study is at the regional level, whereby aggregate economic impacts are analyzed for the three countries: Egypt, Sudan and Ethiopia.

Specific objectives of this study are as follows:

1. To determine the economy-wide impact of water reallocation among Egypt, Sudan and Ethiopia.

2. To investigate the economic wide impact of risks of water reallocation among Egypt, Sudan and Ethiopia.

3. To identify and evaluate potential policies that may enhance the benefits of water use within the basin.

3.1.4 Contributions of the Study

This study seeks to make contributions towards the current literature on water economics, both in terms of methodology and application. In this study, a CGE model is applied to estimate the economic-wide impacts of water reallocation in the Nile River Basin. CGE models have been used to estimate the economic impacts of water reallocation. While estimating economic impacts using this approach is therefore not unique in itself, simulating water reallocation in a multi-country setting and explicitly incorporating risk and uncertainty in model development has yet to be explored in the water economics literature. Previous studies have attempted to incorporate some form of risk or uncertainty into a CGE model. This study represents a novel approach for this, thus adding to the body of knowledge methodologically. Specifically, the CGE model in this study incorporates water reallocation under uncertainty through Chance Constrained Programming (CCP). The results from the study could help decision makers in the basin to establish rational water supply patterns under complex uncertainties, and gain in-depth insights into the trade-offs between the benefits of reliable water supply and associated costs.

3.1.5 Organization of the Chapter

The rest of the study is organized into multiple sections. Section two reviews the quantitative approaches used in water resources economics and the benefits of their applications in the transboundary context. The strengths and weaknesses of each method are presented, as well as their applications in the field of water economics. Section three focuses on the methodologies used for the study. In particular, the section provides a brief background description of the study area, research methods, assumptions and their limitations. Also, the calibration approaches and description of data and their sources are presented.

Section four presents the study's main findings under certain water allocation conditions. The section starts with the development of model scenarios and then presents and discusses the main results. Section five of this chapter deals with the impact of water reallocation under uncertainty conditions. The chapter closes with policy implications and indicates gaps for future research studies.

3.2 Literature Review

3.2.1 Quantitative Approaches in Water Resource Economics

This section presents a review of quantitative approaches for evaluating the impact of water allocation on a given economy. In estimating the impact of a policy change, there are many methods and theories in water resource economics. The focus in this section is on methods that are pertinent to the study's aims. The first part of this section deals with the review of econometric methods and key reasons why they are not suitable for aggregate impact modeling. Next, other models that seek to measure the impact of a policy change at the aggregate level are reviewed. The strengths, weaknesses and applications of these models in evaluating economic impacts are then reviewed. The section ends with a discussion of why computable general equilibrium (CGE) models are selected for this study.

3.2.2 Econometric Models

A variety of methodological approaches exist in the literature on water resource economics. Often, econometric estimation methods are used to investigate factors that affect water demand and supply. These models are based on equations that describe an economic relationship between agents under investigation. Model parameters are estimated by regression methods, using time series, cross-sectional or panel data. For instance, time series econometric modeling approach is generally limited to a significantly smaller number of sectors, but requires data from the variables over many time periods in order to produce acceptable estimates.

Recio et al. (1999) used a regional econometric model to estimate the impact of water quota based policies on agricultural activities in the eastern Mancha, Spain. They found that a 10 percent reduction in water quota leads to 9.6 percent decrease in land use and 5.6 percent decrease in total agricultural output. Shahateet (2008) estimated an applied econometric model to examine the factors that are likely to influence water scarcity problems in Jordan. The study showed that agricultural, industrial and other types of production activities are affected by water uses, which indirectly impact production and other socioeconomic variables including but not limited to population size, the extent of production market, and the size of linkage effects working through certain increases in water consumption. Qaddumi (2005) used an econometric model to determine whether water allocations are efficient, by establishing the relationship between observed water use and the value of water in Vaigai River Basin in India. The reliance of econometric models on national data for forecasting generally renders them less appropriate for the examination of the influence of public policies on disaggregated industries or regional welfare impacts. Additionally, issues of degrees of freedom, costs and time of data collection usually discourage one from using this method for large-scale water resource issues.

3.2.3 Linear Programming Models

Mathematical programming techniques such as linear programming (LP) are frequently used to analyze water resource problems. LP is characterized by a linear objective function, linear constraints, and non-negativity requirements on the variables (Hazell and Norton, 1986; McCarl and Spreen, 1997; Kaiser and Messer, 2011). LP models allow for inequality constraints. This provides flexibility for economic agents to adjust their optimization decisions towards an optimal outcome (Hazell and Norton, 1986; McCarl and Spreen, 1997; Kaiser and Messer, 2011). The LP model is undoubtedly the most commonly used approach to assess the economic outcomes of water allocation in a transboundary context. LP models have been applied to the Mekong River Basin (Ringler et al., 2000); the Maipo River Basin in Chile (Cai et al., 2006); and the Euphrates and Tigris River Basin (Kucukmehm and Guldmann, 2004). These studies identified best allocation strategies by considering allocative efficiency, equitability and sustainability.

LP models focused on the Nile River Basin (NRB) are the Nile Economic Optimization Models (NEOM) presented in Thomas and Revelle (1966), Guariso and Whittington (1987), and Whittington et al. (2005). Thomas and Revelle (1966) were the first to formulate the basic NEOM, which they applied to evaluate the operations of the Aswan High Dam in Egypt. Guariso and Whittington (1987) extended the basic model to include reservoirs on the Ethiopian portion of the BNRB. Their model assumes a single reservoir for the Nile River and was developed on the principle that Ethiopia's main aim is to maximize hydropower production. The study shows that with cooperative development in the basin, Egypt and Sudan stand to benefit more than Ethiopia.

Whittington et al. (2005) applied the NEOM to the entire Nile River Basin. These authors used the model to assess the economic implications of the different water investment projects that have been proposed for countries under a potential cooperative agreement. They investigated the economic benefits of cooperation under two scenarios. These scenarios were: (1) full cooperative developments, where all proposed projects will be developed and (2) *status quo* developments, where no project is implemented and the current water situation prevails. One of the key results from the study was that economic benefit of cooperation will come from two areas: (1) additional hydropower production benefits, mainly in the BNRB; and (2) water savings by using reservoirs in the upstream part of the river. Based on the various scenarios, they recommended Ethiopia and Uganda as the optimal locations for hydropower development projects, while Egypt and Sudan were recommended as optimal locations for irrigation projects.

Block et al. (2007) applied a different model, IMPEND[23], to the Blue Nile River. This model accounts for the stochastic implications of the river flow under variable climate changes. This model differs from the NEOM because the latter incorporates the cost of building hydropower dams on the BNRB. The IMPEND model considered four main projects proposed by the United States Bureau of Reclamation (USBR) (1964) on the BNRB. Under various climatic conditions, the model results indicate that large-scale development projects typically yield cost-benefit ratios greater than one but less than 1.8. However, under stochastic conditions, the cost-benefit ratio was close to one, mainly due to lack of consistently adequate water supply.

LP models do have limitations, given the potential application in this study. For example, LP activities and their interrelationships are assumed to be linear, additive and continuous (McCarl and Spreen, 1997; Buongiorno and Gilless, 2003; Kaiser and Messer, 2011). Also in LP models there is a single objective function and parameters are assumed to be known with certainty. In practice, most of these limitations can be overcome by restructuring economic problems or by using advanced solution algorithms (e.g., mixed-integer and goal programming). However, in measuring a policy change at the aggregate level, several economic agents are certainly going to be affected either positively or negatively. In such situations, LP models are limited in capturing

[23] Investment Model for Planning Ethiopian Nile Development (IMPEND) is an optimization model, which uses stream flow and net evaporation as inputs in different locations of the model (Block et al., 2007). The model covers reservoirs both in Ethiopia and just beyond the border between Ethiopia and Sudan.

the economy-wide impacts of a policy change. Aggregate economic modeling techniques such as Input-Output (IO) models, Social Accounting Matrix (SAM), and Computable General Equilibrium (CGE) models are appropriate to capture the economy-wide impacts of a water policy change. Based on the literature reviewed conducted, to date no study has used an IO model or SAM model to investigate the impact of water reallocation in the Nile Basin while application of CGE models on different economic problems can be found in Robinson and Gehlhar (1995), Lofgren and El-Said (1999) and Strzepek et al.(2008).

3.2.4 Input-Output Models (IO)

Input-Output (IO) models are useful when it necessary to examine the impact of inter-relationships among various sectors in the economy (van Kooten, 1993). Basically, an IO model shows the movement of goods and services from each sector of the economy to different sectors over a given period. Outputs from any sector of the economy are produced with different inputs and distributed either as intermediate inputs in production or final consumption for households, government and exports.

An IO table is presented in a rectangular matrix form or tabular form and is usually divided into four quadrants. Figure 3.1 outlines the basic structure of the input-output table. The production sector of the economy is captured in quadrant A, while quadrant B deals with the final consumption by consumers. Primary inputs used by the various production sectors are documented in quadrant C. The last quadrant (i.e., D) records the direct factor into final demand sectors. It should be noted that entries such as income of government employers, domestic services and aggregate final demand can be captured in this quadrant; however, this quadrant is usually omitted from the IO table. In looking at the relationships among the quadrants, the total output of each sector of the economy is captured by the combined allocation of quadrants A and B. Total inputs used in the production in each sector of the economy are captured by quadrants A and C.

In Figure 3.1, the columns represent the supply sectors while the demand sectors are in the rows. In the IO table framework, the values of final demand are usually considered to be exogenous variables, while the values of total output are considered to be endogenous variables. The equality principle is established when total primary inputs are equal to total final demand. Also, the accounting framework ensures that total outputs equal total inputs for each producing sector in the economy (Figure 3.1). Figure 3.1 shows hypothetical values that illustrate the working principles of an IO table. In this example, the agricultural output is represented in the first row. Of the total output of 82 units, 18 are used within the sector, eight by the industry and 14 by services. The final demand for the agricultural output uses a total of 42 units. The industry and services sectors follow similar distributions and these are recorded in the second and the third rows respectively. Each column shows the cost structure of an industry for primary and intermediate inputs.

Figure 3.1 Hypothetical IO Table (in value units)[a]

Using sector / Supplying sector	Intermediate use					Final Demand	Total Output
		Agriculture	Industry	Services			
Agriculture	A	18	8	14	B	42	82
Industry		14	10	16		48	88
Services		10	5	10		32	57
Primary inputs(e.g., Water)	C	40	65	17	D	-	
Total Input		82	88	57		-	

a. A quadrant in the figure is the cell range directly to the right of the letters (A, B, C, and D).

The first column provides the inputs used for producing 82 units of agricultural output. Given this output, the production requirements are such that 18 units are from the agricultural output, and 14 and 10 units are required from the industry and the services sectors respectively. Similarly, the input requirements for the industry and services sectors are provided in the second and the third columns.

Concerning water, the question posed by an IO model is by how much would water demand change if final demand in the economy changes. To use the IO table to measure the impact of water reallocation, it must be converted into the Leontief inverse matrix. Assuming water is one of the primary inputs required by the three sectors in this hypothetical economy, and then from Figure 3.1, the input-output coefficients matrix (Tw_{ss}) can be derived by dividing the entry of a column by the total of that column. This coefficient matrix represents the direct water use of a sector by the total input to that sector. However, water is used in the economy both directly and indirectly in the production processes of the various sectors. To derive the direct and indirect impact of water use, we denote FD as the quantity of water used by a given sector to meet its own demand and (w_{ss}) as the quantity of water used by the sector. This relationship can be expressed in matrix form as:

$$w_{ss} = Tw_{ss} + FD \tag{3.1}$$

From equation 3.1, the Leontief inverse matrix can be derived in terms of water as:

$$w_{ss} = (I - Tw_{ss})^{-1} FD \tag{3.2}$$

Equation 3.2 can be used to model the direct and indirect requirements of water; that is, the total amount of water any given sector uses with the assurance of meeting an increase in demand. The IO model is the predominant technique for estimating the economic impact of changes in the water sector. The information obtained from the IO model usually plays a significant role in developing water policy, thereby influencing the management of water resources. IO models are appropriate for large-scale water allocation issues. Unlike LP models, the level of analysis revealed by the IO models is technically extended to multi-sectoral levels.

IO models have been used in many studies. Examples include Duarte et al. (2002), who used the model to analyze the effect of water consumption in Spain; Lenze and Foran (2001), who showed that urban dwellers are the major water consumers in Australia; Okadera et al. (2006), who applied the model on the Three Georges Dam in China to show the effects of water demand and pollution; Velazquez (2006), who investigated the inter-sectoral water relationships in Andalusia; and Wang et al. (2009), who studied the regional water consumption effects in Zhangye city, northwestern China. More recently, Yu et al. (2010) used an IO model to study water-consuming sectors in different parts of the United Kingdom (UK).

In spite of its strengths in providing an overview of the way industries in the economy are linked, IO models are based on fixed proportions. These proportions are usually referred to as Leontief technical coefficients (van Kooten, 2003; Varian, 1992). These fixed coefficients indicate that inputs must be used in fixed proportions and cannot be substituted for one another. This means that industries in the economy exhibit constant returns to scale and cannot take advantage of short-run gains by using increasing units of labor together with fixed units of capital (Adamowicz et al., 2000). This characteristic of the IO models implies further that price variables are fixed exogenously and are assumed to be independent of demand. IO models also assume that resources are used efficiently in the economy. This implies that the economy operates with sectors that have extra capacities and that available resources are not fully used (Adamowicz et al., 2000). Also, IO models are not able to fully capture distributional issues associated with economic growth. In essence, IO models are not able to show distributional effects of income to different institutions in the economy due to a policy change.

Typically, IO models are able to show income distribution by dividing the value of a sector into its various components. However, this is not helpful when one has to analyze the impact of policy changes on real incomes at the household level (Basanta et al., 2006). The final weakness of the model deals with the fact that final demand is assumed to be exogenous. This indicates that trading activities do not depend on relative prices. Any feedback effects from induced income changes on production and final demand are ignored (Adamowicz et al., 2000; Basanta et al., 2006). These assumptions contribute to IO models being structurally rigid: the state of technology, market features, and relative prices are all assumed to be unchanging, and distributional effects are ignored (Dervis et al., 1982; Hosoe et al., 2010).

3.2.5 Social Accounting Matrix (SAM)

The Social Accounting Matrix (SAM) was developed to overcome the limitations of the IO model. A major distinction between the SAM and IO model is that the IO model shows how the sectors or industries are interrelated through a transactions table, while the SAM also presents the transaction table and provides the transfers between the different agents in the economy: that is, private, public and exports (Pyatt, 1999; EDRI, 2009). In its basic form, the SAM provides a detailed overview of the economy in matrix form for a given period of time (Pyatt and Round, 1985; Sadoulet and de Janvry, 1995). The SAM is a square matrix with various accounts. Each account is designated by a row and a column (Löfgren et al., 2002; Robinson et al., 1999; Emini, 2002; Taffesse and Ferede, 2005). A value in the SAM shows the payments from the column account to the row account. For a given SAM, the cost of an account appears in its column and revenues in its row. Similar to the IO model, the total costs for the SAM must be equal to total revenues of the economy (Robinson et al., 1999).

A basic SAM has five accounts; activities account, factors account, taxes account, institutions account and the account for the rest of the world. The transactions occur in any or all of these accounts (Figure 3.2). A hypothetical example is provided in this section to explain the SAM working principles. In this example, the activity account consists of the agricultural, industrial and services sectors, while the factor account deals with supply of labor, capital and water. The final demand account shows the transactions between government, households and investment agents, who constitute the final users. Lastly, taxes and external accounts are classified under the rest of the world (ROW) and indirect tax portions in Figure 3.2. The "activity" account row indicates the quantity of intermediate inputs required to produce output in the corresponding column.

The hypothetical example illustrated in Figure 3.2 shows that the intermediate inputs supply for agriculture production costs 18 dollars in the sector, eight dollars from industry and 14 dollars from the service sector. The intermediate inputs for the other production sectors can be explained using the same logic. Capital owners gain 20 dollars in return for its use in the agricultural sector. The labor and water transactions show a similar exchange of services between the factor holders and the agriculture sector for 15 and five dollars, respectively.

In addition, the agriculture sector pays a domestic indirect tax to the government in the form of production taxes and import tariffs. The production tax and the import tariffs for the agriculture sector are five and two dollars, respectively. As shown in Figure 3.2, taxes are then transferred to the government as 12 and five dollars, respectively.

Unlike the IO table, the SAM shows the distribution of income among households, government, and investment institutions, and how income is transferred back to the economy's production sector. The final demand section in Figure 3.2 shows the institutions' incomes. The household earns revenue by supplying factors to the economy's production sectors. It incurs expenses of 33 dollars for purchasing goods from the agriculture sector, 35 dollars from the industrial sector and 24 dollars from the service sector, pays 23 dollars as direct taxes to the government and is able to save 17 dollars.

The government on the other hand, earns 12 dollars from production taxes, five as import tariffs and 23 dollars as direct taxes from households (Figure 3.2). The government agent purchases 13 dollars of goods from the agriculture sector, 14 dollars from the industrial sector, 10 dollars of goods from the service sector and is able to save three dollars. Under the final demand section, the investment agent purchases nine dollars of goods from the agricultural sector, 10 dollars of goods from the industrial sector and 12 from the services for its investment.

The rest of the world account deals with the economy's domestic and external transactions. Imports and exports are captured under this account. The agricultural sector's imports are worth 15 dollars while its exports are worth nine dollars. Similarly, the industrial sector's imports are worth 11 dollars, but its exports are worth six dollars, while the service sector has a balanced account of imports and exports. This hypothetical example shows that there is a trade deficit for this economy, as total imports are more than exports. Thus, the external account captures the transaction between the domestic activities and the foreign activities, and its column corresponds to the balance of payment account. Like the IO model, the SAM also uses multipliers to analyze the impacts of water use in an economy. To use the SAM to analyze the impact of water, there is a need to identify exogenous accounts so as to calculate the multipliers. In Figure 3.2, for example, the exogenous account includes the government account, capital account, rest of the world and the account for indirect taxes. The endogenous accounts include factor accounts, institutions (household and enterprises) and production activity accounts. Subsequently, one has to derive the SAM coefficients or shares that represent the structure of the SAM, which is analogous to an input-output model.

Figure 3.2 Hypothetical Example of Social Accounting Matrix (units in dollars)[a]

		Activity			Factor			Indirect tax		Final Demand			ROW	Total
		Agric	Ind	Serv	Capital	Labor	Water	DTX	TAF	hh	Gov	Inv	ET	
Activity	Agric	18	8	14						33	13	9	9	104
	Ind	14	10	16						35	14	10	6	105
	Serv	10	5	10						24	10	12	5	76
Factor	Capital	20	30	15										65
	Labor	15	25	10										50
	Water	5	10	2										17
Indirect Tax	DTX	5	4	3										12
	TAF	2	2	1										5
Final Demand	hh				65	50	17							132
	Gov							12	5	23				40
	Inv									17	3		11	31
ROW	ET	15	11	5										31
Total		104	105	76	65	50	17	12	5	132	40	31	31	

a: The reported values in the tables are hypothetical and are used to illustrate the working mechanism of the Social Accounting Matrix(SAM). The full definition of the variables in the top and the left sides of the table are given as: Agriculture(Agric), Industry(Ind), Services(Serv), Government(Gov), Household(hh), Investment (Inv), Direct taxes(DTX), Tariffs(TAF), External (ET), Rest of the World (ROW).

With regard to water, the flow matrix of the factors account may be represented as w_{ss}, and XX is denoted as the payments of exogenous account to the factors of production. Also, let Y_{ss} represent the total factor income which is equivalent to the sum of payments to factors by activities and the exogenous injections. In matrix notations, these relationships can be expressed as:

$$Y_{ss} = w_{ss} + XX \qquad (3.3)^{24}$$

The derivation of the SAM multipliers is based on the Leontief inverse matrix assumption; that is, a flow in a row is a linear proportional function of column totals. With this assumption, let A_{ss} denote the production coefficient of the SAM; then:

$$A_{ss} = w_{ss} / Y_{ss} \qquad (3.4)$$

By combining equations (3.3) and (3.4), equation (3.5) is as follows:

$$Y_{ss} = A_{ss}Y_{ss} + XX \qquad (3.5)$$

$$Y_{ss} = [I - A_{ss}]^{-1} XX \qquad (3.6)$$

$$Y_{ss} = M_{ss}XX \text{, where } M_{ss} = [I - A_{ss}]^{-1} \qquad (3.7)$$

M_{ss} is the SAM multiplier, which measures the change in water consumption if the demand for water changes by a unit. IO multipliers capture the direct and indirect impacts of a change in exogenous final demand with water reallocation. However, they do not capture the induced impacts on the factors of production and household incomes, and activity outputs due to income-expenditure multipliers (Basanta et al., 2006). The SAM multipliers deal with these impacts. Because changes in outputs of goods are likely to affects income directly or indirectly. These get neglected in the IO model. Also, the M_{ss} can be decomposed further to capture the impacts of transfers within the economy and the consequences of the circular flow of income within the economy (Basanta et al., 2006; Thorbecke, 2000).

[24] Materials presented in this section are from sources such as: Velázquez (2006); Basanta et al. (2006); Matete (2004); Juana et al. (2006); Thorbecke (2000).

The SAM has been applied in analyzing the impact of water use in several studies. For example, Morilla et al. (2007) used the SAM and Environmental Accounts for Spain to analyze the efficiency of the different sectors in the economy. The authors found that there is no direct relationship between the economy's productive and unproductive sectors. Uwakonye et al. (2010) employed SAM to show the economic impacts of Broken Bow Lake in McCurtain County in the US and Matete (2004) used the SAM to show the impact of inter-basin water transfer between South Africa and Lesotho.

The above hypothetical example demonstrates how the SAM provides a convenient modeling database for analyzing the distributional impact of changes in the economy. It shows the direct linkages between the production, institutional and external sectors and how incomes are transferred among these sectors (Adelman and Robinson, 1986). However, the SAM model is not without its limitations. First, it is an extension of the IO model and assumes a Leontief production function. Second, changes in input demands are unaffected by relative changes in input prices. Third, the model assumes an excess supply of primary inputs in the economy. In spite of these limitations, most recent economic impact studies have used SAM models because of data availability and its simplicity. SAM models serve as the main database for more complex computable general equilibrium (CGE) models.

3.2.6 Computable General Equilibrium Models (CGE)

CGE models have the ability to relax some of the fixed assumptions used by the models discussed previously. For example, in the IO and SAM framework, firms are not price responsive. This means that price mechanisms play no role in the economy; firms' optimization behaviors are constants even when prices are changing. In contrast, CGE models incorporate price-responsive consumers and producers into the inter-industry analysis (Hosoe et al., 2010). CGE employs flexible production functions, which provides the possibility for producers to substitute factor inputs depending on their current relative prices.

CGE modeling approaches are based on general equilibrium theory and adopt a Walrasian perfect competition paradigm to simulate adjustment processes in a given economy (Ginsburgh and Keyzer, 1997; De Melo and Tarr, 1992; Hertel et al., 1997). It can be defined as a multi-market simulation model based on simultaneous optimization behavior of individual consumers and firms, subject to financial budget and resource constraints (Shoven and Whalley, 1992). In a CGE model, producers are assumed to maximize profits, based on their demand for inputs and supply of outputs and services. Consumers maximize utility depending on their endowments and demand decisions for commodities and services. The optimization decisions of these economic agents generate the demand and supply quantities and prices necessary to clear the market. Prices adjust in the markets until demand and supply are equal. The government is introduced into the CGE model, with its basic aims to generate revenue from tax collection and to ensure the distribution of incomes to the various institutions in the economy.

In a typical CGE model, production is specified as a function of combined outputs of domestic supply and imports while consumption specification deals with intermediate demand, government consumption, investment demand and export demand. The outcome of a CGE model is a vector of prices and demand and supply quantities that are derived based on the optimization decisions of various economic agents. CGE models are able to bring different economic agents together in a consistent and systematic manner and to ensure that their optimization decisions resulting from a policy change lead to an equilibrium outcome. CGE models are widely applied to policy analysis in both the developed and the developing world, and have a comparative advantage when it comes to analyzing macroeconomic policy instruments such as taxes and tariffs, or water resource allocations (Bergman, 2005).

When investigating the effects of a policy change in a market-based economic environment, CGE models provide flexible ways to allow for demand and supply factors to interact endogenously in the market. Also, CGE models use non-linear functions to examine the impacts of an exogenous policy change on the economy. For instance, by allowing non-linear functions, producers have the opportunity to substitute a cheaper factor input for an expensive one. In examining inter-sectoral impacts of a policy change, CGE models are useful in capturing the ripple effects of prices and incomes in the economy and also provide the distributional consequences on households, government and trade flows. CGE models' optimization processes provide flexible mechanisms to derive the appropriate set of shadow prices. With this property, a CGE model is preferred over a partial equilibrium modeling framework, especially in situations where price and income impacts are considered to be large. Additionally, CGE models can capture both direct and indirect impacts of a policy on different agents in the economy. The above strengths of CGE models show that they are appropriate to examine the distributional impacts of a water policy change in a transboundary context. Essentially, they represent models based on standard economic theory that are able to demonstrate how the behavior of different economic agents could be affected in the case of a policy change. Thus, they can be significant in shaping current economic policy.

On the other hand, CGE models are complex, have increased scope, are often difficult to calibrate and require a lot of construction time. Despite these limitations and especially data requirement challenges for model development, a CGE model is applied to assess the impact of water reallocation among three countries (Egypt, Sudan and Ethiopia) in the Blue Nile River Basin. Transboundary water rivalries affect many sectors of the economy. As previously mentioned, the strength of CGE models lies in their ability to account for inter-sectoral linkages while satisfying the resource and budget constraints imposed by economic agents and market clearing conditions (Ginsburgh and Keyzer, 1997; Lofgren and El-Said, 1999).

3.2.7 Empirical Review of Water CGE Models

Although there are several CGE models available, there are relatively few examples of this methodology being used to model the effects of water allocation and reallocation on a given economy. Lofting and McCaughey (1968) are among the first few researchers to incorporate water and other economic variables in CGE models. In their model, water was introduced as one of the productive inputs in a traditional input-output format in order to analyze the water needs of California's economy, in the United States. Subsequently, Susangkarn and Kumar (1997) applied a CGE model to incorporate water as a separate productive sector in Thailand's economy. Seung et al. (1998) adopted a regional CGE modeling approach and used nested production functions with labor, capital, land, water and intermediate inputs to examine the impact of reallocating surface water from irrigated agriculture to recreational use in the Walker River Basin of Nevada, United States. Their model accounted for income transfers, but was built based on a Leontief production function assumption with land and water having zero elasticity of substitution. In other studies, Seung et al. (2000a) used a static CGE model to evaluate the impact of water reallocation in the United States. Gómez et al. (2004) analyzed the welfare gains from improved allocation of water rights for the Balearic Islands, Spain. Hewings et al. (2006) adopted a slightly different CGE formulation to evaluate the impact of water reallocation from agriculture to other productive sectors in a recursive fashion that fully captured feedback effects in the northeastern part of Brazil. Velaquez et al. (2007) analyzed the possible effects that an increase in the agriculture water tariff would have on the Andalusian economy of Spain and on water conservation.

There are also CGE models with a global focus. Berrittella et al. (2007) present a CGE equilibrium model of the world economy with water as an explicit factor of production. Berrittella et al. (2008) included water as a production factor in a multi-region, multi-sector CGE model, to assess a series of water tax policies. The dynamic implications of CGE models of water allocation can be found in research by Goodman (2000) and Seung et al. (2000b). Goodman (2000) applied the CGE model to the southeastern Colorado economy and revealed that with temporary transfers, the impact on agriculture is relatively small. However, overall positive impacts were observed for the rural communities. In addition, the study revealed that temporary transfers could provide a lower cost option than constructing new dams to enlarge the existing water storage facilities. Seung et al. (2000) combined a dynamic CGE model with a recreation demand model to analyze the temporal effects of water reallocation in Churchill County (Nevada). Almost all of these studies found that economic gains from water reallocation are greater than for no reallocation situations. This stems from the fact that with reallocation, water is moved from less productive sectors to higher productive sectors of the economy.

CGE models have been applied in various parts of Africa to evaluate different water policies. For example, Decaluwé et al. (1999) used a general equilibrium model to compare different water pricing policies in Morocco. They applied their model to assess the impact of irrigation water tariffs on the Moroccan economy, where the tariffs were priced at either marginal cost or average cost. Two regions were identified based on water scarcity conditions; the North with more water and the South with relatively less water. These regions produce similar goods linked by a Constant Elasticity of Substitution (CES) function.

These goods are sold on the national and international markets as composite goods. A CES production function that allows substitution between factors of production and intermediate inputs was used to model the economy's aggregate production sector. The three simulated pricing policies were: (1) Marginal Cost Pricing (MCP); (2) Boiteux-Ramsey Pricing (BRP); and (3) an arbitrary increase in agricultural water prices. Results showed that the MCP has a greater impact on the equivalent variation (EV), but lesser impacts on water conservation and elimination of subsidies. The arbitrary increases in agricultural water prices had negative effects on the EV and little impact on water conservation and elimination of subsidies. The most effective policy in terms of welfare was BRP, especially when it was combined with a decrease in unregulated production prices. When choosing welfare criteria and water management objectives, BRP seemed to be the best alternative. Also, the study revealed that as water in the economy became scarce, BRP seemed more beneficial whereas the productivity of the MCP decreased.

Briand (2004) used a CGE model to estimate the effects of water price policy on production and employment in Senegal. Unlike Decaluwe et al. (1999), Briand (2004) separated production and distribution of water into separate sectors, and also divided the distribution of water into two sectors: formal (i.e., sectors equipped in capital factors and in formal use of labor) and informal (i.e., sectors equipped with capital factors and relying on informal use of labor). This division was relevant as the informal sector distributes drinking water to the low-income group of the population and its services must be recognized as a contribution to the formal sector. The study sheds light on how water pricing policy affects the development of both formal and informal water distribution in different areas in Senegal, and how policy makers can efficiently supply water to the various consumers in these affected areas.

Diao et al. (2005) analyzed the economy-wide gains in Morocco from allocating surface irrigation water to its most productive sectors, and proposed a decentralized mechanism for achieving this result in a spatially heterogeneous environment. Their model considers capital and labor as two main economy-wide inputs and water as a given assignment. They employ detailed input-output data on crop production and water use at the district level. The analysis shows that the development of a water market appears to have positive consequences for income distribution among users.

Diao et al. (2008) extended their previous model to include surface water and ground water as two intermediate sectors in the Moroccan economy. The model shows that surface water reallocation from the agricultural to the domestic sectors improved the urban sector directly and the rural sector only indirectly. As mentioned already, Diao and Roe (2003) examined the linkages between water and trade policies in Morocco. They presented a dynamic CGE model to analyze the implications of a tariff in the agricultural sector of Morocco's economy. The authors showed how liberalizing the sector could lead to the necessary market environment to develop efficient water-pricing schemes. They created simulations to examine both the short-run and the long-run dynamic impacts of trade reforms and a water-user rights market. Results of trade reform show that the shadow price of water declines in the sector that produces pre-reform restricted crops. Farmers who are worse off after the reforms can earn an income by renting some of their water to others. Also, their study showed that setting up a market for water rights could compensate farmers for their losses due to the trade reforms, and also increase the productivity of water transfer, thus improving welfare of the society.

Mukherjee (1995) used a watershed CGE model to analyze the policy impact of land and water reforms in the Olifants River catchment in South Africa. The model considered factors of production such as land, capital, labor, and water. Water and land formed a composite good in a Leontief production function. Subsequently, this was combined with labor and capital through a CES function at the aggregate level. The author applied the model to two sectors in the economy, agricultural and non-agricultural, and found inefficient use of water in both sectors. However, when water was scarce, the agricultural sector experienced the largest impact. Also, the agricultural sector was very sensitive to water price increases. The study recommended policies to mitigate the impacts of water scarcity in the catchment. It was adduced that modest water and land reform policies could lead to an improvement in the domestic agricultural sector.

Letsoalo et al. (2007) applied a CGE model to analyze the triple dividend of water consumption charges in South Africa. The model also touched on the environmental impact, equity and distributional effect of water use in that country. The authors used the University of Pretoria's CGE model for the South African economy. The model was based on the official 1998 SAM of South Africa. The SAM divided institutions such as households into 12 income groups and four ethnic groups and further distinguished 27 sectors. Furthermore, the energy and agriculture sectors were sub-divided for a total of 39 sectors. Several scenarios were simulated, and the study showed that there can be a triple dividend of water policy, through simultaneous achievement of decreased water scarcity, poverty and improved welfare. In addition, the study showed that effective policy design could improve all dimensions of sustainable development (i.e., environment, economy, and society).

Hassan et al. (2008) employed a CGE model to examine the economic impact of selected macroeconomic and water-related policy reforms on water use and allocations, and rural livelihoods for the South African economy. The authors explored how the CGE model could be useful in evaluating the net impacts of potential shifts in water policy towards more market-based allocation regimes, which the National Water Resources Strategy sought to promote. The authors examined four key scenarios. These were: (1) irrigated water market liberalization with the focus on productive water use among agricultural crop producers within the water management areas; (2) regional liberalization of irrigated water markets with a focus on changes in inter-regional transfers of water for irrigation use based on existing water allocations; (3) increased competition for increasingly expanded areas in non-agricultural, domestic and rural-urban migration, and (4) complete liberalization of water markets with a focus on market-based approaches for transferring water from irrigated agriculture to municipal areas to meet the needs of other growth sectors. Results from the four sets of experiments revealed that liberalizing local water allocation within irrigated agriculture was beneficial for high-value crops, and could possibly facilitate the increase in agricultural domestic output and exports as well as farm employment. Also, providing mechanisms for water trading among the high intensive and less intensive sectors caused a significant loss in the agricultural sector, but a substantial gain was observed in the rural households and non-agricultural households. The authors concluded that there are trade-offs between improved economic productivity and higher water prices, making it difficult to recommend policies to promote irrigation subsidies.

Recently, Juana et al. (2011) updated the SAM for South Africa and applied a CGE model to analyze the impact of water reallocation from agriculture to non-agriculture sectors with the emphasis on output growth and value-added at factor cost. They conducted two experiments: (1) market allocation of water, and (2) sectoral water reallocation from five to 30 percent, computed based on marginal values. Results indicate that market allocation of water among production sectors shows improvement in overall sectoral output, but causes an output decrease in agriculture and related industries. This suggests that when a market for water is introduced, high-value sectors demand more water from the agricultural sector, which can lead to a decline in output. However, their model shows that continuously transferring water from the agricultural sector to other sectors could negatively affect low income households.

Robinson and Gehlhar (1995) used an 11-sector CGE model to analyze policies on land and water use in agriculture in Egypt between 1986 and 1988. The model focused on the impact of output taxes and subsidies across various sectors. In this sector there are large input subsidies in agriculture and no charges for water. Given this situation, the authors conducted three experiments. First, they investigated the sectoral effect of removing agricultural taxes and subsidies. In the second experiment, they evaluated the effect of eliminating restrictive policies from both agricultural and non-agricultural sectors. In the third experiment, they determined the demand for water in the agricultural sector. Results revealed that removing these taxes and subsidies could increase water demand and subsequently increase the market price of water, if there is a free market for water. Furthermore, the study shows that water demand is quite inelastic in the study area. The authors argue that policy reform on the demand side would not significantly influence the water distribution system. In addition, curtailing water consumption when water supply remains unchanged and agricultural output is increasing will make water expensive. To achieve effective water policy reform, Egypt could promote productivity of water use among different users. This will ensure that water is transferred to high-value users.

Lofgren and El-Said (1999) used a CGE model to explore the short-term impacts of a set of feasible options for implementing Egypt's food subsidy system. They focused on the impact of redesigning a subsidy scheme in that country. The simulations were divided into two parts. The first focuses on the implications of targeting or eliminating food subsidies. The second deals with the effect of subsidizing 20 percent of the maize portion in the flour and exploring policies to reduce leakages with a minimal effect on changes in the subsidy policy. Results reveal that the simulated impact of targeting or fully eliminating subsidies (e.g., on oil and sugar) is quite small, thereby reflecting the small scale of this policy. However, savings from such a policy will permit a four-to-six-percent reduction in income taxes. Finally, the study shows that the impact on welfare is progressive if the subsidy focuses on needy households, and regressive if it is eliminated totally. Regarding the entire food subsidy system, the policy was observed to have a much longer-term impact on society. Although the current subsidy policy distorts household decisions, only very minor benefits exist if subsidies were to be eliminated completely. From a wider policy perspective, it will be appropriate for the government to use ration cards for a needy households' subsidy program, while using savings to reduce direct taxes. The benefits from this policy could be greater if the savings are redirected to programs that provide benefits to the needy.

Diao et al. (2000) constructed a CGE model for Morocco. Seven major irrigation regions and perimeters within each were considered. Each region is linked up and down stream of markets, and they compete with the rest of the economy for economy-wide resources. In their study, Diao et al. (2002) estimated the shadow price of water in each district of these seven major agricultural development authorities, and analyzed a water user-rights market among users in each district. Results suggest that a decentralized water trading mechanism could improve agricultural output relative to the baseline. This could also affect the input costs in the agricultural sector, and have aggregate impacts on the standard of living and household consumption at the national level.

Matate and Hassan (2007) used an integrated ecological approach to account for inter-basin water allocations in the Lesotho Highlands. They introduced an ecological effect of water development in a CGE model for South Africa and Lesotho. Unlike previous studies on this subject, these authors further examined the macro-economic inter-linkages between concerned sectors and the rest of the economy. Results show that a water reallocation that significantly alters the agricultural sector's production will be transmitted to the most vulnerable population in the economy. Also, any level of water allocation out of the agricultural sector leads to net job losses.

Most of the studies reviewed here modeled water and land as fixed proportions in the production function and did not analyze the elasticity of substitution between water and other production factors such as capital, labor, and land. Also, these studies aggregate economic activities into key sectors. This limits the ability to investigate two-way effects of micro and macro economy feedback and changes. Roe and Diao (2000) developed a CGE model that can handle such feedback linkages. However, their model was implemented sequentially in a two-step analytical structure with a micro farm model component separate from the macroeconomic CGE model, and water was modeled as an intermediate input. Hassan and Thurlow (2010) were able to overcome this issue and integrated water directly into the production of the South African economy. However, this approach is difficult to replicate in other countries because of data limitations. Existing social accounting matrices do not include water as a factor of production. Collecting such data is time-consuming and expensive. The model constructed in this study is a multi-sectoral, multi-country, and static CGE model that includes water as a factor of production together with land, capital, and labor. Its production structure is similar to that of Mukherjee (1995) and Robinson and Gehlhar (1995), but in a multi-country context. Also, this thesis not only models the production sector in a multi-country model, but opens up several other avenues of research as the techniques developed here can be applied to a variety of transboundary water management issues.

3.3 Methodology

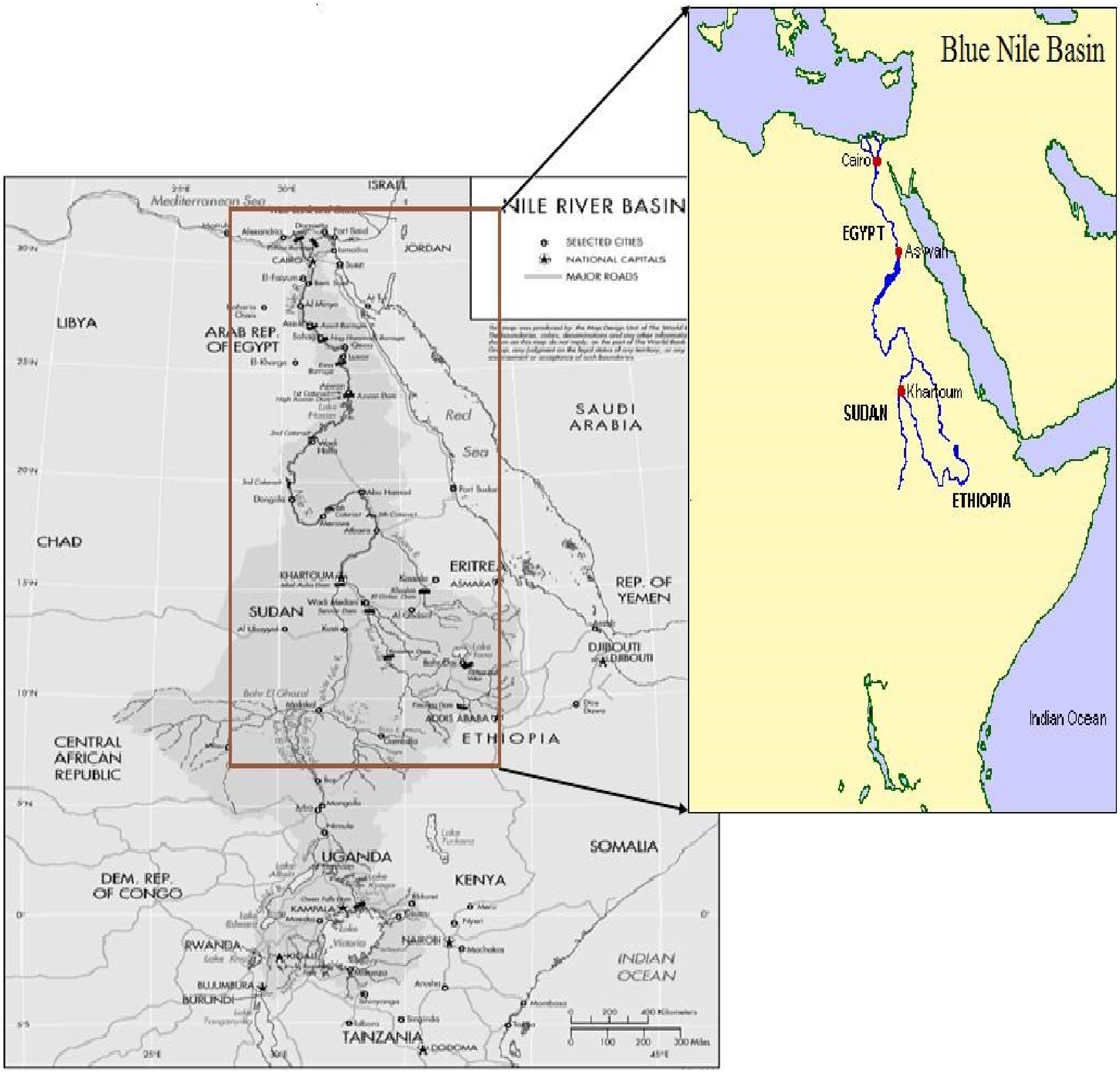
3.3.1 Description of the Study Area

The White and the Blue Nile rivers are the two main water sources of the Nile River Basin. The White Nile's water source is in Uganda. The Blue Nile's water sources are in the highlands of Ethiopia (Figure 3.3). The two rivers meet in Khartoum, the capital city of Sudan, before flowing into Egypt and finally into the Mediterranean Sea (NBI, 2002). Egypt, Sudan, and Ethiopia constitute the Blue Nile River Basin while all the others countries (Rwanda, Kenya, Tanzania, Burundi, Uganda, Democratic Republic of the Congo) are in the White Nile River Basin.

This study focuses on the Blue Nile River Basin (BNRB). This portion of the Nile is selected because of the large-scale hydropower generation and irrigation projects proposed to be developed in this region in the future (USBR, 1964; Whittington et al., 2005; Block (2007); McCartney et al., 2012). Also, the other countries in the White Nile Basin (Figure 3.3) contribute less to the total flow of the Nile in Sudan. Hence these countries have less negotiating power during any water reallocation negotiations.

Egypt has a population of about 83 million people. Ethiopia has a population almost the same as Egypt's while Sudan has about 41 million people (ENTRO, 2008). There are approximately 5.3 million ha of land under irrigation in the Blue Nile River Basin (ENTRO, 2008). Irrigation schemes managed centrally with smallholder farmers cover 3.3 million ha in Egypt and 1.8 million ha in Sudan, while 100,000 ha are covered by farmer-managed schemes in Ethiopia (ENTRO, 2008). Irrigated agriculture contributes 16 percent to Egypt's GDP (i.e., US$ 82,400 million in 2006) and employs 30 percent of the labor force in that country (ENTRO, 2008).

Figure 3.3 Map Showing the Blue and White Nile in Africa



Source: World Bank (1998). Nile River Basin

In 2006, Sudan had a GDP of US$17.8 billion with agriculture contributing about 39 percent of that total (ENTRO, 2008). The agriculture sector employs 57 percent of the labor force in Sudan (ENTRO, 2008). Irrigated agriculture covers 10 percent of the total productive land, but contributes about 50 percent of crop production in total (ENTRO, 2008). In 2006, the GDP of Ethiopia was US$11.5 million with agriculture contributing 44 percent of the GDP in that fiscal year (ENTRO, 2008). The agriculture sector employs 80 percent of the labor force in Ethiopia (ENTRO, 2008). Irrigated agriculture is still in its infant stage in Ethiopia and covers 340,000 ha of land (MoFED, 2006; Awulachew et al., 2007). As mentioned above, the Ethiopian government plans to develop its irrigation sector using water from the Blue Nile River Basin (MoFED, 2006).

Available estimates indicate that for each cubic meter of water that leaves the Ethiopia highlands, about 40 percent is lost before it reaches the Mediterranean Sea (Whittington et al., 2005). Similarly, evaporation losses from the Sudd swamps in Sudan and Aswan High Dam are high, usually forming about 50 percent and 15 percent of the entering flows, respectively (Whittington et al., 2005). If there are no other constraints to using water, it is beneficial to use it upstream for non-consumptive purposes, as this option will decrease evaporation and seepage losses. Whittington et al. (2005) showed that if the water is used for hydropower purposes, its economic value will be higher in Ethiopia than in Sudan or Egypt. This is because the existing lakes in Ethiopia have larger net heads than lakes in the other two countries. Furthermore, the cumulative value derived by a cubic meter of water flowing from the Ethiopian catchment does not change significantly after the border between Ethiopia and Sudan (Whittington et al., 2005). The basic idea of their model was to examine the potential effects of using water upstream to reduce the amount lost through evaporation and seepage. Given these benefits, the Ethiopian government has been able to mobilize local funds to develop a hydropower project. The total water requirement for dam development in Ethiopia is presented in Table 3.1. Concurrently, Egypt and Sudan are also planning potential water development projects and are demanding that water be added to their current allocations (Table 3.1).

Table 3.1 Proposed Water Withdrawal Requirements in the Blue Nile River Basin

Country	Area(ha)	Water Requirement Billion Cubic Meters (BCM) per year [a]
Ethiopia	523,300	5.3
Sudan	727,000	7.9
Egypt	501,900	9.5
Total	1754,200	22.7

Source: ENTRO, 2008. a. Proposed water requirement for each country's development projects in the future. For Egypt and Sudan these are additional requirement on top of their existing allocation. For example, Sudan is demanding more than its current requirement. Sudan received 18.5BCM as per the Nile water agreement in 1959. Currently, Sudan uses 15BCM. This leaves 3.5BCM of water available compared to the 8BCM required for future projects (ENTRO, 2008).

Against this background, there is an economic reason to reallocate water from one country to another to promote efficiency and equitability of water use. Under efficiency conditions, the issue of reallocating water from low- to high-value uses often emerges as rational (Whittington et al., 2005). In most cases, however, efficiency conditions fail to capture distributional or equity issues. Therefore, the question is not how much does a particular sector contribute to the GDP, but also how can a given water resource be allocated such that the welfare of the country's low income residents could be improved. This demands the addition of welfare analysis into the economic evaluation framework (Juana et al., 2011). Thus, this study uses the CGE model to critically analyze the impact of water reallocation in a multi-country context, emphasizing the impact on the agricultural, industrial, and services sectors and how reallocation will improve the general welfare of local population**.**

3.3.2 The CGE Model Specification

Following the standard approach in De Melo and Tarr (1992) a static, multi-sector and multi-country CGE model has been developed for these countries. A detailed description of CGE models in general and multi-country CGE models can be found in previous studies such as Dervis et al. (1982), De Melo and Tarr (1992), Hertel et al. (1997), and Decaluwe et al. (2000). The salient features of CGE models in general and how the current model contributes to the literature are presented in this section. This section presents the theoretical understanding of water reallocation and the CGE model.

Appendix I outlines detailed equations and calibrations of the other building blocks of the full CGE model. The original calibration approach of incorporating water into the CGE model was developed by Robinson and Gehlar (1995). This approach has been used to model similar water allocation issues in Mukherjee (1995) for South Africa, Cirpci (2008) for Turkey, and Cororaton (2004) for the Philippines. However, all of these studies modeled the aggregate impacts of water reallocation for a given country. In particular, these studies focused on the sectoral impacts of water reallocation at the country level. The current study seeks to investigate the impact of water reallocation among three countries in the Blue Nile River Basin. The model developed in this study is used to analyze the impacts of water reallocation under risk and uncertainty as well.

3.3.3 Theoretical Framework

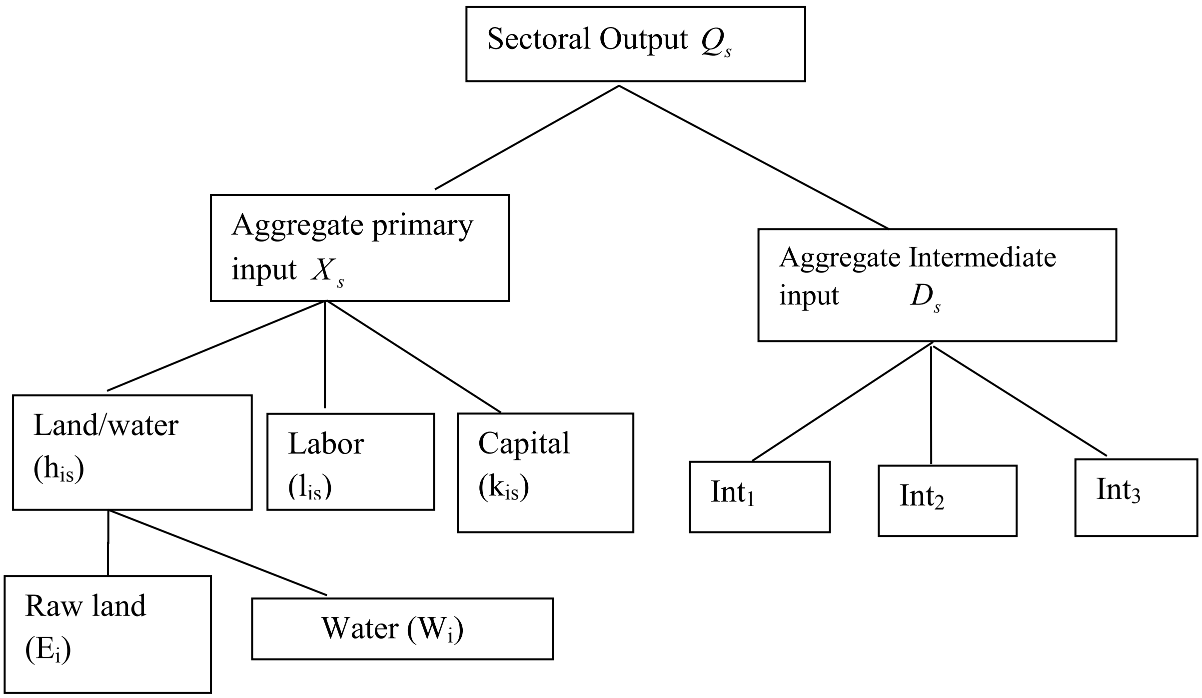
3.3.3.1 Production

In this section, a framework is presented for the Blue Nile Water-Computable Equilibrium Model (BNW-CGE) and how water is incorporated. For a given country, there is a composite factor good from a sector. This is transformed into exports and domestic goods using the gross domestic output production function. Next, the domestic good is combined with imports through an Armington Constant Elasticity of Substitution (CES) production function to produce the composite good for the country. This composite good is then distributed among household consumption, government consumption, investment and intermediate uses. Finally, household utility is generated by the consumption of goods as specified by the utility function.

To show how water is incorporated, Figure 3.4 illustrates a sectoral production function. This figure shows the nested structure of the sectoral production function modeled in this study. At the top level, sectoral output is a function of an aggregate primary input and an aggregate intermediate input (i.e., purchased services, energy and materials). At the second level, the aggregate amount of input from industries is a function of primary inputs (e.g., capital, labor, and land). Land, in turn, is an aggregation of raw land and water. For a given country, let s represent a sector, such that each sector is made of similar industries (e.g., industries in the agricultural sector). Also, let Q_s represent the sector's output and P_s the sector's output market price. This sector uses two main inputs: an aggregate primary input and an aggregate intermediate input.

Define X_s as the aggregate primary input (i.e., the sum of capital, labor and land) and D_s is the aggregate intermediate input (i.e., the sum of goods and services used as inputs).

Figure 3.4 Nested Production Structure of a Sector



Let M_s denote the aggregate primary input price and V_s the aggregate intermediate input price. The production function is defined as $Q_s = F_s(X_s, D_s)$. Profit maximization for the sector is given as:

$$\max_{X_s, D_s} \pi_s = P_s Q_s - [M_s X_s + V_s D_s] \qquad (3.8)$$

$s.t$

$$Q_s = F_s(X_s, D_s) \qquad (3.9)$$

Next, let $i = 1, ..., n_s$ be an industry in the sector such that $(i \in s)$. Subsequently, k_{is} represents capital input used by the ith industry in sector s. We denote l_{is} as labor used in the ith industry and h_{is} represent composite land/water inputs used by the ith industry in the same sector. We define r_{is}^{k} as the rental rate of capital, r_{is}^{l} as the wage rate of labor and z_{is}^{h} as the rental rate of composite land/water. Also, x_{is} and N_{is} are the output generated from the primary inputs used by the ith industry in the sector and associated output market price, respectively.

The profit maximization of the ith industry in sector s is given as:

$$\max_{k_{is},l_{is},h_{is}} \pi_{is} = N_{is}x_{is} - [r_{is}^{k}k_{is} + r_{is}^{l}l_{is} + z_{is}^{h}h_{is}] \qquad (3.10)$$

$s.t$

$$x_{is} = g_{is}(k_{is}, l_{is}, h_{is}) \qquad (3.11)$$

Equation 3.11 represents the production function for the industries in a given sector with capital, labor and land as its arguments. To further simplify, let E_{is} represent raw land and W_{is} denote water supply from the ith industry. Then, the composite land/water input, in turn, is an aggregation of water and raw land used by the ith industry such that:

$$h_{is} = u_{is}(E_{is}, W_{is}) \qquad (3.12)$$

In CGE modeling, the issue surrounding choice of the functional form is well-documented (Hertel, 1997). The most common functional forms are the Cobb-Douglas and the Constant Elasticity of Substitution (CES). The CES functional form is preferable to the Cobb-Douglas because the latter inherently restricts the elasticity of substitution among inputs to be equal to one.

In this study, the functions in (3.9) and (3.11) are defined as CES production functions. Since Arrow et al. (1961) introduced the CES function, it has become popular in CGE modeling. Functions with a CES are used in CGE models because they provide a unique way to represent the technology and preference relations of economic agents. From no substitution (i.e., the Leontief case of fixed coefficients) to perfect substitution (i.e., linearity) there is a range of possibilities for the CES functions to represent the curvature of convex isoquants (Varian, 1992).

Figure 3.4 presents the nested structure of the production used in this study. At the top level, Q_s is a CES function in two inputs, X_s and D_s. We define α_s as the shift or efficiency parameter of the CES production function for sector s. Let β_{X_s} and β_{D_s} represent the share parameters of the CES function such that $(\beta_{X_s} + \beta_{D_s} = 1)$. The substitution parameter of the CES function of sector s is given as ε_s. The substitution parameter is related to the elasticity of substitution (σ_s) by the relation $\sigma_s = 1/(1-\varepsilon_s)$. The sectoral CES production function is given as:

$$Q_s = \alpha_s(\beta_{X_s} X_s^{\varepsilon_s} + \beta_{D_s} D_s^{\varepsilon_s})^{\frac{1}{\varepsilon_s}} \tag{3.13}$$

As mentioned above, the composite land/water input is used by the ith industry; this input is itself a linear aggregation of raw land (in hectares) and water (in cubic meters). Similarly, we define γ_{is} as the shift or efficiency parameter of the ith industry production function for sector s. Let $\delta_{k_{is}}$, $\delta_{l_{is}}$ and $\delta_{h_{is}}$ represent the share parameters of the ith industry's CES production function such that $\delta_{k_{is}} + \delta_{l_{is}} + \delta_{h_{is}} = 1$. The substitution parameter of the CES function of the ith industry in sector s is given as ρ_{is}. The substitution parameter is related to the elasticity of substitution (φ_{is}) by the relationship $\varphi_{is} = 1/(1-\rho_{is})$. The ith industry CES production function is given as:

$$x_{is} = \gamma_{is}(\delta_{k_{is}} k_{is}^{\rho_{is}} + \delta_{k_{is}} l_{is}^{\rho_{is}} + \delta_{k_{is}} h_{is}^{\rho_{is}})^{\frac{1}{\rho_{is}}} \tag{3.14}$$

Let aa_i and bb_i be the units of raw land and water needed to produce aggregate land. We assume that raw land and water are used in fixed proportions to constitute an aggregate land/water input, h_{is}. To generate a single unit of land output, we need aa_i units of raw land and bb_i units of water. Then,

$$h_{is} = \min(aa_{is} E_{is}, bb_{is} W_{is}) \tag{3.15}$$

The above specification is adopted for the BNW-CGE model because water is unavailable in the original SAMs collected from the countries. The marginal values of water cannot be derived from the composite value-added CES function with the other primary inputs. Hassan and Thurlow (2010) presented another approach which was based on crop-water response functions in South Africa. However, a comprehensive literature review showed these functions are unavailable for the study region.

Thus, a specification was adopted to model the effects of water at the aggregate level by examining how crops are produced with a fixed amount of inputs in a stylized Leontief production function (Gersfelt, 2007; Löfgren and El-Said, 1999; Robinson et al., 1999). This implies that land and water inputs may not be substituted for each other. In many instances, they are not paid according to their marginal product contributions or may not even be paid at all. Highly seasonal agriculture production means that these inputs are underused during certain periods of a given year. They usually take inequality constraints in modeling the effect of the agriculture sector on the economy of a given country (Hazell and Norton, 1986).

The demand for factor inputs is derived from equations (3.10) and (3.14) as first-order conditions from the profit maximization and expressed as:

$$r_{is}^{k} = \frac{\partial x_{is}}{\partial k_{is}} N_{is} \tag{3.16}$$

$$r_{is}^{l} = \frac{\partial x_{is}}{\partial l_{is}} N_{is} \tag{3.17}$$

$$z_{is}^{h} = \frac{\partial x_{is}}{\partial h_{is}} N_{is} \tag{3.18}$$

Accordingly, the demand function for raw land and water is derived from equation 3.15 as:

$$E_{is} = aa_{is} h_{is} \tag{3.19}$$

$$W_{is} = bb_{is} h_{is} \tag{3.20}$$

The aggregate land price is a function of raw land price (μ_{is}^{E}) and water price (μ_{is}^{W}) as:

$$z_{is}^{h} = ee_{is}(\mu_{is}^{E}, \mu_{is}^{W}) \tag{3.21}$$

As mentioned above, the land/water aggregate is a linear function of water and land but with separate sectoral land supply $(\overline{E}_s)$ and water supply $(\overline{W}_s)$ constraints as:

$$\overline{E}_s \geq \sum_i E_{is} \tag{3.22}$$

$$\overline{W}_s \geq \sum_i W_{is} \tag{3.23}$$

Given that there are different coefficients for these inputs, it is possible to have both constraints binding. However, it could be that one but not both of these constraints will be binding. Intuitively, this means that if a constraint is not binding the shadow price will be zero. Thus, if in agriculture the supply of water is binding, the overall cost of production is higher. If the water supply is increased (e.g., improvements in irrigation are carried out), this relaxes the constraints and reduces the cost of production.

In order to complete the production side of the BNW-CGE model, two other constraints are needed. These constraints ensure that the relationships between total water supply and the total amount of water available for use are satisfied in each country. Total water available for the jth country is represented by TW_j. Let A_j represent the total land available for the jth country. Let MI_j represent the exogenous quantity of total water available for municipal and industrial uses in the jth country. We define WC_j as the Leontief coefficient for the quantity of water use per unit of land in each country:

$$\sum_s W_{sj} = A_j WC_j \tag{3.24}$$

$$\sum_j A_j WC_j + \sum_j MI_j \leq TW_j \tag{3.25}$$

Also for land, the balance equation is defined as:

$$\sum_j A_j \leq \text{Total irrigable land in each country.} \quad (3.26)$$

3.3.3.2 Trade[25]

Unlike single country or two-country models, the exports and imports sections of the model are modified to ensure an equilibrium condition in the multi-country situation (De Melo and Tarr, 1992). In the single country model, domestic goods are combined with imports to form composite goods, while in a multi-country model composite goods are produced from a three-level nested CES function. The trade component of the BNW-CGE model relies on the Armington[26] assumption (Armington, 1969), which implies that domestic and foreign goods are distinguished by their origins. This assumption helps to accommodate both exports and imports of the same commodity in a given country.

On the demand side, regional imports from other Blue Nile countries are distinguished from imports from the rest of the world. In addition, imports from different Blue Nile countries are imperfect substitutes. A three-level CES function allows us to model the differentiation between imports and domestic commodities. At the first level, domestic absorption (C_s) is a CES function of domestic (QD_s) and import (IM_s) commodities. Let γ_s represent the efficiency parameter in the composite commodity production function and im_s, q_s represent the input share coefficients. The sum of these input shares must be equal to unity. We denote ϑ_s as the substitution parameter and ϖ_s as the elasticity of substitution of the CES function. The relationship between these two

[25] Ethiopia exports agricultural and semi-processed commodities to Egypt. Available data indicate that Egypt imports from Ethiopia have increased from three million US dollars in 2004 to 45 million US dollars in 2011. Major agricultural commodities exported to Egypt are sesamum, camels, ox and kidney beans. Egypt, in turn, exports petroleum oils, soya oil, palm oil, desktop computers, and parts of industrial machinery for food and drink industries in Ethiopia. In 2011, the total imports from Egypt were about 91 million US dollars (Egyptian Ministry of Foreign Affairs, 2014). Ethiopia signed a trade agreement with Sudan, which allows Ethiopia to imports 85 percent of its annual oil consumption from Sudan. In addition, Ethiopia and Sudan signed an agreement to prevent double taxation and to promote flexible economic performance and mutual investment between the two countries. In exchange, Ethiopia plans to supply electricity to Sudan from several plants under construction including the Great Renaissance Dam on the Blue Nile River. Egypt and Sudan have a trade agreement that ensures integration of technology and experience of effective resources utilization in Sudan (Sudan Vision, 2014).

[26] Under this assumption, goods and services produced and imported by the same firm in different countries are not recognized by consumers as the same, regardless of similar production technologies. In the CGE context, this refers mostly to the imperfect substitution between imports and domestic goods.

parameters can be established as $\vartheta_s = (\varpi_s - 1)/\varpi_s$. For the sectoral profit maximization in each country, we define P_s^C as the sectoral output price, while p_s^{QD}, p_s^{IM} represent the import and domestic good prices, respectively. Formally, profit maximization of the sector in the country can be stated as:

$$\underset{D,M}{Max}\ \pi = P_s^C C_s - [p_s^Q QD_s + p_s^{IM} IM_s] \tag{3.27}$$

$s.t$

$$C_s = \gamma_s (q_s QD_s^{\vartheta_s} + im_s IM_s^{\vartheta_s})^{\frac{1}{\vartheta_s}} \tag{3.28}$$

From equations 3.27 and 3.28, the import-and-domestic-commodity demand functions can be derived as:

$$QD_s = C_s \left[\frac{\gamma_s^{\vartheta_s} q_s P_s^C}{p_s^{QD}} \right]^{\frac{1}{1-\vartheta_s}} \qquad \forall_s \tag{3.29}$$

$$IM_s = C_s \left[\frac{\gamma_s^{\vartheta_s} im_s P_s^C}{p_s^{im}} \right]^{\frac{1}{1-\vartheta_s}} \qquad \forall_s \tag{3.30}$$

Next, aggregate imports are obtained by combining, with a CES function at the second level, the aggregate of regional imports and imports from the rest of the world. Finally, at the third level, the aggregation of regional imports is another CES function of imports from the BNRB countries. This nested structure allows the representative agent's decision to take place in the form of multi-step budgeting. In addition, a cost-minimization rule makes it possible to determine the optimal level of each domestic absorption component (Hosoe et al., 2010).

Similarly, exports are differentiated according to their destinations. The three-level nested Constant Elasticity of Transformation (CET) function allows us to capture the imperfect substitution between the different components of the firm's supply in each sector. The gross domestic output (Y_s) is transformed into domestic commodities (DX_s) and composite exports (

ET_s), using the CET function. The price of the gross domestic output is denoted as P_s^Y, and p_s^d represents the domestic commodity prices.

The price of the export commodities in terms of domestic currency is denoted as p_s^e. The share coefficients of the output transformation function are e_s and d_s, while its efficiency parameter is represented as χ_s. Let φ_s denote the parameter that defines the elasticity of transformation (τ_s) such that $\varphi_s = (\tau_s + 1)/\tau_s$. Profit maximization for the sector involved in the output transformation process of a given country can be defined as:

$$\max_{DX_s, ET_s} \pi_s = P_s^Y Y_s - [p_s^e ET_s + p_s^d DX_s] \tag{3.31}$$

$s.t$

$$Y_s = \chi_s (e_s ET_s^{\tau_s} + d_s DX_s^{\tau_s})^{\frac{1}{\tau_s}} \tag{3.32}$$

Similarly, the supply functions for domestic and exports commodities can be obtained as:

$$DX_s = Y_s \left[\frac{\chi_s^{\tau_s} d_s P_s^Y}{p_s^d} \right]^{\frac{1}{1-\tau_s}} \tag{3.33}$$

$$ET_s = Y_s \left[\frac{\chi_s^{\tau_s} e_s P_s^Y}{p_s^e} \right]^{\frac{1}{1-\tau_s}} \tag{3.34}$$

Composite exports are further broken into exports to various destinations, using the CET function. A revenue maximization principle allows firms to allocate the supply of the aggregate output into the domestic and export commodity markets. Lastly, the total current account balance for each country is the sum of its balance with the rest of the world and its regional balance. The latter is the sum of balances with each country's partner in the region (De Melo and Tarr, 1992; Decaluwé et al., 2000).

3.3.3.3 Household Consumption

In each country, we introduce real savings (RS_s) in the households' utility function and θ_s as the intercept of the saving function. Subsequently, we assume that consumers choose their optimal level of real savings the same way they chooses their optimal level for each of the composite good.

Let c_s represents the consumption of sectorial composite good by household, P_s^H denotes the consumer price (inclusive of any tax) of the composite good and HY_s household disposable income. We define U_s as the utility function, γ_s represents the minimum consumption level and β_s denotes marginal income share of good in a sector such that $\sum_{s=1}^{S}\beta_s = 1$. The households' utility functions are of the Stone-Geary type and can be specified as:

$$U_s(c_s) = \prod_{s=1}^{S}(c_s - \gamma_s)^{\beta_s} \qquad (3.35)$$

The utility function specified in equation (3.35) leads to the Extended Linear Expenditure System in LIuch (1973) and Howe (1975). Thus, the consumer utility maximization problem is:

$$U\max_{c,RS} = \sum_{s=1}^{S}\beta_s \ln(C_s - \gamma_s) + \beta_s \ln(RS_s - \theta_s) \qquad (3.36)$$

$s.t$

$$HY_s = \sum_{s=1}^{S} P_s^H C_s + RS_s \qquad \forall s \qquad (3.37)$$

If we set the minimum level of savings equal to zero i.e. $\theta_s = 0,$ the demand functions obtained from solving the above consumer problem are:

$$c_s(P_s^H, HY_s) = \gamma_s + \frac{\beta_s}{P_s^H}\left(HY_s - \sum_{s=1}^{S}\gamma_s P_s^H\right) \qquad \forall s \qquad (3.38)$$

3.3.3.4 Government Income and Expenditure

Government enters the model as an agent to collect taxes and ensure that income is redistributed to households and investment institutions. Government income is generated from direct taxes (DT_s), import tariffs (TG_s) and production taxes (TR_s). We denote the direct tax rate as ω_s^{DT}, import tax rate as ω_s^{TR} and production tax rate as ω_s^{TG}. The equations below describe the mathematical relations of the taxes in the economy.

$$DT_s = \omega_s^{DT} p_s^f FF_s \qquad \forall_s \qquad (3.39)$$

$$TG_s = \omega_s^{TG} P_s^Y Y_s \qquad \forall_s \qquad (3.40)$$

$$TR_s = \omega_s^{TR} p_s^{IM} IM_s \qquad \forall_s \qquad (3.41)$$

We define the share of a good in sector s in government expenditure as τ_s. The sectoral government consumption (B_s) in the country is then given as:

$$B_s = \frac{\tau_s}{P_s^c}\left(DT_s + TG_s + TR_s\right) \qquad \forall_s \qquad (3.42)$$

Finally, in each country, government expenditure comprises the sum of aggregate public consumption, public transfers, and interest payments on public foreign debt. Sectoral public consumption is calculated as a proportion of total public consumption. Each proportion is calibrated as a ratio of sectoral public consumption to aggregate public consumption, which is taken to be a fixed proportion of public revenue. Public transfers are obtained as a proportion of public revenue. Other government expenses consist of transfers to households and net transfers to the rest of the world (Decaluwé et al., 2000).

3.3.3.5 Savings and Investments

As part of market clearing conditions, investments must be equal to savings in the economy. Three types of savings are accounted for in this model; household savings (RS_s), government savings (GS_s) and current account deficits in foreign currency terms (DD). Let t_s denote the expenditure share of sectoral commodities in total investment and ε_j represents the exchange rate of the jth country. Total investment demand (PI_s) for sectoral commodities in a country's economy is defined as:

$$PI_s = \left(\frac{RS_s + GS_s + \varepsilon_j DD}{P_s^c} \right) t_s \qquad (3.43)$$

3.3.3.6 Price Linkages

The "small country" assumption is applied for each country; world prices of imports and exports are assumed to be given exogenously and import and export prices within the country are calculated from these world prices. This implies that the domestic price of imports is the import tariff inclusive of world price multiplied by the exchange rate in each country. The domestic price of exports is simply the world price of exports multiplied by the exchange rate. The composite good price is a function of import and export prices, while the price of value-added is the price of the output net from indirect taxes, less the unit cost of intermediate inputs. In each country, the consumer price index represents a price level against which all relative prices in the model are measured. It is necessary in the CGE models to determine such a numeraire price, because the models only determine relative prices.

The import and export prices in each country are linked with regional and world prices, and the adjustment of the exchange rates leads to an equilibrium. The export and import prices in terms of local currencies are represented as p_s^e and p_s^{IM}. The corresponding import and export prices in foreign currencies are given as $p_s^{W_{IM}}$ and $p_s^{W_{ET}}$. The price linkage equations in the model are defined as:

$$p_s^e = \varepsilon_j p_s^{W_{ET}} \qquad \forall_s \qquad (3.43)$$

$$p_s^{IM} = \varepsilon_j p_s^{W_{IM}} \qquad \forall_s \qquad (3.44)$$

It is relevant to note that with three countries, there are six pairs of bilateral sectoral trade flows between them, governed by endogenous price systems (Egypt-Sudan, Egypt-Ethiopia, Sudan-Ethiopia, both imports and exports). There are six more trade flows and price systems, which are endogenous as well; these are: Egypt-ROW, Sudan-ROW, Ethiopia-ROW imports and exports.

In each country, the balance of payment account constraint is then defined as:

$$p_s^{W_{ET}} ET_s + DD = p_s^{W_{IM}} IM_s \qquad (3.45)$$

3.3.3.7 Market Clearing Conditions

The final part of the model structure is to ensure that certain market clearing conditions "hold" so that demand and supply in all markets are equal. The first condition ensures that the total good supply is equal to the demand (3.46). The second condition adjusts the factor market equilibrium by ensuring that the total factor supply (FF_s) (3.47) is equal to the total factor demand (FD_s). The sub-factor market equilibrium condition is defined such that the supply of total land $(\overline{E}_s)$ and water $(\overline{W}_s)$ must be greater or equal to the demand (E_{is}, W_{is}) (3.48 and 3.49).

$$QQ_s = C_s + B_s + PI_s + D_s \qquad \forall_s \qquad (3.46)$$

$$FF_s = FD_s \qquad \forall_s \qquad (3.47)$$

$$\overline{W}_s \geq W_{is} \qquad \forall_{ss} \qquad (3.48)$$

$$\overline{E}_s \geq E_{is} \qquad \forall_{ss} \qquad (3.49)$$

3.3.3.8 Model Closure

In CGE models, all accounts must consist of the entire circular flow of goods and services in the system; in principle there can be no leakages from the system. In order to achieve this enclosed system, certain macroeconomic variables in the model must be considered. Thus, specific macro "closure" rules need to be applied.

In order to ensure that the system is closed, the model must reconcile aggregate savings and aggregate investment. In addition, the foreign and government accounts must be balanced within the model. To achieve this, it is necessary to choose the variables that will adjust freely to achieve equilibrium, and constrain other variables by fixing them exogenously. For example, in the current model, the current account is equal to its total foreign savings, which is fixed. This equilibrium condition is achieved by an adjustment of the real exchange rate. The water CGE model is considered as "savings-driven" in the sense that investment expenditure is endogenous and is determined by the amount of total available savings.

In each country, the demand for factors and sub-factors may not exceed their respective fixed supply. This ensures the assumptions of full employment of the factors and full mobility between sectors. The sub-factors' equation allows for less than full employment of either factor; in other words, it allows some of the sub-factors to be left redundant in each country. Also, equilibrium should be met between the import and export supply in the bilateral trade of each good and the balance of payment account in each country.

3.3.4 Data, Parameters and Elasticities for the Model

This section deals with the data used in the development of the BNW-CGE model. The main data required for developing the BNW-CGE model are obtained from the Social Accounting Matrix (SAM). The SAM is an important tool in presenting a "snapshot" of the economy in a given year. In recent years, it has been the main database for CGE models. As stated earlier, it is an extended version of the IO table and provides a convenient data framework for the CGE models by presenting aggregate values of an economy in a consistent matrix format. Apart from the data presented in the SAM, two other exogenous data sets were needed before the model could be completed. These exogenous data sets are: (1) data on the land and water sub-factors in the production sector of the economy, and (2) elasticity of substitution parameters. In the SAM, the total value of land is available as one of the factors of production but there are no data on land and water sub-factors. Also, the production and consumption functions specified in equation 3.14 and 3.28 require exogenous elasticity values before they are used to replicate the actual outputs of the economy. The nature of these three data sets is discussed below.

3.3.4.1 Social Accounting Matrix (SAM)

Disaggregated SAMs were collected for the three countries, Ethiopia, Sudan and Egypt. The base-year SAMs for these countries are: Ethiopia (2005 to 2006), Sudan (2004), and Egypt (1997), respectively. The Ethiopian SAM was developed by the Ethiopian Development Research Institute (EDRI, 2009) in collaboration with the Institute for Development Studies, UK. The SAM from Sudan was provided in Saddig (2009). The SAM from Egypt was collected from the International Food Policy Research Institute (IFPRI). It is worth mentioning that a current SAM, developed in 2005, is available for Egypt. However, as it does not provide a detailed account of the agricultural sector and factor inputs, the older SAM was considered more appropriate for this thesis.

For the analysis, these SAMs were restructured to reflect the major sectors in the economies of these countries and the aims of the study. In each country, the SAM was organized to show the aggregate agriculture, services and industrial sectors (Table 3.2). For example, the agriculture sector includes the country's major crops, mining, and food processing. Utilities represent the industrial sector while hotels, real estate, education and health constitute the services sector (Table 3.2).

Table 3.2 Disaggregation of Major Sectors in Egypt, Sudan and Ethiopia

Countries	Egypt	Sudan	Ethiopia
Agriculture	Cereals Cash crops Livestock Other crops	Cereals Cash crops Livestock Forestry Fishery	Cereals Cash crops Livestock Other Agricultural activities
Industrial	Food processing Oil Textile Other industry	Petroleum Mining and Quarrying Food processing Textile Wood products Paper Basic metal Fabricated metal products Non-metallic industries	Milling services(small scale) Food processing Utility Mining and Quarrying Construction Other Industries
Services	Electricity Construction Public Administration Others	Electricity Transport Communication Finance Services Public Administration Health Sanitation Restaurants and hotels Other services	Wholesale and Retails trade Transport and Communication Hotels and Restaurants Financial Services Real estate Public Administration Education Health Other Services Activities

Source: El-Said et al., 2001; Saddig, 2009; EDRI, 2009.

In each country, the factor account was reorganized to have three main factors of production while households, enterprises, governments, investment-savings, and the rest of the world remained the same. The final SAMs are presented in Tables 3.3, 3.4, and 3.5.

Table 3.3 Final Aggregated Social Accounting Matrix for Egypt (1997) in Billion Pounds [a]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				61.719															61.72
2					161														161
3						214													213.8
4	11.27	23.931	1.736							30.691			1.599					0.285	69.52
5	5.133	59.871	43.39							60.608			28.21				3.08	20.69	221
6	2.982	16.775	29.58							101.37		26.1	15.59				0.39	33.9	226.7
7	11.39	13.13	53.23																77.76
8	10.88	46.106	84.7														0.66	3.971	146.3
9	20.06																		20.06
10							77.76	134.9	20.06			9.29						11.05	253.10
11																			
12								11.423						14.59	12.8	8.125		3.021	49.96
13										45.796		7.323						-7.72	45.4
14										14.592									14.59
15	0.008	1.19	1.164	1.244	4.495	4.71													12.81
16				0.646	7.479														8.125
17												4.134							4.134
18				5.912	48.01	8.17						3.114							65.21
19	61.72	161	213.8	69.521	221	227	77.76	146.32	20.06	253.05	0	49.961	45.4	14.59	12.8	8.125	4.13	65.21	

Source: Compiled by the author based on the IFPRI 1997 database. a. The numbers on the left and the top sides of the table indicates the activities account, factor account, institutional and the rest of the world account. Legend: (1) Agriculture activity (2) Industrial activity (3) Services activity (4) agriculture commodity (5) industrial commodity (6) service commodity (7) labor (8) capital (9) land (10) households (11) Enterprise (12) government (13) investment-saving,(14) direct taxes (15) indirect taxes (16) import taxes, (17) subsidies, (18) rest of world, (19) total. The values in the SAM show the payments from the account of its column to the account of its row in constant Egyptian billion pounds. Note that in the SAM, the cost of an account appears in its column and revenues in its row.

Table 3.4 Final Aggregated Social Accounting for Sudan (2004) in SG million [a,b]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				359.3															359.34
2					219.2														219.22
3						341.4													341.37
4	23.67	13.04	5.589							297.7			22.97					25.72	388.64
5	21.37	59.02	54.87							68.06			40.03					75.4	318.74
6	19.65	50.51	79.23							74.66		62.93	61.43					0.034	348.43
7	36.22	18.04	97.16																151.42
8	188.4	69.88	101.5															0.053	359.8
9	68.46																		68.46
10							151.42	3.285	68.46		185.21	22.65						42.16	473.18
11								356.5										0.553	357.03
12											36.791			17.46	13.38	10.95		22.67	101.24
13										18.51	90.625	7.035						8.249	124.42
14										1.074	16.386								17.46
15	1.604	8.738	3.032																13.374
16				1.102	9.155	0.696													10.953
17																			0
18				28.2	90.36	6.359		0.047		13.22	28.017	8.627							174.83
19	359.3	219.2	341.4	388.6	318.7	348.4	151.42	359.8	68.46	473.2	357.02	101.2	124.4	17.46	13.38	10.95	0	174.8	

Source: Compiled by the author based on the original SAM of 2004 reported by Saddig, 2009. a. The numbers on the left and the top sides of the table indicates the activities account, factor account, institutional and the rest of the world account. The full definition of the numbers are: (1) Agriculture activity (2) Industrial activity (3) Services activity (4) agriculture commodity (5) industrial commodity (6) service commodity (7) labor (8) capital (9) land (10) households (11) Enterprise (12) government (13) investment-saving,(14) direct taxes (15) indirect taxes (16) import taxes, (17) subsidies, (18) rest of world, (19) total. The values in the SAM show the payments from the account of its column to the account of its row in constant Sudanese SG million. Note that in the SAM, the cost of an account appears in its column and revenues in its row. b. This SAM represents the entire Sudan. Presently, there are no separate SAMs for South Sudan and North Sudan.

Table 3.5 Final Aggregated Social Accounting for Ethiopia (2005/2006) in Billion Birr [a]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				64.154															64.15
2					20.09														20.09
3						102.3													102.3
4	2.67	2.503	2.729							53.98			3.791					9.13	74.8
5	1.893	4.85	21.5							29.18			0.824					0.86	59.1
6	2.000	1.822	23.83							28.83		16.19	27.35					7.46	107.5
7	43.06	3.918	12.8																59.78
8	0.808	6.918	41.31															0.45	49.48
9	13.73																		13.73
10							59.78	42.5	13.728			1.502						13.5	131.1
11								6.696											6.696
12											5.618			4.1	2.98	7.41		3.46	23.56
13										16.2		5.385						10.4	31.97
14										2.744	1.352								4.096
15				0.143	1.516														1.659
16				7.408															7.408
17																			0
18				3.098	37.49	3.841		0.244		0.122		0.491							45.29
19	64.15	20.01	102.2	74.803	59.1	106.2	59.78	49.44	13.728	131.1	6.97	23.56	31.97	4.1	2.98	7.41	0	45.3	

Source: Compiled by the author based on the 2005-2006 original SAM reported in EDRI, 2009. a. The numbers on the left and the top sides of the table indicates the activities account, factor account, institutional and the rest of the world account. The full definition of the number are: (1) Agriculture activity (2) Industrial activity (3) Services activity (4) agriculture commodity (5) industrial commodity (6) service commodity (7) labor (8) capital (9) land (10) households (11) Enterprise (12) government (13) investment-saving, (14) direct taxes (15) indirect taxes (16) import taxes, (17) subsidies, (18) rest of world, (19) total. The values in the SAM show the payments from the account of its column to the account of its row in constant Ethiopian billion birr. Note that in the SAM, the cost of an account appears in its column and revenues in its row.

3.3.4.2 Water and Land Data

As mentioned already, apart from the data provided by the SAMs, the model also requires data on land and water use in the agriculture sector for each country. The irrigation water demand depends on the crop-water requirement, the amount of land available for irrigation, and the intensity of land use (Table 3.6).

Table 3.6 Land and Water Utilization in the Blue Nile River Basin

Riparian Country	Irrigation potential in million ha	Total irrigated land in million ha	Percent of irrigated land to potential land use	Gross Irrigation Water Requirement in M^3/ha/year
Ethiopia	2.22	0.02	0.9	9,000
Sudan	2.75	1.95	71	14,000
Egypt	4.42	3.25	73.5	13,000

Source: FAO,1997

The aggregate water flow data for the BNW-CGE model were collected from previous studies (Robinson et al., 2008; Awulachew et al., 2008). Under the Nile Water Treaty, Egypt is entitled to use 55.5 BCM per year. Sudan's entitlement is 18.5 BCM per year. Government policies in these countries give municipal and industrial use priority over agricultural use. The distributions of these allocations in the various sectors are presented in Table 3.7.

Table 3.7 Distribution of Nile Water between Egypt and Sudan

	Allocation of Water Entitlement	
Country	Egypt	Sudan [a]
Allocation to key sectors(BCM) per year	55.5 BCM per year	18.5 BCM per year
Agricultural	47	13.32
Domestic	3.6	3.7
Industrial	4.9	1.48

Source: Robinson et al. 2008; FAO, 2005. a. The distribution of the Sudanese allocation is based on sectoral share of water use.

It has been reported that total Nile water abstracted by Ethiopia is 0.003 BCM (Awulachew et al., 2008). However, there is no information on how this quantity of water is distributed among the key sectors in Ethiopia.

3.3.4.3 Elasticity of Substitution

One of the challenges of CGE modeling is finding accurate elasticity values to complete the parameters necessary for the model. This mainly concerns the CES and CET functions, and the export demand equation. In most of the countries in question, no information is available regarding the required factors and sectoral substitution elasticities. Therefore, in order to estimate these parameters, it is necessary to rely on different assumptions about the behavior of production, consumption and trade sectors in these countries (Siddig, 2009). According to Sadoulet and De Janvry (1995), empirical results obtained from simulations with CGE modeling are quite insensitive to the specific values of all these elasticities, but are critically dependent on their order of magnitude. In this regard, Sadoulet and De Janvry (1995) provided a possible range of substitutability that is relatively well represented by four values: 0.3 for low substitutability, 0.8 for medium-low, 1.2 for medium-high and 3.0 for very high. This range serves as a guideline for most CGE modellers in the developing world. Accordingly, this thesis used the current available elasticity values from previous studies as a guide for these countries.

In Sudan, the elasticity values were taken from Elabushra (2007) and Siddig (2009). The authors used a value of 1.2 to represent substitution between production factors. A value of 2.0 was assumed for substitution between commodities. An attempt was made to differentiate between these values according to the substitution possibilities among various commodities; for example, assigning a 1.8 value for commodities with high domestic substitution possibilities (such as agriculture) and assuming a 1.2 value for others (Siddig, 2009). This is because for non-agricultural sectors, the existence of non-price competition will limit the responsiveness of demand to price changes. These values are comparable to estimates from Philippines and Thailand[27], which have similar economic characteristics as Sudan. Based on these considerations, these elasticity values were used in this study for calibration and simulation analysis. The

[27] Cororaton (2004) presented the elasticity values for Philippines as 0.5 to 3.7 for agriculture, 0.4 to 2.5 for manufacturing and 0.25 to 1.30 for industry. Wattanakuljarus (2006) presented elasticity values for Thailand as 0.5 to 1.2 for agriculture and 0.5 to 0.7 for non-agriculture.

elasticity values for the CES and CET functions for Ethiopia were taken from Lashitew (2008). The author summarized similar studies in the region and presented typical ranges of elasticity values for the various CES and CET functions applicable to the Ethiopian economy. For the production side, a typical value of 0.75 was used while a value of 2.0 was taken for the consumption side. The elasticity values for the CES and CET functions for Egypt were taken from previous studies such as Decaluwé et al. 2000 and Löfgren and El-Said (1999). These values are presented in Table 3.8.

Table 3.8 Elasticity Values for CES and CET Functions in Egypt

	CET(Supply) [b]			CES[c]	CES(Armington)		
	Level 1[a]	Level 2	Level 3		Level 1	Level 2	Level 3
Food crops	1.5	3	3	0.45	1.5	3	3
Industrial agriculture	1.5	3	3	0.45	1.5	3	3
Livestock	1.5	3	3	0.45	1.5	3	3
Fishing and forestry	1.5	3	3	0.45	1.5	3	3
Extractive industry	1.5	3	3	0.6	1.5	3	3
Food industry	2	4	4	1.5	2	4	4
Textile industry	2	4	4	1.5	2	4	4
Chemical industry	2	4	4	1.5	2	4	4
Metal industry	2	4	4	1.5	2	4	4
Other industry	2	4	4	1.5	2	4	4
Utilities	2	4	4	1.5	2	4	4
Construction	1.5	3	3	0.95	1.5	3	3
Transportation	1.5	3	3	2	1.5	3	3
Financial services	2	4	4	2	2	4	4
Real estate services	2	4	4	2	2	4	4
Hotels and bars	2	4	4	2	2	4	4
Other services	2	4	4	2	2	4	4
Public administration	-	-	-	2	-	-	-

Source: Decaluwé et al., 2000; Lofgren and El-Said (1999). a. Level 1 (elasticity of value for the substitution between domestic goods and aggregate imports), Level 2 (elasticity value for the substitution between aggregate regional imports and imports from the countries in the region, Level 3 (elasticity values for the substitution between aggregate regional imports and imports from the world). b. CET (Constant Elasticity of Transformation). c. CES (Constant Elasticity of Substitution).

In a multi-country CGE modeling case, additional elasticity values are required for the substitution among imports from individual country destinations. While the elasticity of substitution between composite imports and domestic goods is generally available, the former elasticity is rarely available (Hertel, 1997). Consequently, most studies follow the standard Global Trade Analysis Project (GTAP) modeling practice. The GTAP does not estimate the elasticity values through econometric methods; rather it uses the elasticities reported in the SALTER project (Hosoe et al., 2010). The GTAP assumes the elasticity values to be twice as large as those for the elasticity of substitution between domestic goods and composite imports. Similar assumptions are used in this study. Sensitivity analysis is performed for the elasticity values used for the CES and CET functions in this thesis.

3.3.5 Model Calibrations

In the CGE model, having a well specified set of equations is not sufficient to solve the model; it is necessary to determine the model's parameter values in each functional equation. The procedure commonly used to determine a parameter is called calibration (Mansur and Whalley, 1984; Scarf and Shoven, 1984). Calibration is performed to estimate a model's parameters to replicate the baseline values (Sadoulet and De Janvry, 1995). The calibration process involves specifying behavioral relationships of economic agents and then calibrating parameters such that a model replicates the base-year values.

Calibration requires that a benchmark equilibrium data set be constructed for the economy being studied. The information required comes from sources such as national accounts, input-output tables, surveys, and financial reports (Roberts, 1994). Reconciling data from different sources is a challenge. Various adjustments are needed to create a database for a specific model. The approach often adopted in CGE modeling is to use the SAM to create consistent base-year values (Pyatt and Round, 1985). These values are usually recorded in the SAM. The cells in the sub-matrices represent the outcomes of the behavioral relationships underlying the SAM development. For impact analysis on a policy change, the SAM has to be combined with the CGE models that contain behavioral and technical relationships among key variables within the set of accounts. A major challenge of this approach is that the model cannot be tested statistically because the parameters are selected to replicate the base-year values.

The main reason for this approach is that multi-sector general equilibrium models require a large number of parameters. Limited numerical data for these parameters consistent with the models are available, however. Alternatives such as econometric estimation involve other problems of data structure, time and cost of data collection.

In this study, unknown parameters such as input shares, scale parameters, and tax rates are calibrated based on the initial values from the SAM. While the share parameters are computed from the SAM, the behavioral elasticity parameters in equations (3.13), (3.14), (3.28) and (3.32) are assigned values based on estimates from previous studies. For example, substitution elasticity values are required for the CES production functions of the production equations (3.13) and (3.14) and consumption sides of the model equations (3.28) and (3.32). On the production side at the sectoral level, the elasticity value needed is σ_s, which determines the substitution between value-added and intermediate inputs at the top CES production functions of each activity. From this elasticity value, ε_s is obtained, which is the top level exponent value for the CES production function. At the industry level, the elasticity of substitution (ϕ_{is}) determines the substitution between factors of production, which constitutes a composite value-added input. The top-level exponent for the CES production function of the value-added function (ρ_{is}) is derived from the value of this elasticity.

On the consumption side, different elasticity values were used to calibrate a three-level CES function. The first agent-level elasticity value determines the extent to which agents substitute between the top-level composite commodities (i.e., domestically produced goods and aggregate imports). On the next level, the substitution value deals with the CES production function of aggregate regional imports and imports from the rest of the world. Finally, the third level deals with the elasticity value of the CES production function of aggregate regional imports and those from Blue Nile countries. On the export side, an elasticity value is required for the CET production function of domestic goods and exports. At the next level, an elasticity value is required to model the CET production function of composite exports and exports to various destinations.

The calibration processes used in replicating the base-line values of each country's production functions are presented below. As previously defined, the elasticity of substitution defined in equation (3.14) is ϕ_{is}. We can then obtain the elasticity parameter ρ_{is} in the CES function (i.e., equation 3.14) as:

$$\rho_{is} = (\phi_{is} - 1) / \phi_{is} \tag{3.50}$$

As the elasticity of substitution is obtained for each country, the input share coefficients could be obtained from equation (3.14) as:[28]

$$\delta_{k_{is}} = \left(\frac{r_{is}^{0} K_{is}^{0(1-\rho_{is})}}{r_{is}^{0} K_{is}^{0(1-\rho_{is})} + w_{is}^{0} L_{is}^{0(1-\rho_{is})} + z_{is}^{0} h_{is}^{0(1-\rho_{is})}} \right) \quad \forall_{is} \tag{3.51}$$

$$\delta_{l_{is}} = \left(\frac{w_{is}^{0} L_{is}^{0(1-\rho_{is})}}{r_{is}^{0} K_{is}^{0(1-\rho_{is})} + w_{is}^{0} L_{is}^{0(1-\rho_{is})} + z_{is}^{0} h_{is}^{0(1-\rho_{is})}} \right) \quad \forall_{is} \tag{3.52}$$

$$\delta_{h_{is}} = \left(\frac{z_{is}^{0} h_{is}^{0(1-\rho_{is})}}{r_{is}^{0} K_{is}^{0(1-\rho_{is})} + w_{is}^{0} L_{is}^{0(1-\rho_{is})} + z_{is}^{0} h_{is}^{0(1-\rho_{is})}} \right) \quad \forall_{is} \tag{3.53}$$

The scaling coefficient in the CES function in equation 3.14 is then calibrated as:

$$\gamma_{is} = \frac{x_{is}^{0}}{\left(\delta_{k_{is}} K_{is}^{0} + \delta_{l_{is}} L_{is}^{0} + \delta_{h_{is}} h_{is}^{0}\right)^{\frac{1}{\rho_{is}}}} \tag{3.54}$$

The calibration of the CES for consumption, imports, and CET for exports follows the same approach as described above. The coefficients for the Leontief-type production functions used in equation (3.15) are calibrated as:

$$aa_{is} = \frac{E_{is}^{0}}{h_{is}^{0}} \quad \forall_{is} \tag{3.55}$$

[28] The values for the factor inputs used in the calibration are the original ones from the SAM. These values are used to derive the input share coefficients in each country.

$$bb_{is} = \frac{W_{is}^0}{h_{is}^0} \qquad \forall_{is} \qquad (3.56)$$

In choosing the values for the specified functional forms, there are no rules governing what elasticities should be used for the calibrations. For any calibration, however, one has to ensure that the economy is in equilibrium for the chosen base year. If the initial SAM is not balanced, it should be adjusted to replicate the equilibrium values before the calibration process is used. When the calibration is successful, the model is used to perform comparative static analyzes by varying the exogenous variables in the percentage factor and recording their impact on the endogenous variables (Shoven and Whalley, 1992).

After calibration, equations (3.13), (3.14), (3.28) and (3.32) were combined with the other equations specified in section 3.3.2 to solve the BNW-CGE model.

3.3.6 The BNW-CGE Model's Solution

The Blue Nile Water CGE model has a total of 55 equations and 54 endogenous variables in each country (Appendix I). All these equations are inter-dependent through the equilibrium conditions specified in the model. As CGE models are built on Walras' Law, a feasible outcome can be achieved if any one of the market-clearing conditions is ignored and the model becomes a square which can be fully solved (Robinson and Gehlhar, 1995). The model's optimization process leads to a unique outcome, as it seeks to satisfy numerous demand and supply equations with non-decreasing prices and quantities. However, the current model departs from the traditional neoclassical CGE model in the sense that land and water are incorporated into the model and are specified as a linear cost function (i.e., equation 3.21), with separate supply constraints. The price of any particular sub-factor can be zero, but not all prices can be zero since equation 3.18 only works with prices of inputs in the profit function. The BNW-CGE model used in this study operates on the competitive economy, which ensures optimal profit is achieved subject to the various constraints specified, including the price of land-water aggregate (z_{is}^h). Finally, the mechanism of the model is such that the price of the land-water aggregate input must be equal to the sum of the prices of its components (i.e., prices of land and water utilized).

3.3.7 Equilibrium Solution and Model Validation[29]

As explained in the preceding section, the BNW-CGE model developed in this study used exogenous elasticity values to calibrate the behavioural production and consumption functions in a multi-country setting. These functions were calibrated to replicate the equilibrium quantity values in the SAM as presented in section 3.3.4.1. In order to use the solution of the BNW-CGE model for policy analysis, there is the need to ensure that the calibration approach enables the model to replicate the benchmark values in the SAM. The calibrated functions were then combined with other functions to solve the BNW-CGE model.

In the BNW-CGE model, the prices and quantities are endogenous variables. Therefore, their equilibrium values were computed from the model. Model validation is carried out by solving the model without introducing any policy changes into the system, and checking whether the model reproduces the economy's base-year solution. Model calibration is considered successful when the deviations of the equilibrium solutions from the observed values reported in the SAM are small. Given the restrictive theoretical and empirical assumptions about certain parameters, which were nonetheless necessary for calibration and model solution, it is possible for equilibrium solution to reproduce the actual values observed in the SAM with errors. Several results were obtained from the BNW-CGE model, but the validation analysis focuses on quantities, incomes and prices because of the study's objectives.

Table 3.9 shows a comparison of the observed quantities in the SAM with the equilibrium model solution. Looking at the values, the general trends of the equilibrium quantities in our model are slightly different from the observed values in the SAM. The equilibrium GDP value for Egypt is greater than the observed value in the SAM, while the GDPs for Sudan and Ethiopia are smaller than the observed values. Also, sectoral agricultural value-added outputs are slightly higher than observed values for all sectors except for services in Ethiopia. As reported in Table 3.9, in Egypt, the sectoral agricultural value-added output is 3 percent greater than the observed value, while 0.6 percent and 2.0 percent deviations are seen for Sudan and Ethiopia, respectively. Similar differences are observed for the value-added outputs of the other sectors in all countries. A disparity between model solution and observed values is seen for the intermediate input services

[29] In addition to the explanations provided in the text, rigorous routine checks were conducted to correct any errors in the GAMS code. Also, all equations were checked for misspecifications and other minor mathematical errors.

in all the countries. In addition, differences are observed for both the domestic and composite sectoral outputs in all the countries (Table 3.9). It is not surprising to see this difference in the observed values and the equilibrium model results. One possible explanation for these disparities might be the choice of production elasticity values used in the calibration of the CES functions. As these values were exogenous in the model, it is possible that when they were combined with other values in the model, the model solution could be higher or lower as shown in Table 3.9.

In evaluating the equilibrium solution on imports and exports, sectoral imports are greater than the equilibrium solution in Egypt and Sudan. In Ethiopia, however, a lower value is observed in the imports from the agricultural sector while higher imports are seen in other sectors relative the observed model values. A similar trend is observed for the sectoral exports in Egypt and Sudan, but a variation is seen in the sectoral exports in Ethiopia. The differences in these results could be attributed to the exogenous trade elasticity values used to calibrate the Armington functions of the domestic production and trade sectors of the countries.

Given the solution for the public and private incomes, the equilibrium solution is less than the observed values in Egypt and Ethiopia, but a greater value is seen for Sudan (Table 3.10). In all cases, the differences between model solution and the observed values are less than 5 percent. These differences could be attributed to the use of exogenous direct and indirect tax variables in the general equilibrium model. Also, this dispersion in the equilibrium solution and the observed values are respectively explained by, on one hand, the fact that the quantity of public consumption is assumed to be fixed in the model; and, on the other hand, the specific way gross nominal investment is determined in line with the savings-investment closure in the model.

With regard to household consumption, we compare the equilibrium solution to the observed values. In Egypt, a variation of 1.2 up to 4.6 percent is seen, but a sectoral difference of 3 percent is found in Sudan. A consistent trend is not observed in Ethiopia.

Table 3.9 Comparison of the Observed and Calibrated Quantity Results [a]

Countries	Egypt			Sudan			Ethiopia		
Quantity	Observed values	Model Results	Difference(in percentages)[a]	Observed values	Model Results	Difference(in percentages)	Observed values	Model Results	Difference(in percentages)
GDP	264.164	264.24	0.027	627.723	627.655	-0.011	160.140	159.920	-0.139
Value added: Agriculture	42.325	43.638	3.009	293.057	294.735	0.569	57.591	58.886	2.199
Industry	59.236	60.314	1.787	87.918	87.237	-0.781	10.836	11.233	3.534
Services	137.938	135.900	-1.501	198.657	192.552	-3.171	25.606	25.962	1.371
Intermediate input: Agriculture	19.394	20.229	4.128	64.684	62.484	-3.521	6.563	6.546	-0.260
Industry	100.577	102.720	2.090	122.567	118.925	-3.062	9.175	9.374	2.123
Services	74.711	77.276	3.319	139.685	138.788	-0.646	48.053	48.562	1.048
Domestic output: Agriculture	61.719	60.915	-1.320	359.344	357.797	-0.432	64.154	64.845	1.066
Industry	161.000	167.250	3.737	219.222	218.141	-0.496	20.092	20.135	0.214
Services	213.813	217.870	1.860	341.374	341.377	0.001	102.315	102.310	-0.003
Composite good: Agriculture	67.346	69.033	2.444	361.816	361.837	0.006	58.122	56.011	-3.769
Industry	188.315	194.400	3.131	234.189	230.926	-1.413	56.727	55.580	-2.064
Services	56.727	58.905	3.697	347.699	348.457	0.218	98.694	99.669	0.978
Imports: Agriculture	5.912	6.034	2.022	28.196	28.265	0.244	3.098	2.995	-3.439
Industry	48.009	49.647	3.299	90.362	91.726	1.487	37.491	38.892	3.602
Services	8.172	8.471	3.530	6.359	6.377	0.282	3.841	3.893	1.336
Exports: Agriculture	0.285	0.296	3.716	25.724	25.727	0.012	0.987	0.978	-0.920
Industry	20.694	20.913	1.047	75.395	75.423	0.037	0.856	0.861	0.581
Services	33.902	34.934	2.954	0.034	0.035	2.857	7.670	7.494	-2.349

a: Values are in billions of constant Egyptian Pounds (EGD), Ethiopian Birr (ETB) in billions and constant Sudanese Pound (SDG) millions. Also, values in the table represent the contribution to GDP for the respective countries. The deviations represent percentage difference between the equilibrium solution with the calibrated elasticity values and the observed values reported in the SAM. This method is used because there are not enough data points to perform any rigorous statistical analysis. Based on the calibration approach of Donigian (2002), an acceptance region for model calibration can be classified as: (a) 5-10 percent difference (very good results), 10-15 percent difference (good results) and 15-20 percent difference (fair results).

In Ethiopia, the equilibrium solution for the agricultural sector is 1 percent lower than the observed value, but differences of 1.5 percent and 2 percent are observed in the industrial and services sectors, respectively. These differences in the results may appear because household demand functions were assumed to have a homogenous relation between disposable income and expenditure.

Turning to the factor payments account and performing similar analysis as before, the equilibrium solution in Egypt is 2 percent higher than the observed solution. Similar variations are observed in Sudan and Ethiopia. In Sudan, the equilibrium solution is higher for the agricultural and industrial sectors while a lower value is seen in the service's sector. Conversely, in Ethiopia the equilibrium solution is higher compared to the observed values in the industrial and services, but a lower value is observed in the agricultural sector (Table 3.10). A possible explanation could be from the exogenous water and land values used in the calibration of the total output from land, which is then used in the CES function to model the aggregate production in each country. Also, as factor prices are assumed to be in equilibrium in the general equilibrium market-clearing processes, it is possible that land and water prices used in the calibration are volatile and this may have contributed to the differences in the equilibrium solution and the observed values.

To reiterate, prices in the base year are normalized to unity for calibration purposes. This implies monetary values can be interpreted as physical quantities in the benchmark year. This follows the Walrasian general equilibrium framework, whereby relative prices are assumed to be the only force that determines the flow of quantities and factors in the economy. The equilibrium prices from the model and the observed values are presented in Table 3.11. As shown in the table, the equilibrium prices are slightly different from the observed values in all countries except for export prices for services in Egypt and Sudan. Also, there is no difference in the equilibrium industrial import price and observed price in Egypt. One possible explanation for this might be the role of market-clearing processes which are features of the general equilibrium model and also, how prices are volatile in these economies.

Results presented in this section show that in all cases, there is a moderate difference between the equilibrium solution and the observed values in the SAM. As expected, this dispersion could be associated with the model assumptions and the elasticity values used in calibrating various parameters of the model. A similar magnitude of dispersions between equilibrium solution and observed values have been reported by Ko (1985), who used an inter-regional CGE model to test the performance of the Korean economy and IrLan (2011), who used an inter-regional CGE model to measure the impact of trade variables on the economy of Indonesia. Robinson et al. (2008) also found a difference in equilibrium model solution and observed values in the SAM with regard to their work on the value of the Aswan High dam in Egypt, but they claimed the differences were mainly due to the method of model closure selected.

A review of hydrological studies shows that calibration results can be grouped into three main acceptance ranges. These are: (1) from 5-10 percent difference is classified as very good, (2) 10-15 percent difference is classified as good, and (3) 15-20 percent difference is classified as fair calibration results. Given that all the differences in the equilibrium solution and the observed values reported in this study are within the acceptance range of the first criterion, it is concluded that the model has successfully replicated the benchmark equilibrium values. In addition, because the magnitudes of the differences are not very high, the base model results can therefore be considered as a good departure point for the impact analysis of the different policies. The baseline equilibrium results are detailed in the next section to help compare changes to the counterfactual equilibria for the different water allocation policies. With these differences in the model results and observed values, a sensitivity analysis would be conducted to examine the robustness of the results for policy analysis in the basin.

Table 3.10 Comparison of the Observed and Calibrated Income Results [a]

Countries	Egypt			Sudan			Ethiopia		
Income Impacts	Observed values	Model Results	Difference (in percentages)	Observed values	Model Results	Difference (in percentages)	Observed values	Model Results	Difference (in percentages)
Income									
Public	49.961	48.605	-2.790	94.209	98.417	4.276	18.179	18.022	-0.871
Private	192.664	188.610	-2.152	440.37	451.234	2.408	111.988	111.050	-0.847
Household consumption									
Agriculture	30.691	29.348	-4.576	297.653	301.438	1.256	53.980	53.332	-1.215
Industry	60.608	58.679	-3.287	68.057	68.705	0.943	29.180	29.644	1.565
Services	101.365	100.130	-1.229	74.660	76.822	2.814	28.828	29.533	2.387
Factor income									
Labor	77.756	79.099	1.698	151.421	159.139	4.850	59.776	59.017	-1.2861
Capital	141.685	144.22	1.756	359.751	362.009	0.624	20.529	21.177	3.059
Land	20.058	20.375	1.556	68.460	67.000	-2.179	13.728	13.862	0.967

a: Values are in billions of constant Egyptian Pound (EGD), constant Ethiopian Birr (ETB) billions and constant Sudanese Pound (SDG) millions. Also, values in the table represent the contribution to GDP for the respective countries. The deviations represent percentage difference between the equilibrium solution with the calibrated elasticity values and the observed values reported in the SAM. This method is used because there are not enough data points to perform any rigorous statistical analysis. Based on the calibration approach of Donigian (2002), an acceptance region for model calibration can be classified as: (a) 5-10 percent difference (very good results), 10-15 percent difference (good results) and 15-20 percent difference (fair results).

Table 3.11 Comparison of the Observed and Calibrated Price Results [a]

Countries	Egypt			Sudan			Ethiopia		
Prices Changes	Observed values	Model Results	Difference(in percentages)	Observed values	Model Results	Difference(in percentages)	Observed values	Model Results	Difference(in percentages)
Value added : Agriculture	0.968	1.001	3.297	0.943	0.921	-2.389	0.936	0.903	-3.654
Industry	0.999	1.047	4.585	0.817	0.857	4.667	0.906	0.916	1.092
Services	0.956	0.950	-0.632	0.987	0.995	0.804	0.998	0.994	-0.402
Intermediate input: Agriculture	1.000	1.052	4.943	1.000	1.010	0.990	1.000	1.020	1.961
Industry	1.000	1.032	3.101	1.000	1.036	3.475	1.000	1.017	1.672
Services	1.000	1.018	1.768	1.000	1.024	2.344	1.000	1.023	2.248
Domestic output: Agriculture	1.000	0.990	-1.010	1.000	1.010	0.990	1.000	0.967	-3.413
Industry	1.000	0.997	-0.301	1.000	0.959	-4.275	1.000	0.979	-2.145
Services	1.000	1.016	1.575	1.000	1.004	0.398	1.000	0.966	-3.520
Composite goods: Agriculture	1.000	1.006	0.596	1.000	1.004	0.398	1.000	1.003	0.299
Industry	1.000	1.046	4.398	1.000	0.981	-1.937	1.000	1.009	0.892
Services	1.000	1.006	0.596	1.000	1.008	0.794	1.000	1.002	0.200
Imports: Agriculture	1.000	0.991	-0.908	1.000	0.994	-0.604	1.000	0.978	-2.249
Industry	1.000	1.000	0.000	1.000	1.006	0.596	1.000	1.014	1.381
Services	1.000	1.001	0.100	1.000	1.004	0.398	1.000	1.002	0.200
Exports: Agriculture	1.000	1.001	0.100	1.000	1.016	1.575	1.000	1.004	0.398
Industry	1.000	1.002	0.200	1.000	1.047	4.489	1.000	1.002	0.200
Services	1.000	1.000	0.000	1.000	1.000	0.000	1.000	1.022	2.153

a:Values were computed by checking the difference between the two results. The method was used because there are not enough data points to perform any rigours statistical analysis. The deviations represent percentage difference between the equilibrium solution with the calibrated elasticity values and the observed values reported in the SAM. This method is used because there are not enough data points to perform any rigorous statistical analysis. Based on the calibration approach of Donigian (2002), an acceptance region for model calibration can be classified as: (a) 5-10 percent difference (very good results), 10-15 percent difference (good results) and 15-20 percent difference (fair results).

3.4 Results and Discussions

This section deals with the main findings of the study and discusses the relevant policy implications for Egypt, Sudan and Ethiopia. In particular, the various comparative static results obtained from the BNW-CGE model are presented and discussed. Before presenting the main results of the study, the scenarios used in the simulation analysis are introduced and discussed in relation to the study's objectives. The impacts of water reallocation on the economies of the countries are then outlined with a focus on the changes in their Gross Domestic Products (GDPs). Sectoral impacts of water reallocation are also discussed as well as trade outcomes. Subsequently, the impacts of water reallocation on prices are discussed and outlined in this section. The section ends with a summary of the main results of water reallocation under certainty conditions.

3.4.1 Definition of Experiment for BNW-CGE Model

The comparative static simulation experiments discussed below show the impacts of changing the current water policy and deriving new equilibrium outcomes for the countries in the basin. The policy changes are based on the current water treaty governing the Nile River Basin. In order to simulate the impact of water reallocation in the basin, one key experiment relevant to the current debate in the basin is performed. This experiment (SIM_1) deals with changes in the economies of the countries when the current treaty governing the basin is altered. In this experiment, the following questions are addressed:

(a) What if the historical water right that has been governing the basin is altered to favor Ethiopia?

(b) What would be the economic impacts of such a water reallocation?

(c) Are there feasible strategies for the countries to mitigate associated impacts from reallocation, if any?

Historically, Egypt and Sudan, through the Agreement of 1959, have annual average allocations of 55.5 BCM and 18.5 BCM respectively, with no allocation to Ethiopia (Awulachew et al., 2008). However, as stated in this agreement, it is possible to reallocate water among the riparian countries if any of the states other than Egypt and Sudan claim a share in the Nile waters. Egypt and Sudan are exempted because they have agreed to jointly consider and reach one unified solution regarding any claims (Arsano, 2011).

Eventually, if reallocation is accepted, the agreed amount of water shall be deducted from the allocations of the two countries in equal parts, as calculated at the Aswan High Dam in Egypt. Currently, Ethiopia requires six BCM to fully complete pending water storage projects, especially investments in hydropower development. Thus, if all projects are implemented in Ethiopia, then the current annual allocation for Egypt and Sudan would be reduced to 52.5 BCM and 15.5 BCM, respectively. This first experiment examines the economy-wide impact of this water reallocation, given the base allocation (i.e., 1959 Agreement). The model imposes the initial "shock" of water reallocation on the production functions and then solves for new equilibrium values of all the endogenous variables, such as sectoral outputs, composite goods supply and trade outcomes. In the BNW-CGE model, producers maximize their profits based on the value-added prices for their products. Because of this, it is expected that reducing water could negatively affect aggregate production in Egypt and Sudan, but it may have positive effects in Ethiopia, all things being equal.

3.4.2 Results from Experiment One: The Impact of Water Reallocation on GDP

This section presents simulation results for experiment one and compares with the baseline results. The analysis follows the logic of the CGE model principles as outlined in Section 3.3.2. An exogenous shock affects the quantity ("real") variables, causing imbalances between supply and demand in the respective countries. The equilibrating variables (i.e., the domestic endogenous prices) then adjust in the system to establish new equilibria in each country. Consequently, most price changes are triggered by changes that occur in the quantity variables, while the resulting equilibrium real values can be explained in terms of the adjustments (or changes) in the price variables. In a general equilibrium framework, the solution values for the endogenous variables naturally contain direct and indirect impacts of the introduced shocks. The indirect impact on a single variable is reflected back from the resource constraints that represent the model's equilibrium conditions. In any event, it is difficult to establish the exact causality relationships between the shocks and the chain of repercussions. However, it is safe to assume that the direct impacts are bigger than the indirect impacts. This underscores the system's stability condition. To this extent, an approximate causality relationship can be established between the "shocks" and the intended impacts of water reallocation.

Altering the current water allocation treaty governing the Nile River Basin leads to a reduction in outputs of the major sectors of the economy, but higher values are expected in the agricultural sectors, which are major water users. The alternative water allocation leads to a real decrease in the GDP of Egypt and Sudan by 0.5 and 0.06 percent, respectively, while there is a 3.4 percent increase in Ethiopia's GDP (Table 3.12). The changes observed in the GDPs with the reallocation are driven by the assumption that national product markets function efficiently in the countries. To elaborate on this point, when production losses occur within the affected sectors of the economy because of water shortages, the affected sectors could experience a decrease in demand for their product. Thus, while GDP in Egypt and Sudan is negatively affected, Ethiopia experiences gain in production as resources are shifted to other affected sectors within the economy. Also, it is not surprising to observe that the GDP of Egypt relatively declines more than Sudan, even though both economies highly depend on the Nile River, as explained in section 3.3.1. Egypt has no effective rainfall and the economy depends on the reliable water supply from the Aswan High Dam. Most of the allocated water for Egypt is used in irrigated agriculture. Hence, the economy relies on the agriculture sector, which contributes 16 percent of the GDP and 20 percent of all foreign exchange earnings (ENTRO, 2008).

Although the economy of Sudan depends on the agriculture sector as well, the use of water is not as binding as in Egypt. Alterations in these GDPs are reflected by changes in these countries' sectoral outputs. The next section of the study deals with the impacts of reallocation on the three main sectors identified for the countries as well as the impacts on goods supply and trade effects.

3.4.2.1 Impact of Water Reallocation on Sectoral Outputs

Table 3.12 summarizes the impacts of the simulated policy and price changes on sectoral aggregate variables, such as domestic output, composite good supply, imports and exports. The sectoral analysis starts with percent changes in the value -added output, which is the GDP at the factor cost. When water is a constraint to production, the value-added output of the agricultural sector in Egypt and Sudan decreases and the opposite effect occurs in Ethiopia (Table 3.12). These results are as expected, as simulation results show that agricultural production levels are influenced by water reallocation. For example, value-added output in the agricultural sector decreases by 11.7[30] percent in Egypt (43.638 billion EGP to 39.072 billion EGP) and 8.8 percent in Sudan (294.735 million SDG to 270.790 million SDG) while Ethiopia experiences a 9.1 percent increase (58.886 billion ETB to 64.790 billion ETB). The decline in agricultural value-added output is partly due to the increased competition for other productive resources, such as capital and labor, which leads to an increase in the output of the industrial and services sectors as well. The simulation results show that a reduction in water leads to a 2.8 percent rise in Egypt's industrial output (60.314 billion EGP to 62.039 billion EGP) and 3.2 percent rise in Sudan (87.237 million SDG to 90.078 million SDG). The total increase in the output of these sectors could not offset the total loss in the agricultural sector, however, and this may be attributed to the differences in labor requirements. While the agriculture sector employs most of the unskilled laborers in these countries, the other sectors require more medium and highly skilled laborers. These differences could be attributed to the disparities in wages paid to laborers in these countries. Intuitively, it appears that the wages of an unskilled laborer decline while the wages of medium and highly skilled laborers increase as a result of alterations in the current water allocation schemes. As expected, the shift from agriculture to other sectors causes a slight decline in the economy-wide wage for the different skilled labor groups and in the returns to capital. This shift raises the demand for water in the agricultural sector, the value of which rises because water is reallocated to other countries' water, all things being equal. The decrease in water causes its price to increase in the affected countries, thus favoring the use of it for irrigating less water intensive crops.

Ethiopia's increased water allocation may help its agriculture sector to employ more unskilled labor and possibly use low-capital-intensive technologies. This increases the demand for agricultural land. Returns from the land increase as a result of the water scarcity. As a result, producers in the recipient regions in the country would use newly irrigated lands to shift production from low-valued to high-valued crops. This may be possible as it has happened in South Africa, where irrigators in the Eastern Cape use transferred water to grow high-valued crops such as citrus. On the other hand, irrigators in the two Orange River Basins in South Africa

[30] Three decimal places are used in the accompanying tables to present the absolute values from the simulation and the percentage changes from the baseline scenario and the alternative scenario. However, for ease of presentation, all the percentage change values will be presented in this section to the nearest whole number or one decimal place.

reacted to lower irrigated water supply and rising irrigation water prices by increasing dry-land production of low valued crops such as cereals and fodder crops, and decreasing irrigated vegetable production (Hassan et al., 2008).

From the results reported in Table 3.12, it can be observed that reallocating water within the basin would have a diverse effect on the intermediate input services. The simulation results show a decrease for intermediate input services for the agricultural sector in all countries except for Ethiopia. However, intermediate input services for industrial sectors increased up to 2.3 percent for Egypt (102.724 billion EGP to 105.111 billion EGP) while Sudan and Ethiopia experience 6.2 (118.925 million SDG to 126.728 million SDG) and 1.2 (9.374 billion ETB to 9.489 billion ETB) percent increases, respectively. Similarly, when potential water reallocation occurs, intermediate input for service sectors increase for all countries (Table 3.12). The combined effects of the water reallocation on value-added and intermediate inputs are transmitted through substitution and income effects to the domestic output production. Therefore, it is not surprising to see a decrease in the domestic output of the agriculture sectors in Egypt and Sudan. However, Ethiopia experiences an increase of about 7.7 percent (64.845 billion ETB to 70.229 billion ETB). Concurrently, the output of the other two sectors increases up to 8 percent for Egypt (347.556 billion EGP to 438.538 billion EGP) and 2 percent for Sudan (438.726 million SDG to 685.864 million SDG) while a substantial increase is observed in these sectors in Ethiopia (28 percent).

3.4.2.2 Impact of Water Reallocation on Imports and Exports

The Armington specification specified in section 3.3.2 makes it possible to divide overall consumption into domestic and imported good consumption. This specification makes it possible to examine the substitution and income effects among consumers on the impacts of the policy simulation in the respective countries. Relative to the baseline results, imported agricultural goods became less expensive in Egypt and Sudan. This leads to an increase in their consumption (Table 3.12). This suggests that consumers in each country can purchase more units of imports per unit of exports; thus the terms of trade would improve. The simulation results show a 4.3 percent increase in imported goods in Egypt (6.034 billion EGP to 6.304 billion EGP) and a 0.1 percent increase in Sudan (28.265 million SDG to 28.289 million SDG), but a decrease of 14.1 percent in Ethiopia (2.995 billion ETB to 2.626 billion ETB). Similarly, on the supply side, exports in these sectors decline except in Ethiopia (Table 3.12). Regarding composite goods supply, the simulation results show an increase in all countries. The overall increase in goods supply in Egypt and Sudan could be explained by the increasing import levels because of the relatively higher export prices. These results suggest that as import prices become cheaper relative to exports, imports increase while exports decrease.

Thus, contrary to expectations in Egypt and Sudan with reallocation, the composite good supply increases in each country. With the sectoral impact analysis, for instance, the relatively high agricultural import demand in Egypt and Sudan occurs because consumers increase demand for these products, and producers in these countries are forced to decrease their domestic production in this sector (Table 3.12). This decrease in production could be driven by the increase in imports from the rest of the world. In Egypt and Sudan, these negative effects on trade could be offset through adjustments in the national savings account or by increasing the domestic agricultural output, which can be realized if producers adopt efficient farming practices and the government provides cost-effective support programs (i.e., crop insurance, income stabilization, etc.). In Ethiopia, an increase in domestic agricultural output occurs because factors move from others sectors to the agricultural sector, with water reallocation.

Table 3.12 Impact of Water Reallocation on Quantity Changes for Experiment One[a]

Country	Egypt			Sudan			Ethiopia		
Impacts of quantity changes with water reallocation	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline
Annual water allocations	*55.5bcm*	*52.5bcm*		*18.5bcm*	*15.5bcm*			*6bcm*	
GDP	264.235	262.985	-0.475	627.655	627.264	-0.062	159.918	165.557	3.406
Value added: Agriculture	43.638	39.072	-11.686	294.735	270.790	-8.843	58.886	64.790	9.113
Industry	60.314	62.039	2.781	87.237	90.078	3.154	11.233	12.834	12.475
Services	135.898	138.001	1.524	192.552	200.987	4.197	25.962	27.806	6.632
Intermediate input: Agriculture	20.229	17.891	-13.068	62.484	61.032	-2.379	6.546	7.216	9.285
Industry	102.724	105.111	2.271	118.925	126.728	6.157	9.374	9.489	1.212
Services	77.276	84.189	8.211	138.788	140.513	1.228	48.562	49.923	2.726
Domestic output: Agriculture	60.915	60.239	-1.122	357.797	356.428	-0.384	64.845	70.229	7.666
Industry	167.251	180.305	7.240	218.141	220.585	1.108	20.135	27.075	25.633
Services	217.866	220.672	1.272	341.377	344.487	0.903	102.312	104.633	2.218
Composite good: Agriculture	69.033	70.205	1.669	361.837	367.154	1.448	56.011	59.512	5.883
Industry	194.401	200.589	3.085	230.926	233.329	1.030	55.580	58.405	4.837
Services	58.905	59.600	1.166	348.457	349.399	0.270	99.669	102.438	2.703
Imports: Agriculture	6.034	6.304	4.283	28.265	28.289	0.085	2.995	2.626	-14.052
Industry	49.647	54.771	9.355	91.726	90.728	-1.100	38.892	37.460	-3.823
Services	8.471	8.964	5.500	6.377	6.451	1.147	3.893	3.536	-10.096
Exports: Agriculture	0.296	0.257	-15.175	25.727	25.142	-2.327	0.978	1.212	19.307
Industry	20.913	19.374	-7.944	75.423	75.140	-0.377	0.861	0.919	6.311
Services	34.934	33.337	-4.790	0.035	0.033	-6.061	7.494	7.570	1.004

Source: Author's Simulation Results. a.Values are in billions of constant Egyptian Pounds (EGP), constant Ethiopian Birr (ETB) in billions and constant Sudanese Pound (SDG) in millions. Also, values in the table represent the contribution to GDP for the respective countries. The reported results pertain to the simulation of altering the current allocation scheme governing the Nile River Basin.

3.4.2.3 Impact of Water Reallocation on Price Changes

The variations in sectoral outputs reported in the preceding section are consistent with the changes in sectoral value-added prices. In this experiment, the prices of value-added goods increase in the agricultural sectors of Egypt and Sudan. As shown in Table 3.13, the value-added price of agricultural output increases compared to the baseline results for Egypt and Sudan. A reduction in domestic output discourages agricultural production and pushes up domestic prices in equilibrium. This discourages agricultural exports in favor of imports to the domestic market. The changes in the domestic prices as well as the import prices impact on composite good prices in the economy. The simulation results reveal that the price of composite goods in the agricultural sector increases above the baseline results in all countries, except in Ethiopia. In Ethiopia, the increase in water allocation encourages agricultural exports in favor of the domestic market, but the actual demand of these goods depends on the substitution and income effects on the consumers in the country.

While the price of agricultural goods delivered to the domestic market also decreases, the decrease in agricultural prices is relatively less than the decrease in domestic agricultural prices, providing an incentive to increase agricultural exports in Ethiopia. A higher relative export price induces an increase in exports at the expense of the domestic good. In this regard, the productive sectors in Ethiopia supply more exports and reduce units of the domestic good, as shown in Table 3.13.

Regarding domestic output prices, the simulation results show an increase in agricultural sector prices in Egypt and Sudan, while a decrease is observed for Ethiopia. Changes in domestic support and import subsidies directly affect the price of domestic products. On the other hand, because of the small country assumption used in the model, it is not surprising to observe slight changes in the export prices of goods from these countries, after water reallocation. The price effects in the economy are also observed in the changes in import and exports in the respective countries (Table 3.13).

Table 3.13 Impact of Water Reallocation on Price Changes for Experiment One[a]

Countries	Egypt			Sudan			Ethiopia		
Impact of prices changes with water reallocation	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline
Water allocations	55.5bcm	52.5bcm		18.5bcm	15.5bcm			*6bcm*	
Value added: Agriculture	1.001	1.278	21.674	0.921	1.032	10.756	0.903	0.700	-29.000
Industry	1.047	1.008	-3.869	0.857	0.770	-11.299	0.916	0.772	-18.653
Services	0.950	0.945	-0.529	0.995	0.992	-0.302	0.994	0.914	-8.753
Intermediate input: Agriculture	1.052	1.072	1.866	1.010	1.342	24.739	1.020	0.908	-12.335
Industry	1.032	0.798	-29.323	1.036	0.673	-53.938	1.017	0.895	-13.631
Services	1.018	1.000	-1.800	1.024	0.807	-26.890	1.023	1.006	-1.690
Domestic output: Agriculture	0.990	1.926	48.598	1.010	1.895	46.702	0.967	0.670	-44.328
Industry	0.997	0.721	-38.280	0.959	0.827	-15.961	0.979	0.670	-46.119
Services	1.016	0.950	-6.947	1.004	0.748	-34.225	0.966	0.843	-14.591
Composite goods: Agriculture	1.006	1.104	8.877	1.004	1.125	10.756	1.003	1.001	0.200
Industry	1.046	1.108	5.596	0.981	1.647	40.437	1.009	0.980	2.959
Services	1.006	1.228	18.078	1.058	1.122	5.704	1.002	1.000	0.200
Imports: Agriculture	0.991	0.972	-1.955	0.994	0.983	-1.119	0.978	1.191	17.884
Industry	1.000	0.802	-24.688	1.006	0.829	-21.351	1.014	1.565	35.208
Services	1.001	0.861	-16.260	1.004	0.936	-7.265	1.002	1.189	15.728
Exports: Agriculture	1.001	1.154	13.258	1.016	1.747	41.843	1.004	1.000	0.400
Industry	1.002	1.312	23.628	1.047	1.461	28.337	1.002	1.000	0.200
Services	1.000	0.915	9.290	1.000	1.301	23.136	1.022	1.117	8.505

Source: Author's Simulation Results. a. Based on the standard practice in CGE modeling, the base year prices were set to one in each country (Robinson et al., 1990; Hosoe et al., 2010). This is done to ensure that equilibrium is achieved in all markets across the countries. In most cases, the calibration results reproduced unitary prices for the sectors in each country and across the countries.

3.4.2.4 Impact of Water Reallocation on Aggregate Incomes

Table 3.14 reports water reallocation impacts on public and private incomes as well as factor incomes. With a cheaper relative price for the imported good in Egypt and Sudan, households consume more imported goods and less domestic goods. This may be due to the comparative price advantage for these goods relative to exports goods. The simulation results show household consumption of goods from the industrial and services sectors increase in all the countries. However, consumption of agricultural goods decline by 15.2 percent in Egypt (29.348 billion EGP to 25.465 billion EGP) and 3.6 percent in Sudan (301.438 million SDG to 291.017 million SDG), although consumption increases by 11.2 percent in Ethiopia (53.332 billion ETB to 60.063 billion ETB). Changes in the government's purchase of consumption goods exhibit the same pattern as changes in private consumption. As expected, these effects are transmitted to public and private incomes.

With water reallocation, public income decreases in Egypt and (to a lesser extent) in Sudan, while it increases in Ethiopia (Table 3.14). This result suggests that public income decreases because the consumption of imported goods increases relative to exports goods. This places considerable pressure on the current account balances of these countries, as they already run on deficit budgets. This means that consumers in these countries can purchase more units of imports per unit of exports. However, the benefits in terms of trade in the countries do not reflect positively in their value-added outputs. For example, there is an increase in industrial value-added output for the water reallocation regime. However, this slight industrial expansion is not able to offset the decline in agricultural output, possibly because of the differences in this sector's technologies and labor requirements.

With changes to water reallocation, factor payments change in all three countries. Payments for all factors decline in Egypt and Sudan while variations are observed in Ethiopia. Factors are mobile across sectors and substitution is possible except for land and water, which are modeled through the Leontief production function. This enables production factors to move from the sectors in which the production declines to the sectors in which it increases. On the other hand, because payment for production factors in agriculture is generally low, payment from the other sectors does not lead to a proportionate increase in the aggregate payment in each country.

The sectoral use of factors and returns to those factors relative to the baseline results are discussed below. As expected, the demand for labor declines in Egypt and Sudan while the increased availability of water in Ethiopia benefits the country and creates a labor shift to the agricultural sector. In Egypt, labor demand declines by 5.3 percent (79.099 billion EGP to 75.111 billion EGP), while a slight reduction is observed for capital. Similar changes are observed in Sudan (Table 3.14). The decline in capital is only possible because of the long-run assumption of capital mobility across sectors.

According to the long-run assumption regarding factor mobility, factors are attracted to sectors with relatively higher value-added prices or better value-added terms of trade. Conversely, a great variation is observed in the demand for land; this factor increases by 25.7 percent in Ethiopia (13.862 billion ETB to 18.662 billion ETB). Because agricultural land is specific to agricultural activities, the inter-sectoral mobility takes place within the agricultural sector. This outcome may be explained in terms of the relative change in value-added prices among agricultural sectors. It is possible that producers shift to use land to cultivate water-intensive crops with a high-market value for export, which in the long-run benefits Ethiopia's economy. Also, this finding is a function of the model where the unique characteristic of the Leontief production function produces the strong fixed relationship between the impact on the returns on land and the sub-factors of production, namely water and raw land.

Table 3.14 Impact of Water Reallocation on Income Changes for Experiment One[a]

Countries	Egypt			Sudan			Ethiopia		
Income Impacts	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline	Baseline results	Alternative Water Reallocation results	Percentage Change from Baseline
Water allocations	*55.5bcm*	*52.5bcm*		*18.5bcm*	*15.5bcm*			*6bcm*	
Income									
Public	48.605	34.708	-40.040	98.417	69.433	-41.744	18.022	21.303	15.402
Private	188.605	186.874	-0.926	451.234	437.07	-3.241	111.047	118.757	6.382
Household consumption									
Agriculture	29.348	25.465	-15.248	301.438	291.017	-3.581	53.332	60.063	11.207
Industry	58.679	59.276	1.007	68.705	69.364	0.950	29.644	31.801	6.783
Services	100.134	101.218	1.071	76.822	80.356	4.398	29.533	30.044	1.701
Factor income									
Labor	79.099	75.111	-5.309	159.139	150.465	-5.765	59.017	63.937	7.695
Capital	144.217	144.123	-0.065	362.009	359.952	-0.571	21.177	21.104	-0.346
Land	20.375	18.43	-10.553	67.000	64.253	-4.275	13.862	18.662	25.721

Source: Author's Simulation Results. [a] Values are in billions of constant Egyptian Pounds(EGP), constant Ethiopian Birr (ETB) in billions and constant Sudanese Pound (SDG) in millions. The reported results pertain to the simulation of the altering the current allocation scheme governing the Nile River Basin.

3.4.2.5 Summary[31]

In summary, the simulation results show changes in domestic prices with the alterations in water allocation. With reallocation of water, there is a change in prices and this leads to competition for productive resources among the four main sectors and substitution effects occur whereby some sectors gain and some sectors lose. Given the differences in imports and exports prices in Egypt and Sudan, certain sectors become competitive with increased exports. However, the increase in these sectors does not outweigh the decrease in agricultural sectors. In Ethiopia, an opposite effect is observed, where the agricultural sector output increases and sectoral output increases in all three sectors.

Domestic prices decrease with water relocation and this impact sectors that are water dependent. According to the Stolper-Samuelson theorem (1941), an increase in the relative price of one commodity raises the real return of the factor that is used intensively in the production of that commodity, and lowers the real return to the other factors. Thus, as water reallocation raises the price of water, the demand for less water-intensive goods increases. This, in turn, raises the returns to the factors used intensively to produce the less water-intensive goods (i.e., capital and labor) in Egypt and Sudan. However, the price increases for water are larger than the rental and wage increases for capital and labor. Intuitively, this indicates that domestic prices increase more in water-intensive sectors than in those sectors that use water less intensively, for example, the industrial and services sectors.

Before presenting the policy implications of the study, a sensitivity analysis is conducted to assess the magnitude of change in the results, when certain key parameters are altered. The aim of the sensitivity analysis is to recognize the uncertainty associated with assumed parameters of the model. The outcome of the sensitivity analysis should inform how sensitive model results are

[31] The potential impacts of water reallocation are presented in this study. These results show the aggregate economic impacts of water reallocation, when Ethiopia has full access to the Nile water for irrigation and hydropower developments. As mentioned in the introductory section, Ethiopia is currently developing one of the largest dams in Africa for hydropower generation. The dam is supposed to be completed in 2017. Egypt and Sudan are still resistant to the development of this large scale project on the Nile. Egypt requires more time to study this project and has asked for cooperation with Sudan and Ethiopia on the appropriate design for the dam and how to avoid reduction in the flow of the Nile. It is not clear if this dam will be commissioned as planned, given the position of the Egypt on the potential impacts of the Dam on its economy. Until the dam is commissioned, the results presented in this study are relevant and decision makers should invest policies necessary to mitigate negative impacts of water reallocation while promoting benefit-sharing as outlined in this study.

to changes in assumptions made about the parameters. If the model results do not change or slight changes are observed when we consider the range of reasonable assumptions used, then our analysis is robust and we can have greater confidence in the results. The next section deals with the sensitivity analysis conducted in this study.

3.4.2.6 Sensitivity Analysis

As mentioned in the preceding section, a sensitivity analysis is conducted to test the robustness of the results for policy implications. This is done because many of the parameters used to calibrate the production and consumption functions of the BNW-CGE are exogenous. An econometric estimation is often not possible for many of these model parameters, because of the magnitude of data requirements and also because the available data sets are usually poor or insufficient to implement the model. Since the BNW-CGE model encompasses structures describing various economic activities in the economies of the countries in the basin, many parameters (coefficients and exogenous variables) are included. It is unrealistic to examine the robustness of simulation results with respect to all the assumed parameter values in the model; instead, we focus on certain parameters relevant to the objectives of the BNW-CGE analysis and the key model features that are expected to affect the results most significantly.

The sensitivity analysis is carried out by assessing comparative static results under various assumptions about the different elasticity values. If the comparative static analysis shows significant variations, it means the model is sensitive and policy implications of the study should be confirmed to the elasticity values used in the model. The sensitivity analysis provides the model with partial equilibrium strength by allowing a *ceteris paribus* type of analysis, leaving all variables but one unchanged, making it easier to understand the workings of the general equilibrium model. Without the sensitivity analysis, it would be exceedingly difficult to unravel the complex and intertwined changes in the BNW-CGE model, in which all endogenous variables are determined simultaneously.

In conducting sensitivity analysis, a Monte Carlo approach or an ad hoc approach can be used to assess how changes in certain parameters affect the base case results. In a Monte Carlo approach, a probability distribution is attached to each parameter of interest and multiple simulations are performed. In each time of the simulation, changes occur in the parameters according to their probability distributions. This approach when used could provide an implicit probability distribution for the BNW-CGE model results to which appropriate confidence intervals can be assigned. This approach is useful because it has ability to take account of all the available information about the assumed values of the parameters. Also, the approach directly provides information about the spread of the statistical distribution of the realized output changes.

However, there are limitations in that not all parameters have been estimated in the study area. Thus, a distribution must be imposed for some parameters. Even in cases where estimates are available for some parameters, there is a wide range of values to choose from and given that there are so many parameters of the BNW-CGE model, a large number of simulations would have to be conducted and analyzed. Because of the above reasons, an ad hoc approach is used in this study. This approach involves selecting certain parameters from different sections of the model and altering them from the benchmark values by the same scalar factor or percentages, rather than performing experiments with individual parameters in a distribution.

As mentioned already, there are assumptions made about many parameters of the BNW-CGE model. However, the key parameters that are more likely to influence the model results are the exogenous elasticity values use to calibrate production and consumption functions. In the BNW-CGE model, the CES and CET production functions in equations (3.13 and 3.32) are calibrated based on exogenous elasticity values from previous studies. All other parameters in these functions were obtained from the SAM. Because these functions depend on the exogenous elasticity values, it is important to determine the extent of responsiveness of the base simulation results to different elasticity values. In order to obtain the impacts of the sensitivity results, a large number of permutations and combinations of elasticity values are required, due to the complexity in the nesting structures in the production and consumption functions of the BNW-CGE model. For simplicity, the elasticity values of the CES and CET functions are used to illustrate our results in this section.

In the BNW-CGE model, exogenous elasticity values are used to parameterise equations (3.13) and (3.32). These exogenous elasticity values enable us to calibrate the model to replicate the baseline values in the SAM. In the production sector, the σ_s was used to calibrate the CES production function of equation 3.13. This exogenous elasticity value models the substitution relationships between value-added output and the intermediate inputs of the production function. A reduction in this elasticity lowers the value-added output responsiveness and an increase magnifies supply responsiveness. A decrease in the elasticity widens the wedge between the value-added output and the prices of the intermediate inputs. Concerning the sensitivity analysis of the trade outcomes, ϖ_s was used to calibrate the CET production between exports and domestic demand of equation 3.32.

By increasing or decreasing the value of this parameter, we can examine the range over which the output changes. The original elasticity value (σ_s) in equations (3.13) constitutes the benchmark value for the CES production, while (ϖ_s) in equation (3.32) constitutes the benchmark value for the CET production function. The sensitivity analysis was conducted using the following procedure. First, the elasticity value for the CES production function was changed and the results were examined (Table 3.15). Secondly, the elasticity value for the CET production function was varied and the results were examined (Table 3.16). In all cases, the sensitivity analysis is conducted in a case where the elasticity value is 20 percent higher or lower than the benchmark values presented in section 3.3.4.3. This is done to provide a confidence interval for the original elasticity values. Although the confidence intervals for the elasticity values of CET and CES production functions are subjectively determined, they are consistent with elasticity values reported by previous studies (Pannell, 1997; Löfgren et al., 1996; Saddig, 2009; Hosoe et al., 2010; Kim and Hewings, 2011).

The results of the sensitivity analysis are shown in Tables 3.15 and 3.16. These results are discussed in terms of the impacts on quantities, and trade outputs where elasticity values played a significant role in the calibrating their respective production and consumption functions. As expected, the sensitivity analysis shows a slight variation in quantities when the benchmark elasticity values are changed. With the current changes, the GDP of Egypt increases by 0.5 while Ethiopia's GDP increases by 0.7. Contrary to expectations, there is no change in the GDP of Sudan. This finding indicates that there is no difference in assuming higher or lower elasticity values for the economic impact analysis in Sudan. The fact that there is no change in the GDP of Sudan further confirms that the change in the elasticity parameter does not impact the baseline results. In the case of Egypt and Ethiopia, because slight variations are observed in their GDPs, these findings suggest that the elasticity parameters do not greatly impact the baseline results as well.

At the sectoral level, there is a 6.2 percent increase (12.834 billion EGP to 13.464 billion EGP) in the value-added output of the industrial sector in Egypt, a 4.9 percent increase (62.039 billion ETB to 65.964 billion ETB) is observed for Ethiopia while a minor increase is observed in Sudan (Table 3.15). The trend of these results is consistent with the changes observed in the intermediate inputs, when the elasticity values were increased by 20 percent. On the opposite side, the value- added outputs of agricultural sector decrease more in Egypt and Ethiopia than in Sudan. Concerning intermediate input use, the sensitivity analysis shows a larger decrease in the service sector of Ethiopia than Egypt and Sudan. Output in all sectors is virtually insensitive to changes in the elasticity parameters, and changes in the magnitude of domestic output and composite good supply are minor (Table 3.15). Furthermore, increasing the elasticity value of the CET parameter has a lower impact on the industrial goods supply than on the other sectors. The impact of the sensitivity analysis appears to be restricted to production and trade sectors of the model, leaving the consumption sectors generally unaffected or minimally affected.

Simulation results pertaining to exports appear to be sensitive to the CET production function's increasing elasticity value. However, export results are, in general, less sensitive to changes in the CET parameter than imports are to changes in the CES production function parameter (Table 3.16). For instance, when the benchmark elasticity value is increased by 20 percent, there is a 2.3 (6.304 billion EGP to 6.449 billion EGP) percent increase in the agricultural imports in Egypt while a 1.2(0.257 billion EGP to 0.259 billion EGP) percent increase is observed for agricultural exports.

Table 3.15 Sensitivity Analysis of Quantity Impacts for Experiment One(σ_s) [a]

Quantity Impact Changes	20 Percent lower than benchmark results of alternative water reallocation (values are percentage change decrease from benchmark values)			Alternative Water Reallocation Results(Benchmark results from experiment one)			20 Percent higher than the benchmark results of alternative water reallocation(values are percentage change increase from benchmark values)		
Countries	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia
Water Allocations	*52.5bcm*	*15.5bcm*	*6bcm*	*52.5bcm*	*15.5bcm*	*6bcm*	*52.5bcm*	*15.5bcm*	*6bcm*
GDP	-0.022	-0.004	-0.001	262.983	627.264	165.557	0.473	0.000	0.664
Value added									
Agriculture	-3.477	-2.807	-4.367	39.072	270.790	64.790	2.615	0.954	0.851
Industry	-3.005	-0.098	-0.172	62.039	90.078	12.834	6.327	1.098	4.912
Services	-1.842	-4.381	-0.372	138.001	200.987	27.806	1.078	0.280	0.615
Intermediate input									
Agriculture	-0.902	-0.648	-0.153	17.891	61.032	7.216	0.123	0.011	1.850
Industry	-1.975	-0.325	-1.140	105.111	126.728	9.489	4.743	1.290	3.971
Services	-0.811	-0.075	-3.588	84.189	140.513	49.923	0.382	3.366	2.033
Domestic output									
Agriculture	-0.647	-1.998	-0.426	60.239	356.428	70.229	0.098	0.840	2.366
Industry	-0.292	-0.119	-5.252	180.305	220.585	27.075	4.993	0.124	6.567
Services	-0.215	-1.039	-0.380	220.672	344.487	104.633	0.687	1.840	0.574
Composite good									
Agriculture	-0.189	-0.003	-3.779	70.205	367.154	59.512	2.961	0.589	7.811
Industry	-0.029	-0.065	-0.210	200.589	233.329	58.405	0.360	0.035	0.173
Services	-2.010	-2.723	-0.366	56.600	346.399	102.438	1.144	3.262	0.228

Source: Author's Sensitivity Analysis Results. a. The benchmark values are in billions of constant Egyptian Pounds (EGP), constant Ethiopian Birr (ETB) in millions and constant Sudanese Pound (SDG) in millions. Also, values in the table represent the contribution to GDP for the respective countries. The reported results pertain to percentage difference due to changing the elasticity values used to parameterise the CES function in equation 3.13.

Table 3.16 Sensitivity Analysis of Trade Impacts for Experiment One (ω_s) [a]

Trade Output Impact Changes	20 Percent lower than benchmark results of alternative water reallocation (values are percentage change decrease from benchmark values)			Alternative Water Reallocation Results(Benchmark results from experiment one)			20 Percent higher than the benchmark results of alternative water reallocation(values are percentage change increase from benchmark values)		
Countries	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia
Water Allocations	*52.5bcm*	*15.5bcm*	*6bcm*	*52.5bcm*	*15.5bcm*	*6bcm*	*52.5bcm*	*15.5bcm*	*6bcm*
Imports									
Agriculture	-2.537	-0.687	-1.039	6.304	28.289	2.626	2.302	3.078	2.015
Industry	-1.411	-0.179	-2.768	54.771	90.728	37.46	4.011	2.559	3.232
Services	0.134	-3.119	-1.902	8.964	6.451	3.536	2.001	2.287	4.432
Exports									
Agriculture	-2.472	-2.978	-1.849	0.257	25.142	1.212	1.154	2.906	1.984
Industry	-2.530	-0.178	-0.218	19.374	75.14	0.919	2.585	0.829	0.109
Services	-0.945	-0.002	-0.866	33.337	0.033	7.570	1.780	0.000	2.961

Source: Author's Sensitivity Analysis Results. a. The benchmark values are in billions of constant Egyptian Pounds (EGP), constant Ethiopian Birr (ETB) in millions and constant Sudanese Pound (SDG) in millions. Also, values in the table represent the contribution to GDP for the respective countries. The reported results pertain to percentage difference due to changing the elasticity values used to parameterise the CET function in equation 3.32.

In Sudan, imports increase by 3.1(28.289 million SDG to 28.319 million SDG) percent while exports increase by 2.9 (25.142 million SDG to 25.873 million SDG) percent with a 20 percent increase in the benchmark elasticity values. A similar pattern of results are observed in Ethiopia with a change in the elasticity values. These findings reflect a combination of the switch to relatively cheaper imports at a higher level of elasticity and the dampening in the rise in domestic producer prices in the agricultural and other sectors.

Overall, the sensitivity analysis indicates that the model results are not sufficiently sensitive to cause concern about the simulation results and that there is limited difference in assuming higher or lower elasticity values for economic impact analysis in the countries. Thus, the policy implications to be drawn from the model results are not highly sensitive to the elasticity values used in the simulation analysis.

3.4.2.7 Policy Implications of Water Reallocation under Certainty Conditions

The simulation results presented under certainty conditions of water reallocation have implications for decision makers in the basin. This section presents the main outcomes of water reallocation and policy implications for the countries in the basin. Also, this section proposes policy options that three countries could adopt to improve the benefits of water reallocation.

The simulation results show that with water reallocation the GDP of Egypt and Sudan decrease by 0.5 percent and 0.06 percent, respectively while Ethiopia observes an increase of 3.4 percent in its GDP. The changes in the GDPs of these countries impact the sectoral value-added outputs, domestic output, imports and exports. The detailed analysis shows that the agricultural value-added output is the most affected sector in Egypt and Sudan because it is the largest user of water. The impact of decreased agricultural value-added output is reflected in increased imports in the countries because domestic prices increase relative to import prices. In Ethiopia, however, the increased water leads to positive impacts in the agricultural and the other sectors and it is not surprising to observe that its terms of trade improve. The composite goods supply increases in all the countries with water reallocation. In Egypt and Sudan, the increase in goods supply comes from increased consumption of imported goods while, in Ethiopia, this is possible because of the increased domestic output. In Egypt and Sudan, it is possible to mitigate the negative impacts of water reallocation through adjustments in savings or remittances. Alternatively, if these countries could cooperate and jointly developed water related projects in the basin, this strategy could help mitigate some of the negative impacts on Egypt and Ethiopia.

3.5 CGE Model and Impact of Risk of Water Reallocation

Similar to other CGE models, the BNW-CGE model presented in the preceding section is a deterministic model. The model assumes that the outcomes of water reallocation on the economies of the countries are certain. In this regard, a change in an exogenous parameter would have a certain impact on the endogenous variable. In a deterministic model, equilibrium is achieved by a set of prices and levels of quantities in each sector such that the market demand equals supply for all goods and services. Decision makers in the model are assumed to be rational and the model ignores risks associated with their decision making processes.

Alternatively, a stochastic model includes a random element that would influence the endogenous variables in the model. Stochastic models are more realistic because they are able to capture the uncertainties associated with certain behavioral parameters of the model. Stochastic analysis is important because the outcome of water reallocation is uncertain due to the random nature of the inflow of water into the Nile Basin. Decision makers require a more realistic model which would be able to capture the consequences of this inflow variable during water reallocation. The analysis conducted here demonstrates the benefits of incorporating risk into the decision making processes during water reallocation. Initially, this section deals with a brief introduction to risk analysis and a review of CGE model applications to risk. The methodology selected to measure risks associated with water reallocation in the basin is then presented and its strengths and weakness are outlined. Finally, the main results of the study where risk is incorporated are presented.

3.5.1 A Brief Review of CGE and Impact of Risks

Risk is a complex construct which can be defined in many different ways. One frequently cited definition comes from Knight (1921), who calls it a “measurable” uncertainty. Risk is a pervasive part of all actions. Within the field of economics, risk has played a role in various theories offered up by consumers and producers as well as in investment portfolio analysis (Hazell and Norton, 1986; Hardaker et al., 2004). Although uncertainty and risk are ubiquitous, in water resource allocation they constitute an essential feature of the production environment and arguably warrant a detailed analysis. Over the years, water policy makers have been able to base their allocation decisions on "under certainty" conditions. Policy makers have to deal with future probabilities of trends and events that are outside the scope of their mandate including rapidly evolving drivers of water demand and increasing climate variability. As water is an input to all economic and social activities, policy makers need management tools which reflect the wider consequences of their decisions over a long period of time (UNESCO, 2012).

This study seeks to model water reallocation under stochastic conditions with the focus on aggregate changes in outputs, incomes, and the trade sectors. Few studies have included risks and uncertainty in a CGE model. For example, Boussard and Christensen (1999) used a dynamic CGE model and examined risk associated with price variability in the Polish and Hungarian agricultural sectors. They also modeled the effects of risk on these countries and the ripple effects if they joined the European Union. Burfisher et al. (2000) incorporated a risk premium in the production component of a CGE model for North American countries and found minimal effects of direct payments on outputs.

In all of the above models, there are no explicitly stochastic variables and the models add risk aversion as leading to increased costs of production in a deterministic model (Harris and Robinson, 2001). Adelman et al. (1991) added this dimension to their CGE model and compared different trade strategies conducted by Yugoslavia in the 1980s under the same random shocks to import and export prices, workers' remittances and the exchange rate. In another example, Adelman and Berck's (1990) CGE model of Korea specifies random shocks to both world prices and food productivity. These models use repeated sampling methods to measure the means and variances of crucial variables such as household incomes and production. Harris and Robinson (2001) used a stochastic CGE model to examine the potential distributive effects of improved forecasting of E1 Niño Southern Oscillation (ENSO) events on agriculture in Mexico under different states of preparedness. The authors showed that under an E1 Niño event, the Mexican economy could lose about three percent of crop output. Although these losses are small as a share of the overall economy, the results show that they can be eliminated by improved forecasting. All of these studies modeled risks in a CGE model, but with a focus on trade effects at either a country level or in a regional context.

A study that is more recent and is closely related to this thesis is that by Strzepek et al. (2008) in Egypt. These authors examined the value of the Aswan High Dam under uncertain flow of the Nile River. The authors explored the net economic value of the dam with an emphasis on its years of active operation. At the aggregate level, the impact indicators considered for the study included production, consumption, and trade. In addition, the authors computed a risk premium for variability in the flow of the Nile River and compared the value to the baseline situation, a scenario in which the country had no dam. The authors used expected utility theory to compute the influence of risk behavior on investment and consumption decisions by economic agents. Their analysis covered the impact of the dam through channels such as changes in the supplies of irrigated land and water, changes in the supplies of electric power, changes in yields and production technology, and changes in real costs associated with other investments. The static simulation results show that the economic impact would have been smaller in 1997 if the Aswan High Dam had not been built. Overall, the dam provides significant benefits to the Egyptian economy. Different results were reported, however, for the various sectors. The agricultural sector would have benefited the most while the non-agricultural sectors would have had negative experiences had the dam not been developed. The dynamic simulation results show that as the level of flow of the Nile River decreases, the impact on Egypt's GDP decreases as well. However, a substantial water reduction becomes positive for the economy as high-value productive sectors start absorbing low-skill laborers from the agriculture sector.

The current model departs from the above studies and incorporates risk into the model through the right hand side of the input constraint that defines water flow into the basin. In allocating water among countries, it is often the case that the quantity of water available is uncertain. Thus, current allocation schemes should be designed to reflect the fact that inflows into the basin could be random. Since the uncertainty associated with water reallocation is captured in the right side of the constraint, it is appropriate to apply Chance Constrained Programming (CCP) to model the significance of incorporating risks during water reallocation in the basin. CCP is useful because it explicitly accounts for the variable nature of the inflow water in the basin and confines the analysis to an acceptable risk level.

3.5.2 Chance Constrained Programming (CCP)[32]

Chance constrained programming (CCP) was developed by Charnes and Cooper (1958) to incorporate risk in right hand side values for constraints. Specifically, it considers the feasibility of resource constraints in probabilistic terms. This approach provides an efficient and relatively simple framework to model uncertainties in water resource availability and allocation. Water availability is an uncertain parameter among the countries sharing the BNRB, where producers and policy makers often do not know the exact amount of water they will receive. Because of this, the chance constrained formulation becomes very suitable.

A mathematical illustration of the CCP is presented as follows. Assuming that water availability/allocation is uncertain, CCP proceeds by first specifying a minimum probability level (ψ) for which the water allocation constraint must be feasible; that is, given the risk associated with water availability, the allocation constraint will be infeasible (100 ψ) percent of the time. Let I_i be the random water inflow of the basin in year i. Assuming that the random variable I_i is independently and normally distributed, the ith chance constraint can be specified as:

$$P\left(\sum_{j=1}^{n} TW_j \leq I_i\right) \geq \psi_i \qquad i = 1,2,\ldots,m \qquad \psi_i \in [0,1] \qquad (3.57)$$

where TW_j is the total water available for country j and P is the probability operator. Assuming that each country uses its full allocation of water (TW_j), equation 3.57 specifies the probability that total water use, is feasible (i.e., no greater than water available) must be at least ψ_i.

Let $\bar{I}$ and σ_I be the mean and standard deviation of I_i. By subtracting the mean value from both sides of the inequality in parentheses in equation 3.57 and then dividing both sides by the standard deviation, the constraint is transformed to:

[32] Most of the materials presented on the CCP in this section are based on discussion in Kaiser and Messer (2011); Sengupta (1972); Sposito(1975); Maji and Heady(1978) ; and Gali and Brown (2000).

$$P\left[\frac{\sum_{j=1}^{n} TW_j - \bar{I}}{\sigma_I} \leq \frac{(I_i - \bar{I})}{\sigma_I}\right] \geq \psi_i \tag{3.58}$$

Given the mean and the standard deviation of I_i and the assumption of normality, a Z-score for the distribution of water availability can be defined as:

$$Z_i = \left(\frac{I_i - \bar{I}}{\sigma_I}\right) \tag{3.59}$$

where Z_i~N(0,1). A value of Z_i is associated with a specific probability level that the amount of water available will be no greater than I_i. Given a required water allocation feasibility probability of ψ_i, a value of Z_i can be specified to replace the right hand side of the bracketed inequality in equation 3.58. This would be the Z_i associated with probability (1-ψ_i), the maximum allowable probability that the constraint is infeasible. Define K_{ψ_i} as this standardized normal value (i.e., Z-score) for ψ_i; that is, the constraint will be met ψ_i percent of the time.

Given the specification of K_{ψ_i}, equation 3.58 will be satisfied if and only if:

$$\frac{\sum_j TW_j - \bar{I}}{\sigma_I} \leq K_{\psi_I} \tag{3.60}$$

Equation 3.60 may be re-written as:

$$\sum_j TW_j \leq \bar{I} + K_{\psi_i}\sigma_I \tag{3.61}$$

Hence, the probability constraint 3.58 can be substituted by its deterministic equivalent form in equation 3.61 and the solution to the problem can be obtained by combining this equation 3.61 with the rest of the equations outlined in section 3.3.2 for the BNW-CGE. The amended model now contains an important stochastic component, which accounts for the risk associated with variable river inflow.

The conventional interpretation of the chance constraint specified in equation (3.61), involving the random variable I_i is that the water availability constraint is feasible at least $100\psi_i$ percent of the time. In other words, the constraint may be violated (infeasible) up to $100(1-\psi_i)$ percent of the time. For example, suppose the value of ψ_i is set at 0.95. This indicates that the probability that the water allocation constraint (equation 3.57) is feasible at least 95 percent of the time. In up to five percent of years, conversely, the optimal water allocation may be infeasible; that is, water availability would be insufficient to support the optimal allocation determined in the model.

It should be noted that the CCP model outlined in this section has several limitations. In the CCP model, the probability constraint is converted to deterministic form and this requires a detailed knowledge of the assumption about the probability distribution of the random variable. In this study, it is assumed that the distribution of water is normal and the values of the Z-scores are used in constructing the final constraint (equation 3.61). Also, while CCP models allow for the possibility of optimal model solutions being infeasible with a positive probability, CCP model solutions provide no guidance as to what would happen (or be optimal) if the constraint is infeasible. Lastly, there is no consideration of upside risk in CCP. In spite of these limitations, the CCP model provides insight on the trade-offs among the aggregate economic outputs, tolerance values of the constraint, and the prescribed level of probability, which could be useful to decision makers, producers and consumers in the basin when dealing with risks.

CCP has been applied in various water-related studies. For example, CCP was applied to assess the optimal reservoir operating rule with explicit recognition of the stochastic variables, particularly the inflows into a reservoir (Eisel, 1972). Maji and Heady (1978) applied it to optimal cropping pattern and reservoir management for the Mayurakshi irrigation project in India. Loucks and Dorfman (1975) used a theoretical model to compare and evaluate several linear decision rules used in CCP to estimate efficient reservoir capacities and reservoir operating policies. Duffuaa (1991) applied CCP to analyze the random supply of water that needs to be discharged optimally to satisfy a known demand over a certain period while accounting for storage constraints, scouring damage, and minimizing the possibility of a flood which may endanger the Aswan High Dam in Egypt. Azaiez et al. (2005) used CCP to study the operation of a hypothetical basin under conjunctive use of ground and surface water. Jothiprakash et al. (2005)

used this method to derive optimal cropping patterns and optimal operational strategies for the Sri Ram Sugar project in India with stochastic inflows to the reservoir. The aforementioned studies applied CCP to assess either optimal reservoir allocation or basin level allocation, while this study applies the method in a multi-country CGE modeling framework in Africa.

3.5.3 Results of Impact of Risks and BNW-CGE Model

This section presents the results from the CCP model, which examines the impact of water reallocation under uncertainty conditions. In this regard, the annual inflow of water into the basin is considered to be random. The CCP model is used to capture the stochastic nature of the annual inflow of water into the basin. The CCP model is then integrated into the BNW-CGE model to analyze the impacts of risk, specifically drought and its ripple effects on the economies of Egypt, Sudan and Ethiopia. The major research questions are:

1. What are the impacts of risks associated with water reallocation?
2. What are the cost implications of not factoring risks into water reallocation in a basin-wide context?
3. What can policy makers do to minimize risks, if possible?

A stochastic experiment (SIM_2) is designed to answer these research questions. The experiment captures the random nature of water inflow into the basin and its impacts on the economy. It deals with water reallocation under three main stochastic conditions and compares the policy implications relative to the policies of a deterministic model. In this experiment, the source of variation is due to the risk of not getting adequate water at the specified probability level. This stochastic shock represents risk due to uncertain inflow into the basin, which may affect especially the sectoral agricultural output and ripple effects on outputs of the other sectors of the economy.

Equation 3.61 is used to perform this experiment. The mean and the standard deviation of the annual inflow data (I_i) are used in this experiment. The data were gathered from previous studies such as Robinson et al. (2008), Duffuaa (1991) and McCartney et al. (2012). Given the annual inflow data of the Nile River Basin at the Aswan High Dam in Egypt, the mean of I_i is calculated as 84.37 BCM per year with a standard deviation of 16.66. Given the mean and standard deviation of I_i, four probability (ψ_i) levels for feasibility are considered: 50 percent, 90 percent, 95 percent and 99 percent. These probability levels are chosen to indicate that as the required probability of feasibility increases, the model solutions become more conservative in terms of water availability.

The model results are presented and described for two main scenarios. The first scenario represents the deterministic model which uses the average current allocations of the countries as the right hand sides for the water allocation constraints. An alternative interpretation of this model is as a CCP model where the probability of solution feasibility with respect to water availability (i.e., ψ) is set at 50 percent; that is, the water required to support the CGE model solution will be available at least 50 percent of the time. This corresponds to a Z-score of zero, meaning that the term on the right hand side of equation 3.61 simplifies to the expected level of water availability.

The second scenario makes use of the explicit CCP version of the water availability constraint, incorporating the risk term in equation 3.61. Three alternative required probability levels are modeled; 90 percent, 95 percent and 99 percent. For example, in this scenario using a 95 percent probability level, the water availability constraint (and thus the CGE model solution) will be infeasible at most 5 percent of the time. For the second scenario model runs, the BNW-CGE model is adjusted by replacing equation 3.25 with equation 3.61.

3.5.3.1 Results from Experiment Two: Impact of Stochastic Water Reallocation on GDP

In this section, the results from the CCP model are shown in Tables 3.17 to 3.19. It may be recalled that the CCP model results differ from the results under experiment one because of the differences in the water allocation constraints, which involves annual water inflow into the basin. Policy makers could use the model to investigate the economic impact of a shock to the economy with a particular risk level. Also, this analysis would be insightful for decision makers in estimating the average operating budgets required to meet a specified level of certainty. The deterministic model results, interpreted here as being feasible 50% of the time, are compared with the three other probability levels. This analysis is done to reveal the impacts of risk associated with water reallocation. The initial simulation results show that the aggregate outputs decrease when the 90 percent reliability level is compared with the deterministic model. These differences become more pronounced as the reliability level is increased to 95 percent and 99 percent respectively. Also, at the sectoral levels, the simulation results show similar trend of impacts for all countries, while a major difference is observed in the magnitude of change as the reliability level is increased. The 95 percent reliability level results are used here as representative of the trends associated with the impacts of taking risk into account in water reallocation. All other results are presented in Appendix H.

In this experiment, having at least 95 percent reliability in satisfying the constraint involving water reallocation leads to a 0.8 percent and 0.07 percent decrease in the GDP of Egypt and Sudan, respectively. With regard to Ethiopia, a slight decrease is observed for its GDP when the result under the deterministic model is compared with the stochastic results (Table 3.17). Aggregate outputs for the countries decrease relative to the deterministic model as the water allocation constraint becomes stricter when the optimal solution must be met at the 95 percent of the time. The CCP model shows that without taking risk into account, the countries could be ignoring the risk of 2.02 billion EGP (264.733-262.714 billion EGP), 0.43 million SDG (628.116-627.683 million SDG), and 0.09 billion ETB (159.888-159.8billion ETB).

3.5.3.2 Impact of Stochastic Water Reallocation on Sectoral Outputs

The reduction in the GDP causes diverse effects on various sectors of the economy as seen in the model under certainty. Thus, it is relevant to compare the sectoral results under the stochastic conditions with the deterministic model in order to provide policy makers with information about economic sectors that need immediate intervention in the event of water shortages. At the sectoral levels, various impacts are observed. In particular, the value-added output in the agricultural sectors declines in all countries, relative to the deterministic model (Table 3.17). The negative impacts of water reallocation on the value-added output in the agricultural sectors have consequences on the other sectors, through substitution and income effects. As agricultural output decreases, productive resources could be shifted to other sectors where returns are higher. As expected, the output of the agricultural sector decreases because of the reduction in water usage in the economy. A greater negative impact is observed in Egypt than in Sudan and Ethiopia. In the agricultural sector, the simulation results show that Egypt would be ignoring impact of risk estimated to be 17.939 billion EGP while Sudan and Ethiopia would ignore the risk of potential loss of 44.54 million SDG, and 10.651billion ETB, respectively. These results suggest that under scarcity conditions, water becomes costly and producers in Egypt are more constrained in their production activities. Given that the agricultural sector requires more water for irrigation, it is also not surprising to observe adverse changes in household consumption of agricultural goods under stochastic conditions. Under stochastic conditions, the constraint become stricter with increased costs of meeting the required amount of water for agricultural production. Thus, a large reduction in the available inflow into the basin decreases both the production and consumption of agricultural goods.

With the complementary role of intermediate inputs services to the value-added output of the economies of the countries, it is not surprising to observe negative impacts on the agricultural sectors in the countries. However, the simulation results show a great variation in the output of the other sectors. While there is a loss in the intermediate input use in the industrial sector in Egypt, both Sudan and Ethiopia gain in this sector. These variations could be attributed to the differences in the technological development in the countries. The CCP model results show that intermediate input use for the services sector declines in Egypt and Sudan while an increase is observed for Ethiopia. Services decline during water shortages as demand for trade and transport services falls along with agricultural production in Egypt and Sudan. The combined effects of the value-added output and intermediate inputs use in the economies of these countries are discussed below. The decline in the agricultural value-added output has a diverse impact on the other sectors of the economy. The overall impacts could increase or decrease depending on the substitution and income effects associated with the price changes in the countries with reallocation under uncertainty. As expected, the decrease in the agricultural value-added output in Egypt negatively impacts the domestic agricultural output. With the Armington assumption, households tend to consume relatively cheaper imported goods than the locally produced goods. As the simulation results show, the gain in the other sectors are not enough to compensate the loss in the agricultural sectors. Thus, the composite output supply declines in Egypt. A similar effect is observed in Sudan, but in Ethiopia the gain in the industrial and services sectors partially offsets the loss in the agricultural sector and a minimal effect is seen on the composite good supply (Table 3.17).

Table 3. 17 Impact of Stochastic Water Reallocation on Quantity Changes for Experiment Two[a]

Countries	Egypt			Sudan			Ethiopia		
Quantity Risk Impacts	Baseline results(50 percent)	Alternative Water Reallocation under five Percent Risk Level	Percentage Change baseline Results	Baseline results(50 percent)	Alternative Water Reallocation under five Percent Risk Level	Percentage Change baseline Results	Baseline results(50 percent)	Alternative Water Reallocation under five Percent Risk Level	Percentag e Change baseline Results
Annual water allocations	55.5bcm	52.5bcm		18.5bcm	15.5bcm			6bcm	
GDP	264.733	262.714	-0.769	628.116	627.683	-0.069	159.888	159.800	-0.055
Value added: Agriculture	37.435	19.496	-92.014	293.397	248.857	-17.898	55.261	44.610	-23.876
Industry	46.229	64.091	27.870	61.924	83.972	26.256	9.374	19.306	51.445
Services	135.505	136.566	0.777	192.552	200.354	3.894	34.093	36.060	5.455
Intermediate input: Agriculture	23.864	21.405	-11.488	54.639	50.455	-8.293	25.67	25.599	-0.277
Industry	103.075	103.441	0.354	151.451	149.522	-1.290	1.482	1.304	-13.650
Services	107.512	77.889	-38.032	145.408	138.130	-5.269	35.144	36.670	4.161
Domestic output: Agriculture	60.915	39.089	-55.837	349.445	358.446	2.511	56.931	60.138	5.333
Industry	149.78	189.734	21.058	220.557	157.613	-39.936	10.899	20.326	46.379
Services	242.198	215.596	-12.339	340.943	331.514	-2.844	96.173	100.992	4.772
Composite good: Agriculture	80.418	77.847	-3.303	362.731	361.827	-0.250	44.433	59.355	25.140
Industry	245.652	213.511	-15.054	247.932	234.187	-5.869	47.443	57.500	17.490
Services	204.428	195.191	-4.732	457.685	371.470	-23.209	87.561	78.548	-11.475
Imports: Agriculture	6.655	10.710	37.862	28.167	28.227	0.213	2.173	3.372	35.558
Industry	79.311	51.415	-54.257	102.711	110.099	6.710	71.451	35.695	-100.171
Services	9.048	8.515	-6.260	9.091	6.910	-31.563	3.294	20.354	83.816
Exports: Agriculture	0.295	0.295	0.000	26.415	25.717	-2.714	0.002	9.228	99.978
Industry	10.892	16.375	33.484	79.768	75.395	-5.800	0.507	0.901	43.729
Services	59.025	34.797	-69.627	0.152	0.100	-52.000	1.505	2.193	31.373

Source: Author's Simulation Results. a. The reported results pertain to the simulation of perturbing the current allocation scheme under stochastic conditions. Values are in billions of Constant Egyptian Pound (EGP), Ethiopian Birr (ETB) millions and constant Sudanese Pound (SDG) millions. The results for 50 percent probability with the normality assumption for model represent the solution to the deterministic results, this provide us with a Zi value of zero. Also, 95 percent reliability level allows for 5 percent risk probability of not achieving a feasible solution.

3.5.3.3 Impacts of Stochastic Water Reallocation on Consumption and Incomes

This section deals with the impact of water reallocation on public incomes and the intended effects on private consumption. The simulation results reveal a real decrease in households' consumption of agricultural goods in all countries, when the 95 percent reliability level is assumed. It should be mentioned that at this reliability level, Egypt experiences the largest impact when compared with Sudan and Ethiopia (Table 3.18). Conversely, there is an increase in household consumption of goods from other sectors, which could be attributed to the inelastic nature of water demands in these sectors. Also, it is possible that substitution effect is greater than the income effect, thus households' demand for these goods increases relative to locally produced agricultural goods.

Concerning public income, the stochastic results show a decrease when compared with the deterministic model. In Egypt, public income decreases by 14 percent (37.818 billion EGP to 33.109 billion EGP) when the 95 percent reliability level is compared with the deterministic model. At this level of reliability, Sudan has a decrease of 0.02 percent (100.716 million SDG to 100.696 million SDG) while public income decreases slightly in Ethiopia (Table 3.18). Looking at the results in Ethiopia, the simulation results show that when the reliability level is increased to 95 percent from 50 percent (i.e., the deterministic model), public income decreases from 23.547 billion ETB to 23.543 billion ETB. The simulation results for private incomes are reported in Table 3.18. There is a little variation when the deterministic model is compared with the CCP model at the 95 percent reliability level.

The CCP model results for factor income analysis entail return on capital, land and labor with respect to water reallocation. Concerning labor, there is a decrease in all countries with water reallocation under stochastic conditions. In particular, the simulation results show a decrease of 7.4 percent (106.14 billion EGP to 98.873 billion EGP) in labor demand in Egypt when the 95 percent reliability level is compared with the deterministic model.

At this reliability level, Sudan has a 55 percent (334.344 million SDG to 222.745 million SDG) decrease in labor use while Ethiopia observes a 6 percent decrease (33.794 billion ETB to 31.981 billion ETB) with water reallocation. Table 3.18 reports the impact of water reallocation on returns from land under stochastic conditions. Under stochastic conditions, returns to land decrease further from 18.171 billion EGP to 16.226 billion EGP in Egypt. Ethiopia experiences different impacts on returns to land under stochastic conditions.

Table 3.18 Impact of Stochastic Water Reallocation on Income Changes for Experiment Two[a]

Countries	Egypt			Sudan			Ethiopia		
Income Risk Impacts	Baseline results(50 percent)	Alternative Water Reallocation under five percent risk Level	Percentage change baseline results	Baseline results(50 percent)	Alternative Water Reallocation under five percent risk Level	Percentage change baseline results	Baseline results(50 percent)	Alternative Water Reallocation under five percent risk Level	Percentage change baseline results
Water allocations	55.5bcm	52.5bcm		18.5bcm	15.5bcm			6bcm	
Income									
Public	37.818	33.109	-14.223	100.716	100.696	-0.020	23.547	23.543	-0.017
Private	186.971	186.907	-0.034	456.724	456.71	-0.003	146.419	146.416	-0.002
Household consumption									
Agriculture	29.734	24.911	-19.361	303.557	283.796	-6.963	45.03	43.14	-4.381
Industry	60.954	61.307	0.576	64.944	65.668	1.103	29.193	30.487	4.244
Services	100.38	100.896	0.511	46.961	47.465	1.062	22.395	22.712	1.396
Factor income									
Labor	106.14	98.873	-7.350	344.344	222.745	-54.591	33.794	31.981	-5.669
Capital	146.306	145.203	-0.760	343.941	247.141	-39.168	20.769	20.678	-0.440
Land	18.171	16.226	-11.987	5.211	4.222	-23.425	13.102	12.717	-3.027

Source: Author's Simulation Results. a. The reported results pertain to the simulation of perturbing the current allocation scheme under stochastic conditions. Values are in billions of Constant Egyptian Pound (EGP), Ethiopian Birr (ETB) millions and constant Sudanese Pound (SDG) millions. The results for 50 percent probability with the normality assumption for model represent the solution to the deterministic results, this provide us with a Zi value of zero. Also, 95 percent reliability level allows for 5 percent risk probability of not achieving a feasible solution.

A similar trend is observed in Sudan as in Egypt, though there are slight variations in the magnitude of the impacts (Table 3.18). These results are as expected, as land is a major input in the agricultural sector, and in this study, it is modeled as a fixed proportional input with water. A reduction in water has a direct effect on the use of land in the economy. Conversely, when the deterministic model is compared with the stochastic model, there is a slight variation on the impact of capital in all countries (Table 3.18). This result is because a reduction in water has a direct impact on land and labor, given the choice of the Leontief production technology selected in this study and the differences in sectoral wage requirements. Capital, on the other hand, shows a slight variation with the scarcity of water use in the economy.

3.5.2.4 Impact of Stochastic Water Reallocation on Price Changes

Table 3.19 presents the impacts of price changes on the sectoral outputs under stochastic water reallocation. The simulation results show a slight variation in agricultural value-added output prices in Sudan and Ethiopia, but a larger variation is observed in Egypt. At the 95 percent reliability level, the agricultural sector value-added output price in Egypt increases by 9 percent relative to the deterministic model (1.001 EGP to 1.100 EGP). Simulation results reported in Table 3.19 reveal that at the 95 percent reliability level, agricultural prices of the value-added output decrease by 41 percent in Sudan, relative to the deterministic model (0.921 SDG to 0.653 SDG). In Ethiopia, however, there is a 7 percent increase in the agricultural price of the value-added output (Table 3.19). As the reliability level of the water allocation is increased, the use of water becomes scarce in the agricultural sector and it is costly to meet the required constraint at the 95 percent reliability level. As the constraint becomes more restricted, the cost of water in the agricultural sector increases and this affects the agricultural outputs in the three countries. As water use in Ethiopia is not as restrictive as in Egypt and Sudan, it is not surprising to see a slight impact of water reallocation on the agricultural prices in Ethiopia relative to the other countries. The sectoral value-added prices of the other sectors change as well under stochastic conditions (Table. 3.19). With the reduction of water in the agricultural sectors, and as expected, productive resources would be shifted to other sectors through substitutions and income effects. As factor inputs in the agricultural sector become cheaper relative to other sectors, it appears that factor inputs are mobilized and shifted to other sectors of the economy, and thus, as the simulation results indicate there are slight impacts on the other sectors under stochastic conditions.

In comparing the deterministic model with the stochastic model at the 95 percent reliability level, the simulation results indicate that import prices decrease when compared with the deterministic model. In Egypt, the import prices of agricultural goods decrease from EGP 0.991 to EGP 0.980 at the 95 percent reliability level. In Ethiopia, the import price decreases from ETB 0.978 to ETB 0.976 at the 95 percent reliability level. Contrary to expectations, the simulation results show a slight variation in Ethiopia when the 95 percent reliability level is compared with the deterministic model. Given the salient features of the Armington specification used in this model, the impacts of water reallocation on import prices could be observed for domestic good prices as well as for export prices (Table 3.19). As evident, when import prices decrease relative to domestic prices due to water reallocation under stochastic conditions (i.e., due to the fact that the constraint becoming stricter), households tend to consume more imported goods (Table 3.19).

This result has a significant impact on public income as exports from productive sectors of the economy decrease. Intuitively, this implies that the terms of trade improve which benefits consumers in the respective countries, which affects the export sectors. The impact of substitution and income effects of consumer behavior on imports and domestic goods impacts composite goods supply in the respective countries. The simulation results show that at the 95 percent reliability level the composite good supply price for agriculture increases from 1.006 EGP to 1.023 EGP in Egypt while an increase from 1.004 SDG to 1.016 SDG is observed for Sudan. Ethiopia, experiences a major increase from 1.003 ETB to 1.126 ETB, when the 95 percent reliability level is compared with the deterministic model under water reallocation. The simulation results under stochastic water reallocation show that private and public income decrease because of the consumption of imported goods increase. This places considerable pressure on the current account balances of these countries, as they already run on deficit budgets.

Table 3.19 Impact of Stochastic Water Reallocation on Price Changes for Experiment Two[a]

Countries	Egypt			Sudan			Ethiopia		
Price Risk Impacts	Baseline results(50 percent)	Alternative Water Reallocation under five percent risk Level	Percentage change baseline results	Baseline results(50 percent)	Alternative Water Reallocation under five percent risk Level	Percentage change baseline results	Baseline results(50 percent)	Alternative Water Reallocation under five percent risk Level	Percentage change baseline results
Water allocations	55.5bcm	52.5bcm		18.5bcm	15.5bcm			6bcm	
Value added: Agriculture	1.001	1.100	9.000	0.921	0.653	-41.041	0.903	0.968	6.715
Industry	1.047	1.057	0.946	0.857	0.881	2.724	0.916	0.909	-0.770
Services	0.950	1.096	13.321	0.995	1.052	5.418	0.994	0.990	-0.404
Intermediate input: Agriculture	1.052	0.874	-20.366	1.010	1.011	0.099	1.020	1.216	16.118
Industry	1.032	0.951	-8.517	1.036	1.035	-0.097	1.017	1.190	14.538
Services	1.018	1.009	-0.892	1.024	1.023	-0.098	1.023	0.668	-53.144
Domestic output: Agriculture	0.990	0.941	-5.207	1.010	0.850	-18.824	0.967	0.940	-2.872
Industry	0.997	0.950	-4.947	0.959	0.635	-51.024	0.979	0.855	-14.503
Services	1.016	1.008	-0.794	1.004	1.006	0.199	0.966	0.913	-5.805
Composite goods: Agriculture	1.006	1.023	1.662	1.004	1.016	1.181	1.003	1.129	11.160
Industry	1.046	1.997	47.621	0.981	0.999	1.802	1.009	1.116	9.588
Services	1.006	1.043	3.547	1.058	0.902	-17.295	1.002	0.994	-0.805
Imports: Agriculture	0.991	0.980	-1.122	0.994	0.971	-2.369	0.978	0.976	-0.205
Industry	1.000	0.998	-0.200	1.006	1.006	0.000	1.014	1.013	-0.099
Services	1.001	0.999	-0.200	1.004	1.004	0.000	1.002	1.000	-0.200
Exports: Agriculture	1.001	1.001	0.000	1.016	1.026	0.975	1.004	1.688	40.521
Industry	1.002	0.994	-0.805	1.047	2.032	48.474	1.002	1.066	6.004
Services	1.000	1.001	0.100	1.000	1.000	0.000	1.022	1.563	34.613

Source: Author's Simulation Results. a. The reported results pertain to the simulation of perturbing the current allocation scheme under stochastic conditions. Values are in billions of Constant Egyptian Pound (EGP), Ethiopian Birr (ETB) billions and constant Sudanese Pound (SDG) millions. The results for 50 percent probability with the normality assumption for model represent the solution to the deterministic results, this provide us with a Zi value of zero. Also, 95 percent reliability level allows for 5 percent risk probability of not achieving a feasible solution.

3.5.2.5 Summary

Results presented and discussed in this section show that some sectors benefit while other lose in all three countries, with the consideration of risk in water reallocation. Overall, at the 95 percent reliability level, the GDPs of the countries decrease with a greater effect occurring in Egypt. At the sectoral level, the value-added outputs of the industrial and services sectors improve in all the countries. Conversely, the value-added outputs of the agricultural sector decrease in all countries. Thus, reallocation of water under stochastic conditions tends to significantly affect the agricultural sector, which is the major user of water. In Egypt and Sudan, the gains in the non-water consumptive sectors (i.e., industrial and services) are not able to offset the loss in the agricultural sector. Hence, there is a decrease in the aggregate composite good supply while in Ethiopia, the composite good supply increase because of the gain in these sectors.

Unlike the certainty conditions, the benefits of water reallocation are not as clear-cut at the sectoral level when risks are considered. It is important for the countries to pursue the benefits from water reallocation, but strategies necessary to minimize the impact of risks associated water reallocation should be explored as well. In order to minimize the risks associated with water reallocation, decision makers in the countries may decide whether benefits from increased reliability outweigh required costs necessary to achieve this increased reliability. The next section of this study discusses the policy implications and strategies necessary to minimize the impacts of risks from water reallocation.

3.5.2.6. Policy Implications for Stochastic Water Reallocation

This study seeks to determine if there are benefits from water reallocation when decision makers take risks into consideration. The stochastic simulation is performed at the 95 percent reliability level. At this reliability level, the simulation results show that the GDP of the countries decrease relative to the deterministic model. Also, the simulation results show that both the industrial and services sectors value-added outputs improve, but a substantial loss is seen in the agricultural sector. Based on these results, it may be important for policy makers in the basin to direct resources from the agricultural sector to develop the industry and services sectors (i.e., generally less water intensive), which would benefit the countries during periods when water is a scarce resource to production. In this regard, the countries have to make a structural shift by improving the non-water consumptive sectors and be less dependent on the agricultural sector.

Additionally, results from the stochastic simulation model show that there is a significant loss in composite good supply to Egypt and Sudan while a minimal negative impact occurs in Ethiopia. Although there are benefits associated with reallocation of water among the countries, it is imperative to develop strategies necessary to mitigate future risks in water reallocation. As the benefits from reallocation are not clear cut to the countries when risks are considered, it may be appropriate for the countries to cooperate and explore strategies necessary to minimise risks while maximizing the benefits from reallocation. Under cooperative agreement, the countries could jointly develop strategies necessary to mitigate the risks of water use allocation in the basin. As the simulation results reveal, Egypt and Sudan stand to lose more than Ethiopia when risks are captured in water reallocation. The cost implications of water reallocation under stochastic conditions to Egypt and Sudan should provide an enabling environment toward cooperation in the basin. With the cooperative agreement, it may be beneficial for the countries to engage in benefits sharing from water instead of water reallocation (i.e., changing the sharing of water itself). Under this condition, it may be necessary for the countries to jointly initiate and develop projects that minimize risk, but maximize benefits of water to the countries. In particular, additional infrastructure can be built to provide added storage capacity, and measures can be taken to reduce leakage in diversion canals and water distribution systems, increase the efficiency of irrigation systems, and provide additional supplies, water pricing, and perhaps through desalination.

3.6 Welfare Analysis of Water Reallocation

Given the results presented for changes in household consumption, with losses in Egypt and Sudan but a positive gain in Ethiopia, an analysis of welfare changes would be useful in evaluating whether consumers in all three countries are better off due to the changes in water reallocation. The two common approaches used to evaluate the impact of a policy change on consumers are the compensating and equivalent variations (Varian, 1992). Compensating variation (CV) measures consumers' welfare by using new prices as the base and shows the change in the income needed to compensate the consumers for a given change in prices. An alternative measure, equivalent variation (EV), measures the difference between base equilibrium and counterfactual equilibrium using current prices as the base. Specifically, the equivalent variation seeks to find the additional income needed to make the consumer as well off in terms of utility given the proposed change in prices. In this section, equivalent variation is presented to evaluate the impact of the proposed water allocation among the three countries because it measures consumers' welfare using current prices, which makes it easier to evaluate changes in income.

As previously defined, $U_s(c_s)$ is the utility function, while $V_s(P_s^H, HY_s)$ and $m_s(P_s^H, V_s)$ are the indirect utility function and money metric indirect utility function respectively. The indirect utility function, $V_s(P_s^H, HY_s)$, is obtained by replacing the c_s in the utility function of equation (3.35) with the demand function of equation 3.38. Then,

$$V_s(P_s^H, HY_s) = \prod_{s=1}^{S}\left[\frac{\beta_s}{P_s^H}\left(HY_s - \sum_{s=1}^{S}\gamma_s P_s^H\right)\right]^{\beta_s} \tag{3.62}$$

$$= \left(HY_s - \sum_{s=1}^{S}\gamma_s P_s^H\right)\prod_{s=1}^{S}\left(\frac{\beta_s}{P_s^H}\right)^{\beta_s} \tag{3.63}$$

HY_s in equation 3.63 can be solved for to derive the money metric indirect utility function $m_s(P_s^H, V_s)$, which is a measure of the income needed to attain utility level V_s at the P_s^H:

$$m_s(P_s^H, V_s) = \prod_{s=1}^{S}\left(\frac{P_s^H}{\beta_s}\right)^{\beta_s} V_s + \sum_{s=1}^{S}\gamma_s P_s^H \tag{3.64}$$

The equivalent variation (EV) is measured as:

$$EV = m_s(P_s^{H0}, V_s(P_s^{H1}, HY_s^1)) - m_s(P_s^{H0}, V_s(P_s^{H0}, HY_s^0)) \tag{3.65}$$

$$= m_s(P_s^{H0}, V_s(P_s^{H1}, HY_s^1)) - HY_s^0 \tag{3.66}$$

Using equation 3.64, EV can be specified as:

$$\prod_{s=1}^{S}\left(\frac{P_s^{H0}}{\beta_s}\right)^{\beta_s} V_s(P_s^{H1}, HY_s^1) + \sum_{s=1}^{S}\gamma_s P_s^{H0} - HY_s^0 \tag{3.67}$$

$$=\prod_{s=1}^{S}\left(\frac{P_s^{H0}}{\beta_s}\right)^{\beta_s}\left(HY_s^1-\sum_{s=1}^{S}\gamma_s P_s^{H1}\right)\prod_{s=1}^{S}\left(\frac{\beta_s}{P_s^{H1}}\right)^{\beta_s}+\sum_{s=1}^{S}\gamma_s P_s^{H0}-HY_s^0 \tag{3.68}$$

$$=\prod_{s=1}^{S}\left(\frac{P_s^{H0}}{P_s^{H1}}\right)^{\beta_s}\left(HY_s^1-\sum_{s=1}^{S}\gamma_s P_s^{H1}\right)-\left(HY_s^0-\sum_{s=1}^{S}\gamma_s P_s^{H0}\right) \tag{3.69}$$

Equation 3.69 is used to estimate the EV of the water policy change in the Nile River Basin. EV is calculated for two scenarios. The first scenario (SIM_1) deals with water reallocation under certainty conditions. The second scenario (SIM_2) focuses on water reallocation under stochastic conditions, at the 95 percent reliability level. Results are compared under both scenarios to the GDP calculated without water reallocation. This is relevant when comparing welfare impact between different countries, as the result could indicate whether the alternative polices are welfare enhancing or not.

The EV results for the three countries show an overall increase in welfare for all the countries with water reallocation (Table 3.20) under certainty (SIM_1). With reallocation, Egypt could be worse off by 4.783 billion EGP, Sudan stands to lose by 2.097 million SDG while a gain of 8.351 billion ETB is obtained for Ethiopia. In Egypt and Sudan, water reallocation caused domestic prices to increase, causing households to reduce expenditure on domestic goods and spend more imports goods in order to maintain the same level of utility. However, the net welfare gain summed across the three countries is estimated to be 3.1 percent of GDP under certainty conditions of water reallocation (Table 3.20).[33] These results indicate that water reallocation could improve the welfare of households in the three countries.

Under stochastic conditions, losses in welfare for Egypt and Sudan are 3.9 percent and 0.2 percent of GDP, respectively. Although there is still a gain in welfare for Ethiopia, overall there is a net welfare loss of 0.53 percent of GDP for the three countries (Table 3.20). These results tend to indicate that if these countries could cooperate and jointly implement water related projects within the basin, it is possible to obtain benefits from water reallocation relative to the status quo situation.

[33] This is calculated as the sum (i.e., unweigthed) of the changes in EVs, expressed as percentages of GDP for scenario SIM_1.

Table 3.20 Impact of Water ReAllocation on Welfare

Indictors	Egypt	Sudan	Ethiopia
EV_SIM_1	-4.783	-2.097	8.351
EV percentage of GDP1	-1.810	-0.334	5.221
EV_SIM_2	-10.183	-1.065	5.608
EV percentage of GDP2	-3.876	-0.169	3.509

Note: EV_SIM1: Equivalent variation in billions of constant Egyptian Pounds (EGP), constant Ethiopian Birr (ETB) in billions and constant Sudanese Pound (SDG) in millions. EV percentage of GDP1: Equivalent variation as percentage of GDP1. The reported results pertain to the simulation of altering the current allocation scheme governing the Nile River Basin under certainty conditions. EV_SIM2: Equivalent variation in billions of constant Egyptian Pounds (EGP), constant Ethiopian Birr (ETB) in billions and constant Sudanese Pound (SDG) in millions. EV percentage of GDP2: Equivalent variation as percentage of GDP2. The reported results pertain to the simulation of altering the current allocation scheme governing the Nile River Basin under stochastic conditions.

3.7 Summary and Conclusions

In this chapter, the impacts of water reallocation on the economies of the three countries in the Blue Nile River Basin (BNRB) are analyzed in a general equilibrium framework. Specifically, the analysis focuses on the implications of altering the 1959 Agreement between Egypt and Sudan, in which Ethiopia has no allotment in the allocation of water. Contrary to the single country model and general equilibrium models in water allocation studies, a multi-country CGE model is used. The advantage of using a multi-country CGE model is that in addition to analyzing changes in factor inputs, the model also permits comparative analysis of how factors shift from one sector to another sector in relation to the other two countries with reallocation of water. Furthermore, multi-country CGE models incorporate a detailed analysis of trade flows, unlike single country CGE models.

In applying the BNW-CGE model, all activities in the economy of each country were aggregated into four main sectors: agricultural, industrial, services, and the rest of the world, the latter of which focuses on trade analysis. Changes to the existing water allocation and a possible future allocation scenario were simulated. This was done to evaluate the way in which altering the current water allocation could affect the economies of the countries and, more importantly, the sectors with major consumptive use, such as agriculture.

The policy changes stipulated by altering the current allocation schemes in relation to the sectors are also expected to have different implications for the different countries in the basin. Based on the 1959 Agreement, Egypt and Sudan are the major users of the Nile River water. However, six other countries have also signed the current cooperative framework (CFA) to increase the benefits derived from Nile River water. Because the agriculture sectors of Egypt and Sudan depend heavily on the Nile River flow, it is relevant to assess the changes that could occur if the current allocation scheme were altered. From the six other countries, Ethiopia is selected for this study because of its relatively higher contributions to the flow of the Nile.

The 1959 Agreement governing the Nile River Basin specified that 55.5 BCM of the annual total flow of 74 BCM be allotted to Egypt while Sudan would receive 18.5 BCM. The BNW-CGE model developed in this study is used to evaluate two scenarios. The first scenario focuses on changes in outputs -- six BCM is allotted to Ethiopia with equal reduction from the other two countries. The second scenario deals with the stochastic conditions associated with water reallocation. In this scenario, the impact of risks associated with water reallocation was evaluated at one percent, five and 10 percent, respectively, for Egypt, Sudan, and Ethiopia.

Results from the first scenario show that the proposed water reallocation schemes on the Nile River Basin potentially lead to a slight decline in the GDP of Egypt and Sudan, and an increase in that of Ethiopia. This has various implications on the sectoral outputs of the countries, with Egypt's agricultural sector experiencing the most significant impact. With a decline in agricultural value-added output, resources may shift to other productive sectors of the economy. Because of the differences in labor requirements, the agricultural sectors' losses are partially offset by gains in other sectors. In Egypt and Sudan, the decline in agricultural production leads to a decline in domestic output and an increase in the price of agricultural output. Agricultural exports decrease and imports increase to partially satisfy the domestic demand for agricultural products and household consumption. However, the increase in industry and service sectors does not outweigh the decrease in agricultural sectors. An opposite effect is observed for Ethiopia, where the agricultural sector output increases with reallocation. These findings are consistent with partial equilibrium studies that modeled water reallocation in the basin (Whittington et al., 2005; Guariso and Whittington, 1987).

Unlike the deterministic scenario, more significant impacts were observed under stochastic conditions. Compared to the deterministic model, the GDP of these countries declined under all risk levels, with the most significant effects occurring in Egypt and Sudan. The significant negative impacts continued to occur in the agriculture sector. However, the industrial and services sector improved under stochastic conditions. The simulation results show that there are economic losses when risks are incorporated during reallocation. Results from the study show that when appropriate measures are put in place, the three countries could avoid the risk of 2.02 EGP billion, 0.43 million SDG and 0.09 billion ETB respectively, at the aggregate level. Thus, risk mitigation measures such as improved efficiency of water use through demand management approaches and investment in additional infrastructure can be developed to provide rationed added supplies.

As the simulation results show, with reallocation, Egypt and Sudan could increase net imports while Ethiopia could increase net exports. However, in Ethiopia, the increased water cannot be used to improve agricultural output since the potential land area that could be used for large scale irrigation is less than 10 percent of the total area (FAO, 1997). Thus, Ethiopia stands to benefit from reallocation if the water is used primarily in the other sectors. With the increased water, Ethiopia could maximize the use of water by investing in water storage developments that could have potential ripple effects on the rest of the economy. In this regard, the country could also use the potential allocated water for hydropower generation. These results are further supported by the welfare analysis, which show that reallocation of water could be welfare enhancing for the three countries in the basin under certainty condition. These results tend to support the need for cooperation in the Nile River basin, if the three countries seek to minimize the impacts from water reallocation.

There are a number of limitations associated with the analysis in this study. In accordance with the scope of the study, changes in water allocation with major-consumptive sectors and non-consumptive sectors were not specified. The sub-sectors in each of the four major sectors were aggregated together for the simulation analysis. This could limit the magnitude of the impact of the changes in the rest of the economy due to water reallocation. One possible area for future research is that of accounting for the distinction between major consumptive and non-consumptive sectors in evaluating the impact of water reallocation on the economy as a whole.

In addition, the calibration approach used to integrate water in the model needs further refinement, particularly in relation to the rest of the data in the social accounting matrix. Water is not a direct factor of production in the social accounting matrix collected from the different countries. Hence, it was calibrated through a Leontief production assumption to the baseline value of total land input in the economy. Future research should explore the possibilities of using the SAMs in countries where water is one of the factor inputs in the economy. This may help to offset the inevitable criticism that will be generated by the calibration approach adopted for the model.

Another interesting avenue of research could be to investigate the extent to which the normality assumption of the CCP model could impact the model results. In the CCP model, normality is usually assumed for the random variable and this needs to be tested rather than assumed. With the CCP model, assuming normality when the distribution is not normal biases the results. The test of normality was not possible to perform in this study because of data limitations.

As Ethiopia is developing one of the largest dams in Africa for hydropower production, it would be appropriate to extend the current model to estimate the impact of potential electricity supply to the economy of Ethiopia and other countries in the basin. While the current model considered aggregate sectors (i.e., agriculture, industry and services), a future model could develop a detailed electricity supply as part of the disaggregated sectors of the economy. On the production side, the current model could be extended to incorporate energy as part of the value-added nest (i.e., Figure 3.4). Total energy commodities could be divided into electricity and non-electricity and this in turn will form the energy composite nest. The energy composite should be combined with capital to produce an energy-capital composite nest. This is in turn combined with other primary factors in a value-added-energy nest through a CES Structure[34]. A detailed electricity component was not included in the current study because of data limitations and time requirement for the calibration approach.

Results from the study tend to suggest that these countries could benefit if they cooperate towards the development of water related projects. Given the fact that the current treaty governing the basin is contested, strategies necessary to encourage the countries to adopt benefit sharing

[34] The following papers could serve as a starting point for further studies on the impacts of electricity supply: Burniaux and Truong (2002); Aydin (2010); and Pizer et al., 2003.

principles[35] could be relevant. With this approach, it is possible that benefits such as irrigation and energy could be shared among the three countries. For example, the potential income generated from the electricity trading could be used to mitigate some of the negative impacts of water reallocation in agriculture, in Egypt and Sudan. Another benefit that the countries could derive from this approach is the gain in reducing evaporation and seepage losses at the Aswan High Dam in Egypt. A critical question that still remains, however, is how these benefits can be shared when there are contested water rights in the basin. Nevertheless, it is possible to share the benefits through negotiation-based approaches (Alam et al., 2009; Furlong, 2006). All these issues are not captured in this study because of model complexities and data challenges.

[35] The main idea behind benefit sharing is that riparian countries should not seek to share the water itself, but instead share various benefits from the water,a zero-sum game of water sharing being substituted by a positive sum game of benefit sharing (Sadoff and Grey, 2002; Alam et al., 2009; Dombrowsky, 2009).

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Chapter 4: Summary, Conclusion, and Policy Recommendations

4.1 Introduction

This chapter provides a summary of the main results and policy implications of the study. It begins with a brief background description of the economic problem investigated and how demand management approaches, such as water trading, are used to evaluate water use-efficiency in southern Alberta, Canada and an economic modeling approach is applied to assess the impacts of water reallocation in the Nile River Basin, Africa. Next, the key objectives, research methods and major research findings of the key papers are presented. Subsequently, the policy implications of each research paper as well as the overall implications of the study are outlined. The last section deals with limitations of the thesis and future research options.

4.2 Summary and Main Conclusions of the Two Research Papers

The overall purpose of the study was to evaluate how the application of water trading could encourage efficiency of water use among irrigated farmers in southern Alberta, Canada and to assess aggregate economic impacts of water reallocation among Egypt, Sudan and Ethiopia, Africa. Although the study was carried out in two distinct geographical locations, they are linked by a central theme: water scarcity. In both locations, water scarcity is a major challenge to policy makers and relevant key stakeholders. Thus, effective strategies necessary to minimize the impact of water scarcity are imminently needed.

The impact of water scarcity has become more prominent in these areas in recent years because of increasing population growth, urbanization rates, and unexpected changes in climate patterns. Water scarcity occurs when the demand for water is relatively greater than the supply. In the past, traditional water management approaches have focused on strategies to supply more water to multiple users in the society. However, with increasing scarcity issues, the cost of water supply is increasingly high. Policy makers as well as water resource economists have begun to consider the use of demand management principles. Demand management principles are based on the use of economic instruments.

Economic instruments are rooted in the use of market based incentives to stimulate economic agents to adopt certain behavior. The application of economic instruments to encourage water-use efficiency can be found in studies such as Sawyer et al. (2005), Burness and Quirk (1980) and Bjornlund, H. and J. McKay (2002). In this study, an economic instrument in the form of water trading is applied in southern Alberta, Canada (i.e., Chapter Two). Economic modeling approaches are applied to assess the impacts of water reallocation in the Nile River Basin, Africa (i.e., Chapter Three).

In Chapter Two, the study focuses on the application of water trading to encourage water-use efficiency among irrigated farmers in southern Alberta. Irrigated agriculture, which is a major user of water, is mostly practised in the southern part of the province (Alberta Environment, 2002). With increasing demand for water, policy makers are challenged to implement policy to increase efficiency of water use. One of the strategies adopted by the province and the irrigation districts is to promote the use of economic instruments to achieve an increase of 30 percent in overall efficiency and productivity of water use by 2015, relative to 2005 levels (Alberta Water Council, 2008).

This chapter contributes to this policy agenda by exploring how economic instruments such as water trading can serve as an incentive for efficient irrigation technologies to be adopted in the South Saskatchewan River Basin (SSRB). The aims of this chapter were achieved through a calibrated short-run profit maximizing farm model. The profit model was a function of land quality, crops, irrigation effectiveness and costs of adopting irrigation technology. Two main policy scenarios were developed: (1) non-drought conditions (i.e., full water allocation) and (2) drought conditions (i.e., scarcity of water). These scenarios were used to examine the gains of water trading and the potential of investing these gains in adopting irrigation technologies and crop choices under restricted and unrestricted models. A restricted model was defined as situations whereby water traders are allowed to switch to efficient irrigation technologies or remain with their current irrigation technology while in an unrestricted model a switch may be made to more or less efficient technology, or the current irrigation technology may be kept, post trade.

Under no-scarcity conditions, the unrestricted model shows limited opportunity for both traders to switch to efficient irrigation technologies, post trade. These results suggest that the gains from water trading do not provide sufficient incentives for traders to switch to efficient irrigation technologies. Under scarcity conditions, however, the unrestricted model results show that traders are more likely to switch to less efficient irrigation technologies, post trade. These results tend to suggest that water trading in these circumstances does not encourage the adoption of efficient irrigation technologies.

Similarly under non-drought conditions, the restricted model results show that farmers are not willing to switch to an improved irrigation technology after water trading. This result indicates that the price of traded water does not serve as an incentive for either the buyer or the seller to switch to an improved irrigation technology, although there are gains in terms of increased crop yield and possible water savings for alternative uses. However, under drought conditions, the restricted model results reveal that farmers are at least somewhat more likely to switch to improved irrigation technology after water trading. Intuitively, this result suggests that during drought years, farmers could trade water and when the potential gains from trading are sufficiently high, it is possible for them to switch to an improved irrigation technology to produce profitable crops, all other things being equal. In addition, the sensitivity analysis shows that during periods of water abundance, farmers are more likely to switch to an improved irrigation technology under subsidy considerations as well as the assurance of higher crop price regimes. These results are consistent with previous studies on irrigation technology adoption (e.g., Caswell and Zilberman, 1986; Dridi and Khanna, 2005; Scheierling et al., 2006), which found that farmers are more likely to adopt an improved irrigation technology when crop prices are high, switching cost of irrigation technology is low, land quality is poor and during scarcity conditions.

In Chapter Three, the economic impact of water reallocation in the Nile River Basin was analyzed in a transboundary water allocation context. As discussed in Chapters One and Three, the Nile River is shared among 10 countries in Africa. Ethiopia, an upstream country which contributes approximately 60 percent of the flows of the river, has no water allocation. The two main downstream countries (i.e., Egypt and Sudan) have full rights to the Nile waters (Awulachew et al., 2008). Ethiopia, which is one of the poorest countries in Africa and persistently faces erratic rainfall patterns, has challenged the validity of the current treaty governing the use of the Nile River (i.e., 1959 Nile River Agreement). This agreement was signed between Egypt and Sudan before any other country within the basin gained independence. Unfortunately, Ethiopia was not included in the agreement.

According to the 1959 agreement, of the annual average of 84 billion cubic meters (BCM) of Nile River water, 66 percent is allocated to Egypt and 22 percent to Sudan with the remaining 12 percent going to surface evaporation and seepage at the Aswan High Dam (Guariso and Whittington, 1987; Waterbury and Whittington, 1998; Küng, 2003; Block, 2007).

Presently, all 10 countries in the Nile River Basin have recognized the benefits of sharing the water for current and future economic development projects within the basin. In order to allow for more equitable use of the Nile water, the Cooperative Framework Agreement (CFA) was signed in 2010 without Egypt and Sudan, which allows upstream countries the opportunity to use the Nile water for irrigation and hydropower developments (IWLP, 2011; NBI, 2011; Arsano, 2011; Conniff, et al., 2012). Six countries in the basin have signed the CFA already, but Egypt and Sudan are still reluctant to any agreement on the Nile unless upstream development projects on the Nile do not adversely affect their water security, current use and historical rights of water allocation (Asano, 2011; Mekonnen, 2010). After unsuccessful attempts to pursue Egypt and Sudan to agree to the current CFA on the Nile, Ethiopia decided to adopt unilateral decision making regarding the use of the Nile waters. As mentioned in the introductory section of Chapter Three, in April 2011, Ethiopia started the construction of the Grand Ethiopian Renaissance Dam (GERD). This dam has a water storage capacity of 63 billion cubic meters and could generate electricity up to a capacity of 6,000MW (Conniff, et al., 2012). The Ethiopian Government stated that the dam will not only provide electricity to Ethiopians, but it can generate surplus energy for all the countries within the basin. However, the concern for Egypt and Sudan still remains that their available water resources might be constrained by the construction of the GERD. Egypt, in particular, stressed that there is limited information of how the GERD would affect downstream flows (Hammond, 2013; Ferrari et al., 2013).

This chapter investigates the economic impact of altering the current agreement among the countries in the basin. Specifically, the study focuses on the Blue Nile River Basin, which is shared among three countries: Egypt, Sudan and Ethiopia. To pursue the objectives of the study, a multi-country Blue Nile Water Computable General Equilibrium (BNW-CGE) was developed.

Unlike previous CGE models developed for the study area (e.g., Robinson et al., 1998; Robinson et al., 2008), the model used in this study explicitly captures the impact of water reallocation in a multi-country context. Another significant contribution of the study to the literature is that the model was augmented with chance constrained programming to assess the impact of water reallocation in the basin under stochastic conditions. Two main simulations were performed to analyze the impact of water reallocation. The first simulation deals with water reallocation under certainty conditions, where the current treaty governing the Nile River is altered as follows: 52.5 BCM to Egypt, 15.5 BCM to Sudan and 6 BCM to Ethiopia. The second simulation deals with stochastic inflow of water reallocation and compares the policy implications relative to the policies of a deterministic model. In this experiment, the source of variation is due to the risk of not getting adequate water at the specified probability level.

The first simulation results show that altering the current agreement governing the Nile River will have minimal impacts on Egypt and Sudan while Ethiopia could benefit from water reallocation. With reallocation, the simulation results show that the GDP of Ethiopia improves by 3.4 percent. Also, the simulation results show that with reallocation, all sectors in Ethiopia are improved. The value-added output of the agricultural sector improves by 9.1 percent (58.886 billion ETB to 64.790 billion ETB), while industrial and services sectors improve by 12.5 percent (11.233 billion ETB to 12.834 billion ETB) and 6.6 percent (25.962 billion ETB to 27.806 billion ETB), respectively. Conversely, when all six BCM is reallocated to Ethiopia, the simulation results show that the GDP of Egypt decreases by 0.5 percent while a decrease of 0.06 percent is observed for Sudan. In Egypt, at the sectoral level, the simulation results show that the value-added output of the agricultural sector decreases by 11.7 percent (43.638 billion EGP to 39.072 billion EGP) while industrial and services sectors increase by 2.8 percent (60.314 billion EGP to 62.039 billion EGP) and 1.5 percent (135.898 billion EGP to 138.001 billion EGP), respectively. Similarly, with water reallocation, the value-added output of the agricultural sector decreases by 8.8 percent (294.735 million SDG to 270.790 million SDG) in Sudan, but the industrial and services sectors improve by 3.2 percent (87.237 million SDG to 90.078 million SDG) and 4.2 percent (192.552 million SDG to 200.987 million SDG), respectively. The impact of decreased agricultural value-added output is shown in the increased imports in Egypt and Sudan.

As the simulation results indicate, public income decreases by 40 percent (48.605 billion EGP to 34.708 billion EGP) in Egypt while a 41 percent decrease (98.417 billion EGP to 69.433 billion EGP) is observed in Sudan. Public income increases by 15 percent (18.022 billion ETB to 21.303 billion ETB) in Ethiopia. This result suggests that public income decreases because the consumption of imported goods increases relative to domestic goods. This places considerable pressure on the current account balances of these countries, as they already run on deficit budgets. In Ethiopia, however, the increased water leads to positive impact in the agricultural and the other sectors. The composite goods supply increases in all the countries with water reallocation. In Egypt and Sudan, the increase in goods supply came from the increased consumption of imported goods while in Ethiopia, this is possible because of the increased domestic output.

Overall, the simulation results show that reallocation of water impacts prices and this leads to competition for productive resources among the agricultural, industrial and services sectors considered for the study. The simulation results reveal that income and substitution effects occur with the shift of productive resources due to price changes, whereby some sectors gain and some sectors lose. Intuitively, improvement in terms of trade in parallel with decreasing domestic prices and wage rates lead to services and industrial sectors becoming competitive in export markets for Egypt and Sudan. However, the net export gains could not compensate for other sectoral losses and rising import levels were observed in these countries. Ethiopia on the other hand gains from water reallocation and experiences an increase in the value added output of the agricultural sector, which could be enough to cause a decrease in the import levels into the country. With the policy change, the simulation results further reveal that Ethiopia could generate net exports while Egypt and Sudan could experience net imports.

The second simulation results which deal with stochastic water reallocation show that at a 95 percent reliability level, the GDP of Egypt and Sudan decrease further by 0.8 percent and 0.07 percent, respectively. With regard to Ethiopia, a slight decrease is observed for its GDP when the results under the stochastic model are compared with the deterministic results. The differences between the outputs for the 95 percent reliability level and the deterministic model represent a cost of risk aversion. Thus, the chance constrained programming (CCP) model shows that without taking risk into account, the countries could be ignoring the risk of 2.02 billion EGP (264.733-262.714 billion EGP), 0.43 million SDG (628.116-627.683 million SDG), and 0.09 billion ETB (159.888-159.8 billion ETB). This indicates that when water is a scarce resource, using a deterministic approach could lead to over estimation or under estimation of policy outcomes in the basin. The value-added output in the agricultural sectors declines in all countries relative to the deterministic model. However, a greater negative impact is observed in Egypt than in Sudan and Ethiopia.

In addition, welfare analysis show that under certainty conditions the welfare of the households in the three countries could be improved. The overall net welfare gain for the three countries is estimated to sum to 3.1 percent across these three countries, GDP. However, under stochastic conditions, results show that the welfare of households in the three countries could be decreased, although Ethiopia still stands to gains from water reallocation. The net welfare loss for the three countries is estimated to sum to 0.53 percent of the GDP. These results tend to suggest that if these countries could cooperate and jointly develop water related projects within the basin, it is possible to mitigate some of these impacts from water reallocation, especially under stochastic conditions.

4.3 Policy Recommendations

Overall, the first case study concludes that the application of water trading could encourage efficiency of water use at the regional level. The study results show that the application of economic instruments such as water trading, under subsidy considerations and high crop prices regimes could encourage farmers to adopt higher efficiency irrigation technologies to produce profitable crops. However, it should be stressed that these instruments are helpful in increasing crop yield and improving farm profit levels. For an effective policy on efficiency of water use with a focus on improving farm profits and conserving water, the adoption of efficient irrigation technologies should be used to cultivate the most profitable crops under careful market considerations.

Given that hydrologic conditions in Alberta vary greatly from year to year, season to season and district to district, water management policies that could lead to efficient water use are required. For example, periods of drought in the SSRB put pressure on available water supplies. There is a need to develop mechanisms to ensure that water is used where it is most valuable. Also, this mechanism when implemented needs to respond to variation in water availability from year to year. One such mechanism could be active water trading in the province. As the model results show, water trading could be beneficial to farmers in the SSRB and eventually making extra water available for other sectors to use in the economy. When water trading is properly implemented, farmers could sell water to users who have high value for the water. Over the years, however, water can be directed to where it is most needed and can provide income to those who sacrifice their water use. Since agriculture is the major user of water, ensuring efficient use of water could increase the amount of food that can be produced. Thus, water management projects that would improve farm yields in the SSRB while balancing the available water supplies with existing demands are relevant for current policy discussions in the province.

In the transboundary African context, simulation results show that when water reallocation occurs, the economies of Egypt and Sudan would be negatively affected while the economy of Ethiopia is improved. As the simulation results indicate, Egypt and Sudan could realize positive net imports from the water reallocation impact, while Ethiopia could see positive net exports. However, in Ethiopia, the increased water cannot be used to improve agricultural output since the potential land area that could be used for large scale irrigation is less than 10 percent (FAO, 1997). Thus, Ethiopia stands to benefit from reallocation if the water is used primarily in other sectors. With the increased water, Ethiopia could benefit by investing in water storage development projects that could have potential ripple effects on the rest of the economy. In this regard, the country could also use the potential allocated water for hydropower generation. These results are further supported by welfare analysis, which shows that reallocation of water could be welfare enhancing for the three countries in the basin. These results point to the need for cooperation in the Nile River basin, if the three countries seek to minimize the impacts from water reallocation.

Additionally, results from the stochastic analysis show that there is a significant loss in composite good supply to Egypt and Sudan while a minimal negative impact occurs in Ethiopia. Although there are benefits associated with reallocation of water among the countries, it is imperative to develop strategies necessary to mitigate future risks in water reallocation. As the benefits from reallocation are not as certain when risks are considered, it may be appropriate for the countries to cooperate and explore strategies necessary to minimise risks while maximizing the benefits from reallocation. Under a cooperative agreement, the countries could jointly develop strategies necessary to mitigate the risks of water allocation in the basin. As the simulation results reveal, Egypt and Sudan stand to lose more than Ethiopia when risks are captured in water reallocation. The cost implications of water reallocation under stochastic conditions to Egypt and Sudan should provide an enabling environment toward cooperation in the basin.

With the incorporation of risk, the model shows that the value-added output of the industrial and services sectors improve, but a substantial loss is observed in the agricultural sectors. Hence, policies are needed to improve efficiency of water use in this sector. In this regard, demand management measures which aimed at improving efficiency of water use could be adopted and monitoring and routine evaluation of the flow of the Nile River is also recommended. The findings from the study could help policy makers in the basin to establish rational water supply patterns under complex uncertainties, and gain in-depth insights into the trade-offs between the benefits of reliable water supply and associated costs.

This study contributes to the water resource economics literature both methodologically and in an applied sense. This is not the first study to apply the farm level profit model to examine the irrigation technology adoption and the influence of land quality. However, it is the first study to examine the impact of land quality and irrigation technology adoption in southern Alberta, Canada. Also, the study contributes to the body of knowledge by sequentially modeling the gain from water trading and the likelihood of farmers adopting improved irrigation technologies and profitable crops, post trade. The chapter on CGE modeling contributes to the body of knowledge of the water literature by examining the economic impact of water reallocation in a multi-country context. In addition, the study uses a novel model to analyze the impact of water reallocation, hence adding to the body of knowledge methodologically. The CGE model used in study contributes academically by not only examining the impact of water reallocation under certainty conditions, but also the incorporation of water reallocation under stochastic conditions through the chance constrained programming (CCP).

4.4 Limitations and Future Research Opportunities

There are several ways in which the current study on efficiency of water use in Canada and Africa could be extended. For example, in the case of the Canadian study in the context of southern Alberta, transaction costs were assumed to be zero during water trading. However, many previous studies have found that transaction cost is one of the critical factors that limit the potential gains from water trading. In this study, it was not possible to include this part in the model because of data limitations. Future study may also focus on the differences in water trading and irrigation technology adoption behavior for the different districts in the SSRB. Farmers in the districts use different irrigation technologies to produce various crops for the market. Hence, it will be necessary to investigate whether the adoption decisions of farmers would be different after water trading across the districts. Also, the means by which to apply the current model to achieve optimality between water-use efficiency and energy efficiency is ignored. Efficient irrigation technologies could help in reducing the amount of water applied to the crop, but these technologies also require high amounts of energy to operate. Thus, there is the need to strike a balance between achieving water-use efficiency by using efficient irrigation technologies that requires less energy as well. This aspect was not captured in this study because of data limitations and the challenges of calibrating the model with an explicit energy parameter to replicate the baseline model.

In this study, water supply is assumed to be certain and year to year variations are not considered in the model. Given that hydrologic conditions in Alberta vary greatly from year to year, season to season, and district to district, policies that could improve reliable water supply are needed. In wet years residents experience the effect of floods, while in drought years the ability of fixed supplies of water to meet demands is in question. It is pertinent to extend the current model to include water supply uncertainty. Also, agricultural crop prices are subject to market forces, which could cause great year to year variations in farmers' crop production decision making processes. Although the sensitivity analysis shows that changes in crop price have less impact on the model results, it would be important to extend the model to capture crop price uncertainty and the impacts on farm yield and profits in the SSRB. It should be stressed that both water supply and crop price uncertainties are not included in the current study because of time and computer programming difficulties of choosing appropriate distributions to best describe the data for the stochastic simulation.

One key assumption used to model the gains from irrigation technology adoption is that farmers are more likely to adopt efficient irrigation technologies after water trading to grow profitable crops. However, it is possible that farmers would rather keep their current irrigation technologies or switch to a less efficient irrigation technology because of high fixed costs or due to uncertainties associated with the benefits of adopting efficient irrigation technologies. Although the incorporation of these factors may not affect the current results, it could be an improvement for further studies on irrigation technology adoptions and crop choices in SSRB. Especially, it will be relevant to examine different factors to examine why farmers are more likely to switch to less efficient irrigation technologies after water trading. Also, the effect of market dimensions on irrigation technologies and crop choices were not explicitly incorporated into the current model. Crop price increases could influence farmers' decisions on certain types of irrigation technologies to be adopted. Also, some crops require special marketing arrangements and this could affect farmers' decision to adopt efficient irrigation technologies, which have high adoption costs. All these possibilities could be considered in a future study in the SSRB.

With regard to the African component of the study, water was modeled as a Leontief production function together with land. The main database for CGE model is the Social Accounting Matrix (SAM). The SAMs collected from these countries had only capital, labor and land as the main inputs. Thus, water and land were calibrated in a Leontief production function to replicate the benchmark total land in the SAM. Since this production function has several limitations (i.e., as noted in Chapter Three), it would be appropriate to adopt a more flexible functional form for future studies in the basin. One key result of the study is that water reallocation could be welfare enhancing for the three countries. However, the critical question still remains on how to equitably share the benefits among the countries. This question could be addressed in a future study. Finally, the model developed in this study was applied only to the Blue Nile River Basin. It would be relevant to extend it to cover all 10 countries in the Nile River Basin. In this regard, a basin-wide approach that focuses on the policy implications of water reallocation among the countries could be used.

This current study show that with reallocation, the economy of Ethiopia could improve while the Egypt and Sudan stand to lose. However, the scenario developed for this analysis focuses on general impacts from water reallocation. Since the Government of Ethiopia is currently developing one of the largest dams in Africa, it would be relevant to extend the current study to examine the costs and benefits of electricity supply among the three countries. In carrying out this study in the future, a detailed electricity supply model should be developed as part of the disaggregated sectors of the economy. On the production side, the current model could be extended to incorporate energy as part of the value-added CES nesting structures. Total energy commodities could be divided into electricity and non-electricity and this in turn will form the energy composite nest. The energy composite should be combined with capital to produce an energy-capital composite CES nesting structures. This is in turn combined with other primary factors in a value-added-energy composite CES nesting structure. A detailed electricity component was not included in the current study because of data limitations and time requirement for the calibration approach.

In accordance with the scope of the study, changes in water allocation with more consumptive sectors and less-consumptive sectors were not specified. All sub-sectors in each of the four sectors considered were aggregated together for the simulation analysis. This could limit the magnitude of the impact of the changes in the rest of the economy due to water reallocation. One possible area for future research is to account for the distinction between major consumptive and non-consumptive sectors when evaluating the impact of water reallocation on the economy. Another interesting avenue of research could be to investigate the extent to which the normality assumption of the CCP model could influence the model results. In the CCP model, normality is usually assumed for the random variable and this need to be tested rather than assumed. With the CCP model, assuming normality when the distribution is not normal biases the results of the analysis. The test of normality was not possible to perform in this study because of data limitations. Finally, it is possible that when the countries adopt benefit-sharing principles, some of the negative impacts could be reduced. This is especially so given the current status that Ethiopia is developing one of the largest dams in the basin. If the countries jointly work with Ethiopia on this project, it may be possible to minimize the impacts from reallocation. The benefits from this strategy could be shared through negotiation-based approaches. Future studies could incorporate these aspects in the economic modeling problem and examine the benefits of cooperative management approaches in the basin. Given data limitations and model complexities, these aspects were not considered in this current study.

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Appendix A: Irrigated Areas Occupied by the 13 Irrigation Districts in (acres)

Crop types	AID	BRID	EID	LID	LND	MID	MVID	RCID	RID	SMRID	TID	UID	WID	Total Irrigated area	Percentage share of irrigation
Tame grass	72	9676	49208		5426	1207			1522	8439	2737	1245	3382	82914	6.84
Barley	1288	15537	20100	265	19195	1555	349	157	7938	18638	9628	4143	7387	106180	8.76
HRS wheat		51,301	43292		5518	1446			4720	70,393	13081	1006	1061	191818	15.83
SWS wheat		8129	175		6493				320	24219	1669		2156	43161	3.56
Alfalfa two		3890	39372							12492		2188	5798	63740	5.26
Alfalfa three		118	1616							2979	366			5079	0.42
Barley silage		2941	5912		42968	281			721	10335	1127		3479	67764	5.59
Silage corn		4252	10720		20880			122	1439	13387	3001		414	54215	4.47
Canola	135	17317	34580		22574	2278		116	8684	54974	3330	3380	8323	155691	12.85
Flaxseed		6192	10279		1248	90				2770	161			20740	1.71
Dry bean		7668	1633							18915	1694			29910	2.47
Potatoes			11585	2627		838				16863	9973	2	400	42288	3.49
Sugar beets			11493	1282		3908				12536	6379			35598	2.94
Total for each district	2961	202478	287405	4714	175666	12774	3617	770	37163	346078	75048	21003	42320	899098	74.18
Total irrigated area for all District														1211997	

Source: Alberta Agriculture, Food and Rural Development (2011)

Appendix B: Crop Prices($/t) from 1990 to 2010

Year	Sugar beets	Potatoes	Dry beans	Canola	Barley	All wheat	Flaxseed
1990	47.997	168.330	445.423	302.991	97.114	126.461	234.933
1991	35.617	149.220	371.572	264.185	85.617	116.192	172.115
1992	41.744	215.190	525.565	300.736	90.367	120.085	234.963
1993	42.026	216.420	646.622	338.82	83.0165	132.823	248.846
1994	45.885	211.630	584.087	373.402	104.345	183.800	285.963
1995	45.562	206.870	570.953	387.991	161.378	218.358	305.393
1996	42.959	182.760	696.873	407.783	120.831	154.735	322.764
1997	48.300	163.800	597.447	377.868	119.418	143.298	318.110
1998	33.403	189.650	603.143	341.854	104.790	136.087	314.576
1999	34.025	183.390	495.126	244.375	96.955	117.229	238.317
2000	41.563	234.600	669.206	308.646	130.023	165.480	259.888
2001	57.810	212.640	739.425	357.991	164.909	191.681	340.831
2002	44.676	236.180	756.252	425.710	189.893	221.164	407.408
2003	49.642	234.180	524.860	401.605	153.536	180.601	408.580
2004	51.694	215.170	577.674	398.448	138.704	173.402	429.465
2005	50.642	217.740	590.717	294.615	110.048	141.768	393.710
2006	43.941	207.210	516.106	295.532	113.890	130.100	244.699
2007	44.597	192.130	630.066	386.544	171.011	190.618	339.057
2008	45.730	209.440	774.035	489.862	209.900	289.168	581.102
2009	44.086	246.460	779.526	438.194	168.242	218.066	405.846
2010	52.644	223.070	607.380	417.301	144.743	171.508	427.628

Note: 1990-1999(converted using 1997Alberta Consumer Price Index): 2000-2010(Converted using 2008 Alberta Consumer Price Index). Source: Agriculture Statistics Year Book, 2010.

Appendix C: T-test Results for Price Periods (1990-1999; 2000-2010)

		Paired Differences					t-values	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference: Lower	Upper			
Pair 1	sug - sug1	-5.686	8.196	2.592	-11.549	0.177	-2.194	9	.056
Pair 2	pot - pot1	-31.849	23.397	7.399	-48.586	-15.112	-4.305	9	.002
Pair 3	dry - dry1	-102.106	180.567	57.100	-231.276	27.064	-1.788	9	.107
Pair 4	can - can1	-45.714	99.436	31.445	-116.847	25.419	-1.454	9	.180
Pair 5	bar - bar1	-48.633	48.595	15.367	-83.395	-13.870	-3.165	9	.011
Pair 6	whet - whet1	-45.298	68.006	21.506	-93.947	3.351	-2.106	9	.064
Pair 7	flx - flx1	-113.461	99.797	31.559	-184.851	-42.070	-3.595	9	.006

Note : sug(sugar beets), pot(potatoes), dry(dry beans), can(Canola), bar(Barley), whet(Wheat), Fix(Flaxseed)

Appendix D: Selected Fixed Costs for Irrigation Technologies

Irrigation Technologies	Lower values of fixed cost of Irrigation Technology ($/ha)	Moderate values of fixed cost of Irrigation Technology ($/ha)	Higher values of fixed cost of irrigation Technology ($/ha)
Gravity-flood	310	315	458
Gravity-developed	645	703	990
Sprinkler-wheel move	1042	821	1360
Sprinkler-high pressure	1167	1109	1665
Sprinkler-low pressure	1600	1838	2055
Micro-Drip	2720	4725	5059

Source: Fixed cost of Irrigation Technology(Irrigation Water Management Study Committee,2002.vol.5)

Appendix E: Illustration of Price and Amount of Water Exchanged

1000 iterations	Minimum	Mean	Median	Standard deviation	Maximum
Price of water($/ha/mm)	1.43	4.11	3.82	1.47	9.18
Amount of water exchanged(mm)	2.72	236.73	227.66	140.378	494.70

Note: These values depend on irrigation technologies and crops and the random values of land qaulity.

Appendix F: Mathematical Derivation of equations, optimal conditions of the Model

Let

c	Denote crops
P^c	Vector of output price for crops
a_0, a_1, a_2	Represent the constants of production function
ETp^c	Crop potential evapotranspiration
ETa	Actual evapotranspiration
SSM	Spring Soil Moisture
$PRCP$	Effective Precipitation

(A) Irrigation technology choice consideration

Let

θ_i	Represent farmer heterogeneity (i.e., differences in land quality, management skills, etc.)
t	Type of irrigation technology measured in terms of application efficiency
w_i^{tc}	Applied water (mm)
$\overline{w}_i$	Total water allocated to the farmer
e_i^{tc}	Effective water use
$h_i^t(\theta_i)$	Irrigation effectiveness of technology t

(B) Production Function Considerations

Let

y_i^{tc} Actual yield per crop per hectare

$y_i^{tc} = f(Z)$

$$Z = \frac{ETa + w_i^{tc} h_i^t(\theta_i)}{ETp^c} \quad \text{(F.1)}$$

Using equation (F.1), the augmented production function for farmer i can be formulated as;

$$y_i^{tc}(w_i^{tc}, h_i^t(\theta_i)) = \left(a_0 + a_1(Z) + a(Z^2)\right).Yp_i^c \quad \text{(F.2)}$$

(C) Profit maximization and irrigation technology choice

Let π_i^{tc} denotes quasi-rent per ha at this stage for irrigation technology t and crop c.
Then,

$$\pi_i^{tc} = \max_{w_i^{tc}} (P^c y_i^{tc}(Z) - g^t w_i^{tc} - k^t) \qquad \text{(F.3)}$$

Subject to: $0 \leq w_i^{tc} \leq \overline{w}_i$

FOC for equation (F.3) is expressed as:

$$\frac{\partial \pi_i^{tc}}{\partial w_i^{tc}} = P^c y_i^{tc'}(Z) h_i^t(\theta_i) - g^t = 0, \ \forall \theta \qquad \text{(F.4)}$$

$$\frac{\partial^2 \pi_i^{tc}}{\partial w_i^{tc^2}} < 0 \qquad \text{(F.4.1)}$$

Equation (F.4) shows that optimal production occurs when the value of the marginal product of effective water is equal to its price. The concavity of the production function ensures that equation (F.4.1) is satisfied (Caswell and Zilberman, 1986; Dridi and Khanna, 2005).

From equation (F.4), we obtain equation (F.4.2) as below:

$$P^c \left(\frac{a_1}{ETp_i^c} - 2a_2 \left(\frac{ETa + w_i^{tc} h_i^t(\theta_i)}{ETp_i^c} \right) \frac{1}{ETp_i^c} \right) h_i^t(\theta_i) - g^t = 0 \qquad \text{(F.4.2)}$$

$$\frac{2a_2 w_i^{tc} h_i^t(\theta_i)}{ETp_i^{c^2}} = \frac{a_1}{ETp_i^c} - \frac{2a_2 ETa}{ETp_i^{c^2}} - \frac{g^t}{P^c h_i^t(\theta_i)} \qquad \text{(F.4.3)}$$

By simplifying and rearranging equation (F.4.3), we obtained the interior solution as:

$$w_i^{tc^*} = \frac{a_1 ETp_i^c}{2a_2 h_i^t(\theta_i)} - \frac{ETp_i^{c^2} g^t}{2a_2 P^c h_i^t(\theta_i)^2} - \frac{ETa}{h_i^t(\theta_i)} \qquad \text{(F.5)}$$

Let $\hat{\pi}_i^{tc}$ denote the second stage quasi-rent for farmer i and $\hat{P}^c$, $\hat{y}_i^{tc}$, $\hat{g}_i^t$, and $\hat{k}^t$ are the associated output price, yield, variable irrigation costs and fixed costs of irrigation technology. Given optimal quantity of water use in equation (F.5), the optimization decision process at this stage can be formulated as:

$$\hat{\pi}_i^{tc} = \max_{t,c} (\hat{P}^c \hat{y}_i^{tc}(Z) - \hat{g}_i^t w_i^{tc^*} - \hat{k}^t) \qquad \text{(F.6)}$$

(D) Bilateral Water Trading

From equation (F.3), farmer i and j profit maximization decision making processes before water trading can be specified as:

$$\pi_i^{tc}(w_i^{tc}, h_i^t(\theta_i)) = P_i^c y_i^{tc}(w_i^{tc}, h_i^t(\theta_i)) - g_i^t w_i^{tc} - k_i^t \tag{F.8}$$

$$\pi_j^{tc}(w_j^{tc}, h_j^t(\theta_j)) = P_j^c y_j^{tc}(w_j^{tc}, h_j^t(\theta_j)) - g_j^t w_j^{tc} - k_j^t \tag{F.9}$$

The first order conditions from equations (F.8) and (F.9) are:

$$\frac{\partial \pi_i^{tc}}{\partial w_i^{tc}} = P_i^c \left(\frac{a_{1i}}{ETp_i^c} - 2a_{2i} \left(\frac{ETa + w_i^{tc}(\theta_i)}{ETp_i^c} \right) \frac{1}{ETp_i^c} \right) h_i^t(\theta_i) - g_i^t = 0 \tag{F.10}$$

$$\frac{\partial \pi_j^{tc}}{\partial w_j^{tc}} = P_j^c \left(\frac{a_{1j}}{ETp_j^c} - 2a_{2j} \left(\frac{ETa + w_j^{tc}(\theta_j)}{ETp_j^c} \right) \frac{1}{ETp_j^c} \right) h_j^t(\theta_j) - g_j^t = 0 \tag{F.11}$$

We define the trading rules as follows: if $\dfrac{\partial \pi_i^{t_i c_i}}{\partial w_i^{t_i c_i}} \neq \dfrac{\partial \pi_j^{t_j c_j}}{\partial w_j^{t_j c_j}}$, there are mutually gainful trade opportunities assuming that transaction cost is zero. Suppose that $\dfrac{\partial \pi_i^{t_i c_i}}{\partial w_i^{t_i c_i}} > \dfrac{\partial \pi_j^{t_j c_j}}{\partial w_j^{t_j c_j}}$, farmer i buys water from farmer j for both private gains and investment in efficient irrigation technologies and the opposite is true for farmer j. Let $w_{ji} \equiv w_{ji}(\theta_i, \theta_j)$ be the amount of water exchanged between the farmers. If trade occurs between these farmers, we can derive the amount of water exchanged as;

$$\frac{\partial \pi_i^{t_i c_i}(w_i^{t_i c_i} + w_{ji})}{\partial w_i^{t_i c_i}} = \frac{\partial \pi_j^{t_j c_j}(w_j^{t_j c_j} - w_{ji})}{\partial w_j^{t_j c_j}} \tag{F.12}$$

From equation (F.12), we simplify and rearrange to obtain equation (F.12.1) below:

$$\frac{P_i^{c_i} a_{1i} h_i^{t_i}(\theta_i)}{ETp_i^{c_i}} - \frac{2P_i^{c_i} a_{2i} {h_i^{t_i}}^2(\theta_i) w_i^{t_i c_i}}{{ETp_i^{c_i}}^2} - \frac{2P_i^{c_i} a_{2i} h_i^{t_i}(\theta_i) w_{ji}}{{ETp_i^{c_i}}^2} - \frac{2P_i^{c_i} a_{2i} h_i^{t_i}(\theta_i) ETa}{{ETp_i^{c_i}}^2} - g_i^{t_i} = \frac{P_j^{c_j} a_{1j} h_j^{t_j}(\theta_j)}{ETp_j^{c_j}} - \frac{2P_j^{c_j} a_{2j} {h_j^{t_j}}^2(\theta_j) w_j^{t_j c_j}}{{ETp_j^{c_j}}^2} + \frac{2P_j^{c_j} a_{2j} h_j^{t_j}(\theta_j) w_{ji}}{{ETp_j^{c_j}}^2} - \frac{2P_j^{c_j} a_{2j} h_j^{t_j}(\theta_j) ETa}{{ETp_j^{c_j}}^2} - g_j^{t_j}$$

From equation (F.12.2), we further simplify and rearrange to obtain the solution for the amount of water traded $w_{ji}(\theta_i, \theta_j)$; i.e., equation (F.13) below:

$$w_{ji} = \frac{\frac{a_{1i} P_i^{c_j} h_i^{t_i}(\theta_i)}{ETp_i^{c_i}} - \frac{a_{1j} P_j^{c} h_j^{t_j}(\theta_j)}{ETp_j^{c}} - \left(\frac{2a_{2j} P_j^{c_j} {h_j^{t_j}}^2 (\theta_j) w_j^{t_j c_j}}{ETp_j^{c_j\,2}} - \frac{2a_{2i} P_i^{c_i} {h_i^{t_i}}^2 (\theta_i) w_i^{t_i c_i}}{ETp_i^{c_i\,2}} \right) - 2ETa. \left(\frac{a_{2j} P_j^{c_j} h_j^{t_j}(\theta_j)}{ETp_j^{c_j\,2}} - \frac{a_{2i} P_i^{c_i} h_i^{t_i}(\theta_i)}{ETp_i^{c_i\,2}} \right) + g_j^{t_j} - g_i^{t_i}}{2. \left(\frac{a_{2i} P_i^{c_i} h_i^{t_i}(\theta_i)}{ETp_i^{c_i\,2}} + \frac{a_{2j} P_j^{c_j} h_j^{t_j}(\theta_j)}{ETp_j^{c_j\,2}} \right)}$$

Appendix G: Matlab Code for Water Trading Simulation

****

G.K.Danso PhD Thesis Main code (2014): All parameters and associated values are presented in the main body of the thesis (Chapter 2).

Requires water (w.m), yield(y.m), profit(Pr.m), trade and simul

Warning: Code is sensitive (Matlab 7.4)

clear all

clc

format short

format compact

% Global constants

Crop potential evapotranspiration (ETp); Output price (P); Actual evapotranspiration (ETa); Production coefficient (a0, a1, a2); Irrigation technologies (tech); land quality (th_Lc)

global ETp P a0 a1 a2 Prec tech3 th_L c

global b1 b2 b3 b4 b5 b6

global crop Alloc

global Results Niter

Niter=5;

Results=zeros(Niter,14);

%Allocation (mm):457.2-609.6 mm (18-24 inches) depending on districts.

%Allocation(mm):228.6-304.8mm(9-12inches) under scarcity

%Precipitation(Prec) + average spring soil moisture(ARD,2009)

%Alberta Irrigation Information(2008) Approx. value.[250-300];ARD,2009

crop={'Alfalfa','Barley','Barley Silage','Canola','Dry Beans','Tame Grass','HRS/Durum Wheat','SWS Wheat','Potatoes','Sugar Beets','Flaxseed','Silage Corn'};

(Data sources: Alberta Agriculture Statistics Yearbook 2006; Service bulletin: Canadian Potato Production, Statistics Canada 2007; Kaliel et al.,2008: 2006 Cost and Return Guide, ARD(2006-2008))

% P: Price ($/t) for 12 crops (for 2006)

```
P = [88 170 39 415.34 500.03 95 381.03 314.16 194.58 43.24 338.95 35];

% Coefficients of a quadratic production function for 12 crops

A0=[-0.297 -0.299 -0.201 -0.021 -0.650 -0.334 -0.291 -0.291 -0.618 -0.501 -0.021 -0.364];

A1=[1.272 1.696 2.763 1.121 2.498 1.781 1.628 1.628 2.467 2.528 1.121 2.57];

A2=[-0.313 -0.644 -0.244 -0.360 -1.038 -0.701 -0.557 -0.557 -1.014 -1.144 -0.360 -1.335];

% Calibration coefficients

Ka=[1.44 1.18 1.18 1.22 1.22 1.20 1.20 1.20 1.19 1.19];

Km=[3.95 2.05 1.30 7.50 1.20 2.00 11.50 11.10 7.50 9.85];

% Maximum yield

B0=[-2970 -2990 -2010 -21 -6500 -334 -291 -437 -6180 -5010];

B1=[12720 16960 27630 1121 24980 17810 1628 2442 24670 25280];

B2=[-3130 -6440 -2440 -360 -10380 -7010 -557 -836 -10140 -11440];

%ETp values for Alfalfa, Sugar beet, Barley, and SWS wheat, all other values

%are from Cobb and Krogman,Kulshreshtha and Tewari,1991,ARD website, AIPA

%Crop Potential (ETp) evapotranspiration (mm)

ETm=[604.52 401.32 401.32 452.12 604.52 550 401.32 452.12 502.92 467 375.92 510];

%ETm=[604.52 401.32 510 550 401.32 401.32 452.12 452.12 375.92 502.92 467 604.52];

ETp=ETm;

%Ym=Km.*(B0+B1.*ETm/1000+B2.*(ETm/1000).^2)/1000;

%Potential yields value(Kulshreshtha and Tewari,1991,ARD website,UMA(1982)

% Converting tmp(acre Ym to ha Ym per ton)

Ym=[5.5*tmp 2.6*tmp 11*tmp 1.4*tmp 1.1*tmp 8.44 2*tmp 2.7*tmp 20*tmp 25*tmp 1.2*tmp
9*tmp];

%Ym=[5.71 15.58 3.42 33.93];

%Ym=[5.5*tmp 11*tmp 9*tmp 8.44 2.6*tmp 2*tmp 2.7*tmp 1.4*tmp 1.2*tmp 20*tmp 25*tmp
1.1*tmp];

a0=-Ym.*A0;
```

```
a1=Ym.*A1;

a2=-Ym.*A2;

% Percentage of lands using each irrigation method

q1=0.0657; q2=0.0533;q3=0.2005;q4=0.1882;q5=0.4881;q6=0.0042;

% Values for alpha

% Irrigation: Gravity-flood, Gravity-dev, Sprinkler-move, Sprinkler-high,

% Sprinkler-low, Micro(efficiency figures from AIPA report,Vol 5)

b1=log(0.30)/log(.5);

b2=log(0.62)/log(.5);

b3=log(0.70)/log(.5);

b4=log(0.74)/log(.5);

b5=log(0.80)/log(.5);

b6=log(0.87)/log(.5);

b=[b1, b2, b3, b4, b5, b6];

tech3=b;

g=[0.1075 0.099 0.319 0.351 0.293 0.279];

c=[310 990 1360 1665 1600 2720];
```

****

These functions calculate optimal water, crop yield and profits, marginal benefits and best choice of irrigation technologies and crops. These are the pre-trade functions for the simulation. Inputs require are land quality (t), irrigation technology (tech), crops (crop) and global parameters such as moisture (i.e., ETp, Prec), output price(P), production function coefficient(a0 a1 a2), variable cost of irrigation (g), and water allocation (Alloc).

Optimal applied water (mm): This function calculate optimal water for irrigation technology and crops

```
function w_s = w(t,tech,crop)
global ETp Prec P a0 a1 a2 g Alloc th_L:
global b1 b2 b3 b4 b5 b6
alpha=0;
if tech==1
   alpha=b1;
```

```
    g(tech)=0.1075;
end
if tech==2
    alpha=b2;
    g(tech)=0.099;
end
if tech==3
    alpha=b3;
    g(tech)=0.319;
end
if tech==4
    alpha=b4;
    g(tech)=0.351;
end
if tech==5
    alpha=b5;
    g(tech)=0.293;
end
if tech==6
    alpha=b6;
    g(tech)=0.279;
end
h=th_L+t.^alpha;
w=(ETp(crop)*a1(crop)./(2*a2(crop)*h))-(ETp(crop).^2*g(tech)./(2*P(crop)*a2(crop)*h.^2))-
(Prec./h); % calculate optimal water
w_s= min(Alloc,max(0,w)); % restrict water use
end
```

Production function (t/ha): This function calculate optimal yield for irrigation technology and crop

```
function z=y(w,t,tech,crop)
global ETp a0 a1 a2 Prec th_L
global b1 b2 b3 b4 b5 b6
alpha=0;
if tech==1
    alpha=b1;
end
if tech==2
    alpha=b2;
end
if tech==3
    alpha=b3;
end
if tech==4
    alpha=b4;
```

```
end
if tech==5
   alpha=b5;
end
if tech==6
   alpha=b6;
end
h=th_L+t.^alpha;
z=max(0,-a0(crop)+a1(crop).*(h.*w+Prec)./ETp(crop)-a2(crop).*((h.*w+Prec)./ETp(crop)).^2);
% calculate yield
end
```

Optimal profit ($/ha): This function calculates optimal profit for irrigation technologies and crops

```
function P_s=Pr(w,t,tech,crop)
% P: price ($/t); gw: irrigation cost $/ha; c: irrigation capital cost ($/ha)
global P g ETp a0 a1 a2 Alloc C_Matrix th_L
global b1 b2 b3 b4 b5 b6 CropCost c
alpha=0;
tmp=2.47105381;
if tech==1
   alpha=b1;
   c=310;
end
if tech==2
   alpha=b2;
   c=990;
end
if tech==3
   alpha=b3;
   c=1360;
end
if tech==4
   alpha=b4;
   c=1665;
end
if tech==5
   alpha=b5;
   c=1600;
end
if tech==6
   alpha=b6;
   c=2720;
end
h=th_L+t.^alpha;
```

```
P_s=P(crop).*y(w,t,tech,crop)-g(tech)*w- (tech);% calculate optimal profit
end
```

Marginal benefit function: This function calculates marginal benefit for irrigation technologies and crops

```
function M_x = mz(w,t,tech,crop):
global ETp P a1 a2 g Prec th_L
global b1 b2 b3 b4 b5 b6
if tech==1
   alpha=b1;
   g(tech)=0.1075;
end
if tech==2
   alpha=b2;
   g(tech)=0.099;
end
if tech==3
   alpha=b3;
   g(tech)=0.319;
end
if tech==4
   alpha=b4;
   g(tech)=0.351;
end
if tech==5
   alpha=b5;
   g(tech)=0.293;
end
if tech==6
   alpha=b6;
   g(tech)=0.279;
end
h=th_L+t.^alpha;
M_x=P(crop)*h*(a1(crop)./ETp(crop)-2*a2(crop)*(Prec+w*h)./ETp(crop).^2)-g(tech);
end
```

Crop technology choice function1: This function selects the best irrigation technology and crops pre-trade based on the maximum profit condition.

```
function choice_s=choice(t,ChoosedCrop)
PrR=zeros(6,12);
for tech=1:6
  for crop=1:12
     if(crop ~= ChoosedCrop)
        PrR(tech,crop)= -inf;
     else
```

```
            wtemp=w(t,tech,crop);
            PrR(tech,crop)=Pr(wtemp,t,tech,crop);
        end
    end
end
PrR
[tmp,i_t]=max(PrR);
[tmp,i_c]=max(max(PrR));
choice_s=[i_t(i_c) i_c]
end
```

***These functions are used to create the trading rules for the farmers. The functions are amount of water that set the marginal benefits equal before trade, trading conditions which are based on marginal benefits and land quality, amount of water exchanged, price of water and other functions to search for optimal water traded and equivalent prices for post-trade conditions.

Equilibrium amount of water: This function set the marginal benefits of the farmers equal before trading

```
w_b = wbar(t1,tech1,crop1,t2,tech2,crop2)
global P ETp Prec a1 a2 g th_L
global b1 b2 b3 b4 b5 b6
% lineare term
a11=a1(crop1);
a12=a1(crop2);
% quadratic term
a21=a2(crop1);
a22=a2(crop2);
ETp1=ETp(crop1);
ETp2=ETp(crop2);
P1=P(crop1);
P2=P(crop2);
if tech1==1
    alpha1=b1;
    g1=0.1075;
end
if tech1==2
    alpha1=b2;
    g1=0.099;
end
if tech1==3
    alpha1=b3;
    g1=0.319;
end
if tech1==4
```

```
    alpha1=b4;
    g1=0.351;
end
if tech1==5
    alpha1=b5;
    g1=0.293;
end
if tech1==6
    alpha1=b6;
    g1=0.279;
end
if tech2==1
    alpha2=b1;
    g2=0.1075;
end
if tech2==2
    alpha2=b2;
    g2=0.099;
end
if tech2==3
    alpha2=b3;
    g2=0.319;
end
if tech2==4
    alpha2=b4;
    g2=0.351;
end

if tech2==5
    alpha2=b5;
    g2=0.293;
end
if tech2==6
    alpha2=b6;
    g2=0.279;
end
h1=th_L+t1.^alpha1;
h2=th_L+t2.^alpha2;
v11=P1*h1*a11/ETp1;
v12=P2*h2*a12/ETp2;
v21=2*P1*h1*a21/ETp1^2;
v22=2*P2*h2*a22/ETp2^2;
temp=(v22*h2-v21*h1);
if(temp==0)
    temp=10^(-4);
```

```
end
%w_b=(v12-v11-g2+g1)./temp;
w_b=(v12-v11-g1+g2+Prec*(v21-v22))./temp;
end
```

Amount of water exchanged (traded water): Optimal amount of water exchanged between the traders

```
%x is a function of crop1*tech1*crop2*tech2 Matrix
function [x]=FuncFindx(t1,t2)
global P a1 a2 tech3 Alloc ETp g Prec th_L
h1=th_L+t1*tech3;
h2=th_L+t2*tech3;
x=zeros([12,6,12,6]);% water
% x=zeros([1,6,1,6]);
for crop1=1:1:12
   for tech1=1:1:6
      for crop2=1:1:12
         for tech2=1:1:6
%              if(crop1 ~= ChoosedCrop | crop2~= ChoosedCrop)
%                 x(crop1,tech1,crop2,tech2)= inf ;% amout of water is zero.
%              else
               F1=P(crop2)*a1(crop2)*h2(tech2)/ETp(crop2);
               F2=P(crop1)*a1(crop1)*h1(tech1)/ETp(crop1);
               D1=P(crop2)*a2(crop2)*h2(tech2)/ETp(crop2);
               D2=P(crop1)*a2(crop1)*h1(tech1)/ETp(crop1);
               Up=(F1-F2)-2*Alloc*(D1*h2(tech2)/ETp(crop2)-D2*h1(tech1)/ETp(crop1))-
2*Prec*(D1/ETp(crop2)-D2/ETp(crop1))+g(tech2)-g(tech1);
               Bottom=(D1/ETp(crop2)+D2/ETp(crop1));
               x(crop1,tech1,crop2,tech2)=0.5*Up/Bottom;
%              end
         end
      end
   end
end
```

Price of water: This function calculates and search for the price of traded water

```
function p=FuncFindpp(t1,t2)
p=zeros([12,6,12,6]);
for crop1=1:1:12
   for tech1=1:1:6
      for crop2=1:1:12
         for tech2=1:1:6
%              if(crop1 ~= ChoosedCrop | crop2~= ChoosedCrop)
%                 p(crop1,tech1,crop2,tech2)= inf ;% price of water is zero.
%              else
```

```
                 wb=wbar(t1,tech1,crop1,t2,tech2,crop2);
                % x=FuncFindx(t1,t2);
                 Fb=mz_t(wb,t1,tech1,crop1);
                 p(crop1,tech1,crop2,tech2)=Fb;
%                end
          end
       end
   end
end
```

Crop technology choice function2: This function check if the post-trade profits are greater or equal to the pre-trade profits.

```
Function jp=jumptrade(X,t_s,t_b)
global Alloc;
PrS=zeros(6,12);
PrB=zeros(6,12);
for (tech=1:6)
   for (crop=1:12)
%         PrS(b,c)=Pr(w(ts,b,c)-X,ts,b,c);
%         PrB(b,c)=Pr(w(tb,b,c)+X,tb,b,c);
      PrS(tech,crop)=Pr(w(t_s,tech,crop),t_s,tech,crop);
      PrB(tech,crop)=Pr(w(t_b,tech,crop),t_b,tech,crop);
          end
      end
[tmp,i_ts]=max(PrS);
[tmp,i_cs]=max(max(PrS));
[tmp,i_tb]=max(PrB);
[tmp,i_cb]=max(max(PrB));
jp=[i_ts(i_cs) i_cs; i_tb(i_cb) i_cb];
```

Trade Simulation: Picking random t1 and t2 to give tech, crop, and water traded with marginal benefits

```
function choice_t=trade(t1,t2,BestChoice,x,ChoosedCrop)
global Alloc Results iter;
Res=zeros(1,14);
tmp=choice(t1,ChoosedCrop);
tech1=tmp(1);
crop1=tmp(2);
tmp=choice(t2,ChoosedCrop);
tech2=tmp(1);
crop2=tmp(2);
% Marginal benefits
MB1=mz(w(t1,tech1,crop1),t1,tech1,crop1);
MB2=mz(w(t2,tech2,crop2),t2,tech2,crop2);
if (MB1 >= MB2)
```

```
   t_b=t1;
   tech_b=tech1;
   crop_b=crop1;
   t_s=t2;
   tech_s=tech2;
   crop_s=crop2;
else
      t_b=t2;
   tech_b=tech2;
   crop_b=crop2;
   t_s=t1;
   tech_s=tech1;
   crop_s=crop1;
end
crop1=BestChoice(1);tech1=BestChoice(2);
crop2=BestChoice(3);tech2=BestChoice(4);
wb=wbar(t_s,tech_s,crop_s,t_b,tech_b,crop_b);
Fb=m_z(wb,t_s,tech_s,crop_s);
% Water traded
X=x(crop1,tech1,crop2,tech2);
%X<=wbar;
else
if (X>0)
   %tmp=jumptrade(X,t_s,t_b)
   %tmp=[x(Tech1),x(Crop1);x(Tech2),x(Crop2)]
    tmp=[tech1,crop1;tech2,crop2];
   %User1_PI=SellerProfits + p.*x;
Res=[iter,t_s,t_b,wb,Fb,X,tech_s,crop_s,tech_b,crop_b,tmp(1,1),tmp(1,2),tmp(2,1),tmp(2,2)];
   Results(iter,:)=Res;
else
   Res(1,1)=iter;
   Results(iter,:)=Res;
end
```

****

Post-trade decisions: These functions calculate post-trade profits for the parties. The main functions are seller profits and buyer profits.

Buyer post-trade profits: This function calculate the buyer's post-trade profit

```
function z=FindBuyerProfit(x,t2)
global Alloc
z=zeros([12,6,12,6]);
% z=zeros([1,6,1,6]);
for crop1=1:1:12
   for tech1=1:1:6
```

```
        for crop2=1:1:12
            for tech2=1:1:6
                water=Alloc + x(crop1,tech1,crop2,tech2);
                Temp=Pr(water,t2,tech2,crop2);
                z(crop1,tech1,crop2,tech2)=Temp;%(Tech2);
            end
        end
    end
end
```

Seller post-trade profits: This function calculate the seller's post-trade profit

```
function z=FindSellerProfit(x,t1)
global Alloc
for crop1=1:1:12
    for tech1=1:1:6
        for crop2=1:1:12
            for tech2=1:1:6
                water=Alloc-x(crop1,tech1,crop2,tech2);
                Temp=Pr(water,t1,tech1,crop1);
                z(crop1,tech1,crop2,tech2)=Temp;
            end
        end
    end
end
```

****

This code calls all the functions for the Simulation. The inputs are optimal water traded, price, seller and buyer post-trade profits, trade, jumpt trade, best chosen technology and crops post-trade.

```
function out=simul;
global Results Niter iter
rand('seed',12345)
randn('seed',12345)
%ChoosedCrop=9;
for iter=1:1:Niter
    i=iter;
t1(i)= betarnd(3,3,1,1);
t2(i)= betarnd(3,3,1,1);
 [x]=FuncFindx(t1(i),t2(i),ChoosedCrop);% x is the amount of water that can be traded.
p=FuncFindp(t1(i),t2(i),x,ChoosedCrop);% p is the price of traded water.
SellerProfits=FindSellerProfit(x,t1(i));
User1_PI=SellerProfits + p.*x;
BuyerProfits=FindBuyerProfit(x,t2(i));
User2_PI=BuyerProfits - p.*x;
[FinalMatrix,BestChoice]=FuncSortFind(User1_PI,User2_PI,ChoosedCrop);
```

```
trade(t1(i),t2(i),BestChoice,x,ChoosedCrop);
end
csvwrite('Results.csv',Results);
disp('*** done! ***')
```

**This code calculates the potential mean gains from trade, price of water, amount of water exchanged, optimal water, yield and pre-trade and post-trade profits.

Calculation of mean values for illustrations

```
global Results Niter iter crop ;
seller=zeros(Niter,19);
buyer=zeros(Niter,19);
for iter=1:Niter
th_L=betarnd(3,3,1,1);
t1= betarnd(3,3,1,1);
t2= betarnd(3,3,1,1);
x=FuncFindx(t1,t2);% x is the amount of water that can be traded.
p=FuncFindp(t1,t2);% p is the price of traded water.
SellerProfits=FindSellerProfit(x,t1);
User1_PI=SellerProfits + p.*x;
BuyerProfits=FindBuyerProfit(x,t2);
User2_PI=BuyerProfits - p.*x;
profit1=zeros(6,12);
profit2=zeros(6,12);
waterH1=zeros(6,12);
waterH2=zeros(6,12);
yield1=zeros(6,12);
yield2=zeros(6,12);
for techs=1:6
   for crops=1:12
      waterH1(techs,crops)=w(t1,techs, crops);
      waterH2(techs,crops)=w(t2,techs,crops);
      yield1(techs,crops)=y(waterH1(techs,crops),t1,techs,crops);
      yield2(techs,crops)=y(waterH2(techs,crops),t2,techs,crops);
      profit1(techs,crops)=Pr(waterH1(techs,crops),t1,techs,crops);
      profit2(techs,crops)=Pr(waterH2(techs,crops),t2,techs,crops);
   end
end
max_profit1=max(max(profit1));max_profit2=max(max(profit2));
max_user1_p=max(max(max(max(User1_PI))));
max_user2_p=max(max(max(max(User2_PI))));
%% calculate seller max,min,mean,median profits and corresponding tech,crop for maximum
seller(iter,1)=iter;seller(iter,2)=t1;
seller(iter,3)=mean(mean(profit1));
```

```
seller(iter,4)=median(median(profit1));
seller(iter,5)=std2(profit1);
seller(iter,6)=mean2(User1_PI);
seller(iter,7)=median(median(median(median(User1_PI))));
seller(iter,8)=std2(User1_PI);
seller(iter,9)=mean2(p);
seller(iter,10)=median(median(median(median(p))));
seller(iter,11)=std2(p);
seller(iter,12)=mean2(x);
seller(iter,13)=median(median(median(median(x))));
seller(iter,14)=std2(x);
seller(iter,15)=seller(iter,6)-seller(iter,3);
[technology,crops]=ind2sub(size(profit1), find(profit1==max(profit1(:))));
seller(iter,19)=technology;seller(iter,20)=crops;
[cr1,te1,cr2,te2]=ind2sub(size(User1_PI), find(User1_PI==max(User1_PI(:))));
seller(iter,21:24)=[te1,cr1,te2,cr2];
seller(iter,25)=min(min(profit1));
seller(iter,26)=min(min(min(min(User1_PI))));
seller(iter,27)=mean(mean(profit1));
seller(iter,28)=mean(mean(mean(mean(User1_PI))));
seller(iter,29)=median(median(profit1));
seller(iter,30)=median(median(median(median(User1_PI))));
%seller(iter,3)=waterH1(technology,crops);seller(iter,4)=yield1(technology,crops);
seller(iter,16)=max_profit1;seller(iter,17)=max_user1_p;
seller(iter,18)=max_user1_p-max_profit1;
%% Buyer
buyer(iter,1)=iter;buyer(iter,2)=t2;
buyer(iter,3)=mean(mean(profit2));
buyer(iter,4)=median(median(profit2));
buyer(iter,5)=std2(profit2);
buyer(iter,6)=mean2(User2_PI);
buyer(iter,7)=median(median(median(median(User2_PI))));
buyer(iter,8)=std2(User2_PI);
buyer(iter,9)=mean2(p);
buyer(iter,10)=median(median(median(median(p))));
buyer(iter,11)=std2(p);
buyer(iter,12)=mean2(x);
buyer(iter,13)=median(median(median(median(x))));
buyer(iter,14)=std2(x);
buyer(iter,15)=buyer(iter,6)-buyer(iter,3);
[technology,crops]=ind2sub(size(profit2), find(profit2==max(profit2(:))));
buyer(iter,19)=technology;buyer(iter,20)=crops;
[cr1,te1,cr2,te2]=ind2sub(size(User2_PI), find(User2_PI==max(User2_PI(:))));
buyer(iter,21:24)=[te1,cr1,te2,cr2];
buyer(iter,25)=min(min(profit2));
```

```
buyer(iter,26)=min(min(min(min(User2_PI))));
buyer(iter,27)=mean(mean(profit2));
buyer(iter,28)=mean(mean(mean(mean(User2_PI))));
buyer(iter,29)=median(median(profit2));
buyer(iter,30)=median(median(median(median(User2_PI))));
%buyer(iter,3)=waterH1(technology,crops);buyer(iter,4)=yield1(technology,crops);
buyer(iter,16)=max_profit2;buyer(iter,17)=max_user2_p;
buyer(iter,18)=max_user2_p-max_profit2;
end
csvwrite('seller.csv',seller);
csvwrite('buyer.csv',buyer);
disp('*** done! ***')
```

****

This code calculates the optimal values of water, crop and profit for each irrigation technology and crop under different land qualities.

Optimal water: This code calculates the optimal water values under each irrigation technology and crop for different land qualities.

```
water_table1=zeros(6,12);water_table2=zeros(6,12);water_table3=zeros(6,12);
theta=0.25;
   for technology=1:6
      for crops=1:12
         water_table1(technology,crops)=w(theta,technology,crops);
      end
   end
   theta=0.5;
   for technology=1:6
      for crops=1:12
         water_table2(technology,crops)=w(theta,technology,crops);
      end
   end
   theta=0.75;
   for technology=1:6
      for crops=1:12
         water_table3(technology,crops)=w(theta,technology,crops);
      end
   end
   w_min1=min(min(water_table1));
   w_mean1=mean(mean(water_table1));
   w_median1=median(median(water_table1));
   w_std1=std2(water_table1);
   w_max1=max(max(water_table1));
```

```
    w_min2=min(min(water_table2));
    w_mean2=mean2(water_table2);
    w_median2=median(median(water_table2));
    w_std2=std2(water_table2);
    w_max2=max(max(water_table2));

    w_min3=min(min(water_table3));
    w_mean3=mean2(water_table3);
    w_median3=median(median(water_table3));
    w_std3=std2(water_table3);
    w_max3=max(max(water_table3));

    w1=[w_min1 w_mean1 w_median1 w_std1 w_max1];
    w2=[w_min2 w_mean2 w_median2 w_std2 w_max2];
    w3=[w_min3 w_mean3 w_median3 w_std3 w_max3];

    table=cell(4,6);
    table{1,1}='theta';
    table{1,2}='min';
    table{1,3}='mean';
    table{1,4}='median';
    table{1,5}='std';
    table{1,6}='max';
    table{2,1}=0.25;
    table{3,1}=0.5;
    table{4,1}=0.75;
    for index=2:6
    table{2,index}=w1(index-1);
    table{3,index}=w2(index-1);
    table{4,index}=w3(index-1);
end
        csvwrite('w_table_0.25.csv',water_table1);
       csvwrite('w_table_0.5.csv',water_table2);
         csvwrite('w_table_0.75.csv',water_table3);
        %  csvwrite('summary_water.csv',table);
```

Crop yield: This code calculates the crop yield values under each irrigation technology and crop for different land qualities

```
yield_table1=zeros(6,12);yield_table2=zeros(6,12);yield_table3=zeros(6,12);
theta=0.25;
    for technology=1:6
        for crops=1:12
          yield_table1(technology,crops)=y(w(theta,technology,crops),theta,technology,crops);
        end
```

```
end
theta=0.5;
for technology=1:6
   for crops=1:12
     yield_table2(technology,crops)=y(w(theta,technology,crops),theta,technology,crops);
   end
end
theta=0.75;
for technology=1:6
   for crops=1:12
     yield_table3(technology,crops)=y(w(theta,technology,crops),theta,technology,crops);
   end
end
y_min1=min(min(yield_table1));
y_mean1=mean(mean(yield_table1));
y_median1=median(median(yield_table1));
y_std1=std2(yield_table1);
y_max1=max(max(yield_table1));

y_min2=min(min(yield_table2));
y_mean2=mean2(yield_table2);
y_median2=median(median(yield_table2));
y_std2=std2(yield_table2);
y_max2=max(max(yield_table2));

y_min3=min(min(yield_table3));
y_mean3=mean2(yield_table3);
y_median3=median(median(yield_table3));
y_std3=std2(yield_table3);
y_max3=max(max(yield_table3));

y1=[y_min1 y_mean1 y_median1 y_std1 y_max1];
y2=[y_min2 y_mean2 y_median2 y_std2 y_max2];
y3=[y_min3 y_mean3 y_median3 y_std3 y_max3];

table=cell(4,6);
table{1,1}='theta';
table{1,2}='min';
table{1,3}='mean';
table{1,4}='median';
table{1,5}='std';
table{1,6}='max';
table{2,1}=0.25;
table{3,1}=0.5;
table{4,1}=0.75;
```

```
for index=2:6
   table{2,index}=y1(index-1);
   table{3,index}=y2(index-1);
   table{4,index}=y3(index-1);
end
      csvwrite('y_table_0.25.csv',yield_table1);
     csvwrite('y_table_0.5.csv',yield_table2);
       csvwrite('y_table_0.75.csv',yield_table3);
      %  csvwrite('summary_yield.csv',table);
```

Profit values: This code calculates the profit values under each irrigation technology and crop for different land qualities

```
profit_table1=zeros(6,12);profit_table2=zeros(6,12);profit_table3=zeros(6,12);
theta=0.25;
   for technology=1:6
      for crops=1:12
        profit_table1(technology,crops)=Pr(w(theta,technology,crops),theta,technology,crops);
      end
   end
   theta=0.5;
   for technology=1:6
      for crops=1:12
        profit_table2(technology,crops)=Pr(w(theta,technology,crops),theta,technology,crops);
      end
   end
   theta=0.75;
   for technology=1:6
      for crops=1:12
        profit_table3(technology,crops)=Pr(w(theta,technology,crops),theta,technology,crops);
      end
   end
   p_min1=min(min(profit_table1));
   p_mean1=mean(mean(profit_table1));
   p_median1=median(median(profit_table1));
   p_std1=std2(profit_table1);
   p_max1=max(max(profit_table1));

   p_min2=min(min(profit_table2));
   p_mean2=mean2(profit_table2);
   p_median2=median(median(profit_table2));
   p_std2=std2(profit_table2);
   p_max2=max(max(profit_table2));

   p_min3=min(min(profit_table3));
```

```
   p_mean3=mean2(profit_table3);
   p_median3=median(median(profit_table3));
   p_std3=std2(profit_table3);
   p_max3=max(max(profit_table3));

   p1=[p_min1 p_mean1 p_median1 p_std1 p_max1];
   p2=[p_min2 p_mean2 p_median2 p_std2 p_max2];
   p3=[p_min3 p_mean3 p_median3 p_std3 p_max3];

   table=cell(4,6);
   table{1,1}='theta';
   table{1,2}='min';
   table{1,3}='mean';
   table{1,4}='median';
   table{1,5}='std';
   table{1,6}='max';
   table{2,1}=0.25;
   table{3,1}=0.5;
   table{4,1}=0.75;
for index=2:6
   table{2,index}=p1(index-1)
   table{3,index}=p2(index-1)
   table{4,index}=p3(index-1)
end
      csvwrite('p_table_0.25.csv',profit_table1);
     csvwrite('p_table_0.5.csv',profit_table2);
       csvwrite('p_table_0.75.csv',profit_table3);
      %  csvwrite('summarp_profit.csv',table);
```

***Now, these codes calculate the transition probabilities for irrigation technologies and crops for both traders from the potential gains from trade

Record matrix: This matrix records all the gains from trade and transition probabilities are calculated from the potential gains after simulation.

```
function NeededMatrix=GetNeededRecordMatrix(RecordMatrix)

[x,y]=size(RecordMatrix);

k=1;

for i=1:1:x

   if(sum(RecordMatrix(i,:))~=0)

      NeededMatrix(k,:)=RecordMatrix(i,:);
```

```
        k=k+1;

    end

end
```

function [Tech1TallyMatrix,Crop1TallyMatrix,Tech2TallyMatrix,Crop2TallyMatrix]=...FuncFindTallyMatrix(RecordMatrix); % to calculate tallymatrix for traders

```
[xM,xY]=size(RecordMatrix);%xM equals Nter and xY is the number of columns of tech and crops

for i=1:1:6

User1TechStateNum(i)=sum(RecordMatrix(:,1)==i); % how many original states, User1TechStateNum is 6*1 matrix. % User1TechStateNum(1,1) means how many tech 1 states at the beginning

User2TechStateNum(i)=sum(RecordMatrix(:,3)==i); % how many original states

end

for i=1:1:12

User1CropStateNum(i)=sum(RecordMatrix(:,2)==i); % how many original states

User2CropStateNum(i)=sum(RecordMatrix(:,4)==i);% how many original states

end

Tech1TallyMatrix=zeros(6,6);

Tech2TallyMatrix=zeros(6,6);

Crop1TallyMatrix=zeros(12,12);

Crop2TallyMatrix=zeros(12,12);


% 1, for the first user, technology transfer probability

for k=1:1:xM

    for i=1:1:6

        for j=1:1:6

            if((RecordMatrix(k,1)==i) && (RecordMatrix(k,5)==j));

                Tech1TallyMatrix(i,j)=1+Tech1TallyMatrix(i,j);
```

```
            end
        end
    end
end
Tech1Seller=Tech1TallyMatrix;% 2, for the second user, technology tranfer probability
for k=1:1:xM
    for i=1:1:6
        for j=1:1:6
            if((RecordMatrix(k,3)==i) && (RecordMatrix(k,7)==j));
               Tech2TallyMatrix(i,j)=1+Tech2TallyMatrix(i,j);% how many times from tech i to tech j
            end
        end
    end
end
Tech2Buyer=Tech2TallyMatrix; % 3, for the first user, crops  transfer probability
for k=1:1:xM
    for i=1:1:12
        for j=1:1:12
            if((RecordMatrix(k,2)==i) && (RecordMatrix(k,6)==j));
                Crop1TallyMatrix(i,j)=1+Crop1TallyMatrix(i,j);
            end
        end
    end
end
Crop1Seller=Crop1TallyMatrix; % 4, for the second user, crops  transfer probability
for k=1:1:xM
    for i=1:1:12
```

```
      for j=1:1:12
        if((RecordMatrix(k,4)==i) && (RecordMatrix(k,8)==j));
          Crop2TallyMatrix(i,j)=1+Crop2TallyMatrix(i,j);
        end
      end
    end
end
Crop2Buyer=Crop2TallyMatrix;
function [FinalMatrix,BestChoice]=FuncSortFind(BuyerProfits,...
    SellerProfits,ChoosedCrop) % find best choice pre-trade and post-trade.
BestChoice=ones(1,4);
[crop1,tech1,crop2,tech2]=size(BuyerProfits);
iROW=crop1*tech1*crop2*tech2;
iCOLLUMN=6;
BuyerMatrix=zeros(iROW,iCOLLUMN);
SellerMatrix=zeros(iROW,iCOLLUMN);
n=0;
for crop1=1:1:12
    for tech1=1:1:6
      for crop2=1:1:12
        for tech2=1:1:6
          n=n+1;
          BuyerMatrix(n,1)=n;
          BuyerMatrix(n,2)=crop1;BuyerMatrix(n,3)=tech1;
          BuyerMatrix(n,4)=crop2;BuyerMatrix(n,5)=tech2;
          BuyerMatrix(n,6)=BuyerProfits(crop1,tech1,crop2,tech2);
          SellerMatrix(n,1)=n;
```

```
            SellerMatrix(n,2)=crop1;SellerMatrix(n,3)=tech1;
            SellerMatrix(n,4)=crop2;SellerMatrix(n,5)=tech2;
            SellerMatrix(n,6)=SellerProfits(crop1,tech1,crop2,tech2);
            if(crop1~=ChoosedCrop | crop2~= ChoosedCrop)
                BuyerMatrix(n,6)=0;
            end
        end
    end
  end
end
% 2, sort the profits
[B,IX]=sort(BuyerMatrix(:,iCOLLUMN),'descend');
BuyerFinalMatrix=zeros(iROW,iCOLLUMN);
for i=1:1:iCOLLUMN;
  BuyerFinalMatrix(:,i)=BuyerMatrix(IX,i);
end
 [B,IX]=sort(SellerMatrix(:,iCOLLUMN),'descend');
SellerFinalMatrix=zeros(iROW,iCOLLUMN);
for i=1:1:iCOLLUMN;
  SellerFinalMatrix(:,i)=SellerMatrix(IX,i);
end
BuyerNonZeroProfitsNum=1;
while(BuyerFinalMatrix(BuyerNonZeroProfitsNum,6)>0)
  BuyerNonZeroProfitsNum=BuyerNonZeroProfitsNum+1;
end
SellerNonZeroProfitsNum=1;
while(SellerFinalMatrix(SellerNonZeroProfitsNum,6)>0)
```

```
    SellerNonZeroProfitsNum=SellerNonZeroProfitsNum+1;
end
NonZeroProfitsNum=min(BuyerNonZeroProfitsNum,SellerNonZeroProfitsNum);



% 3, to find the first place that (t_s - t_b==0, and c_s - c_b==0)
FinalMatrix=SellerFinalMatrix-BuyerFinalMatrix;
nTimes=0;
Location=0;
for i=1:1:NonZeroProfitsNum
    TestValue=abs(FinalMatrix(i,3)) + abs(FinalMatrix(i,5));
    if (TestValue<1)
        Location=i;
        nTimes=nTimes+1;
        break;
    end
end
% 4, Swiching back;
Temp2=FinalMatrix(:,2);Temp3=FinalMatrix(:,3);
FinalMatrix(:,2)=Temp3;FinalMatrix(:,3)=Temp2;
Temp4=FinalMatrix(:,4);Temp5=FinalMatrix(:,5);
FinalMatrix(:,4)=Temp5;FinalMatrix(:,5)=Temp4;
if(Location~=0)
    %disp([BuyerFinalMatrix(Location,:)])
    %disp([SellerFinalMatrix(Location,:)]);
    disp(FinalMatrix(Location,2:5));
```

```
    BestChoice=[BuyerFinalMatrix(Location,2:5)];
    %BestChoice=[FinalMatrix(Location,2:5)];
   disp('*********** Best choice **********************')
    disp(['     tech1=',num2str(BestChoice(2)), ' crop1=',num2str(BestChoice(1))]);
    disp(['     tech2=',num2str(BestChoice(4)), ' crop2=',num2str(BestChoice(3))]);
    disp('*********************************************')
%    BestChoice=[BuyerFinalMatrix(Location,3),BuyerFinalMatrix(Location,2),...
%   BuyerFinalMatrix(Location,5),BuyerFinalMatrix(Location,4)]
else
    disp('No Match found.');
end
% disp(FinalMatrix(1:Location,2:5));
```

Function AfterSimulMain: This code displays the final transition matrix results

```
clear;clc;
AllM=csvread('Results.csv');
RecordMatrix=AllM(:,7:14);
[x,y]=size(RecordMatrix);
[Tech1TallyMatrix,Crop1TallyMatrix,Tech2TallyMatrix,Crop2TallyMatrix]=...
    FuncFindTallyMatrix(RecordMatrix);
%disp('find tally matrix with total rows and columns')
%[Tech1countS,Crop1countS,Tech2countB,Crop2countB]=FuncFind4NewTallyMatrix(Tech1Ta
llyMatrix,...
% Crop1TallyMatrix,Tech2TallyMatrix,Crop2TallyMatrix);
disp('Find transfer probability')
[Tech1Seller,Tech2Buyer,Crop1Seller,Crop2Buyer]=...
   FuncFindTransferMarkov(RecordMatrix,...
   Tech1TallyMatrix,Crop1TallyMatrix,Tech2TallyMatrix,Crop2TallyMatrix);
```

```
MarkovMatrix=[Tech1Seller,Tech2Buyer;Crop1Seller;Crop2Buyer];
MarkovMatrix=round(MarkovMatrix*10000)/10000;
csvwrite('Markov.csv',MarkovMatrix);
disp('__________________Now it is after creating the Markov.csv file._________________')
M = csvread('Markov.csv');
Tech1Seller=M(1:6,1:6)
Tech2Buyer=M(1:6,7:12)
Crop1Seller=M(7:18,1:12);
Crop2Buyer=M(19:30,1:12);
SellerMarkovMatrix=kron(Tech1Seller,Crop1Seller);
BuyerMarkovMatrix=kron(Tech2Buyer,Crop2Buyer);
S2=sum(sum(SellerMarkovMatrix));
temp=SellerMarkovMatrix;
size(temp);
csvwrite('SellerMarkovMatrix.csv',SellerMarkovMatrix);
csvwrite('BuyerMarkovMatrix.csv',BuyerMarkovMatrix);
disp('----------tech1*crop1 before and after----------------')
[SellerMarkovMatrix_Table,BuyerMarkovMatrix_Table]=...
   FindSellerMarkovMatrix(RecordMatrix);
csvwrite('SellerMarkovMatrix_Table.csv',SellerMarkovMatrix_Table);
csvwrite('BuyerMarkovMatrix_Table.csv',BuyerMarkovMatrix_Table);
% S_M=SellerMarkovMatrix_Table - SellerMarkovMatrix
% S_M_sum=sum(sum(S_M))
% B_M=BuyerMarkovMatrix_Table - BuyerMarkovMatrix
% B_M_sum=sum(sum(B_M))
% S1=sum(sum(SellerMarkovMatrix_Table))
% B1=sum(sum(BuyerMarkovMatrix_Table))
```

```
disp('__________________Now find new Markov, only forward._________________')

[Tech1ForwardTallyMatrix,Crop1ForwardTallyMatrix,Tech2ForwardTallyMatrix,Crop2ForwardTallyMatrix]=...

    FuncFindForwardTallyMatrix(RecordMatrix);
[Tech1SellerForward,Tech2BuyerForward,Crop1SellerForward,Crop2BuyerForward]=...

   FuncFindForwardTransferMarkov(RecordMatrix,...

Tech1ForwardTallyMatrix,Crop1ForwardTallyMatrix,Tech2ForwardTallyMatrix,Crop2ForwardTallyMatrix);

csvwrite('Tech1SellerForward.csv',Tech1SellerForward);

csvwrite('Tech2BuyerForward.csv',Tech2BuyerForward);

csvwrite('Crop1SellerForward.csv',Crop1SellerForward);

csvwrite('Crop2BuyerForward.csv',Crop2BuyerForward);
```

Appendix H: Stochastic Results for All Scenarios of Experiment Two

Table H-1: Impacts of Stochastic Water Reallocation on Quantity Changes for Experiment Two[a]

Quantity Risk Impacts	Deterministic Results			Alternative reallocation under 10 Percent Risk level			Alternative reallocation under five Percent Risk level			Alternative reallocation under one Percent Risk level		
Countries	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia
Annual water allocations	55.5bcm	18.5bcm		52.5bcm	15.5bcm	6bcm	52.5bcm	15.5bcm	6bcm	52.5bcm	15.5bcm	6bcm
GDP	264.733	628.116	159.888	262.752	627.686	159.869	262.714	627.683	159.800	262.406	627.637	159.774
Value added: Agriculture	37.435	293.397	55.261	25.249	256.842	44.957	19.496	248.857	44.610	17.409	245.684	44.539
Industry	46.229	61.924	9.374	64.433	74.342	19.073	64.091	83.972	19.306	62.321	86.076	19.322
Services	135.505	192.552	34.093	136.457	200.361	36.733	136.566	200.354	36.06	136.405	196.614	35.494
Intermediate input: Agriculture	23.864	54.639	25.67	21.476	53.085	25.721	21.405	50.455	25.599	20.400	48.995	25.059
Industry	103.075	151.451	1.482	103.679	150.792	1.534	103.441	149.522	1.304	103.288	149.472	1.029
Services	107.512	145.408	35.144	78.229	141.739	36.803	77.889	138.130	36.67	75.845	138.251	35.905
Domestic output: Agriculture	60.915	349.445	56.931	45.610	358.550	60.170	39.089	358.446	60.138	35.817	356.294	60.138
Industry	149.78	220.557	10.899	190.328	199.371	22.425	189.734	157.613	20.326	189.667	204.704	19.056
Services	242.198	340.943	96.173	215.768	331.643	100.886	215.596	331.514	100.992	214.464	331.379	101.025
Composite good: Agriculture	80.418	362.731	44.433	77.890	360.541	59.377	77.847	361.827	59.355	77.645	361.832	59.812
Industry	245.652	247.932	47.443	213.818	234.977	55.792	213.511	234.187	57.500	213.379	234.092	55.047
Services	204.428	457.685	87.561	194.614	371.975	80.827	195.191	371.47	78.548	194.486	371.356	68.933
Imports: Agriculture	6.655	28.167	2.173	8.886	28.214	3.294	10.710	28.227	3.372	11.782	28.710	3.361
Industry	79.311	102.711	71.451	51.368	101.526	33.913	51.415	110.099	35.695	51.578	123.918	37.679
Services	9.048	9.091	3.294	8.502	5.684	18.958	8.515	6.910	20.354	8.540	6.917	20.696
Exports: Agriculture	0.295	26.415	0.002	0.295	25.727	9.252	0.295	25.717	9.228	0.295	25.627	9.138
Industry	10.892	79.768	0.507	16.575	72.704	0.899	16.375	75.395	0.901	16.275	75.393	0.924
Services	59.025	0.152	1.505	34.231	0.152	2.085	34.797	0.100	2.193	34.883	0.040	2.228

Source: Author's Simulation Results. a. The reported results pertain to the simulation of perturbing the current allocation scheme under stochastic conditions. Values are in billions of Constant Egyptian Pound (EGP), Ethiopian Birr (ETB) billions and constant Sudanese Pound (SDG) millions. The results for 50 percent probability with the normality assumption for model represent the solution to the deterministic results, this provide us with a Zi value of zero. Also, 90 percent reliability level allows for 10 percent risk probability of not achieving a feasible solution, 95 percent reliability allows for five percent risk probability of not achieving a feasible solution, 99 percent reliability level allows for one percent risk of not achieving a feasible solution.

Table H-2: Impacts of Stochastic Water Reallocation on Income Changes for Experiment Two [a]

Income Risk Impacts	Deterministic Results			Alternative reallocation under 10 Percent Risk level			Alternative reallocation under five Percent Risk level			Alternative reallocation under one Percent Risk level		
Countries	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia	Egypt	Sudan	Ethiopia
Water allocations	*55.5bcm*	*18.5bcm*		52.5bcm	15.5bcm	6bcm	52.5bcm	15.5bcm	6bcm	52.5bcm	15.5bcm	6bcm
Income												
Public	37.818	100.716	23.547	35.230	100.708	23.547	33.109	100.696	23.543	30.127	100.695	23.544
Private	186.971	456.724	146.419	186.908	456.723	146.418	186.907	456.710	146.416	186.905	456.701	146.413
Household consumption												
Agriculture	29.734	303.557	45.030	28.415	294.515	43.197	24.911	283.796	43.140	20.028	287.552	43.178
Industry	60.954	64.944	29.193	61.240	65.346	30.376	61.307	65.668	30.487	61.750	65.773	30.573
Services	100.380	46.961	22.395	100.501	47.304	22.698	100.896	47.465	22.712	100.914	47.882	23.866
Factor income												
Labor	106.14	344.344	33.794	99.448	278.314	32.180	98.873	222.745	31.981	98.764	214.192	31.619
Capital	146.306	343.941	20.769	146.062	248.136	20.681	145.203	247.141	20.678	145.518	244.508	20.677
Land	18.171	5.211	13.102	17.133	4.886	12.776	16.226	4.222	12.717	15.010	4.143	12.654

Source: Author's Simulation Results. a. The reported results pertain to the simulation of perturbing the current allocation scheme under stochastic conditions. Values are in billions of Constant Egyptian Pounds, Ethiopian Birr and constant Sudanese SG millions. The results for 50 percent probability with the normality assumption for model represent the solution to the deterministic results, this provide us with a Zi value of zero. Also, 90 percent reliability level allows for 10 percent risk probability of not achieving a feasible solution, 95 percent reliability allows for five percent risk probability of not achieving a feasible solution, 99 percent reliability level allows for one percent risk of not achieving a feasible solution.

Appendix I: BNW-CGE Full Model

Consideration:

- General CGE model
- Water incorporation
- Uncertainty

Let
$r =$ Countries (Egypt, Sudan and Ethiopia)
$i =$ Sectors (Agriculture (Agric), Industry (Ind), Services (Serv))
$f =$ Factors of production (labor (l), capital (k), and Land (Lad)).
$ff =$ Subfactors of production (water (w) and raw land (rlad)).
$h =$ Households
$firm =$ Enterprise
$Gov = Government$
$ROR =$ Rest of the world
$ie =$ Sectors with export demand functions
$im =$ Sectors with import demand function

Key CGE building blocks and extensions

Price
Production
Income and final demand
Trade
Current account balance
Equilibrium conditions

Model setup

Price Block

EXR_r	Exchange rate
PX_r^i	Domestic output price
PD_r^i	Domestic sale price
P_r^i	Armington's composite good price
PVA_r^i	Value added price
$PINT_r^i$	Intermediate input price
PE_r^i	Export price in local currency
PM_r^i	Import price in local currency
PWE_r^i	World price of exports
PWM_r^i	World price of imports
PC_r	Price index

WF_r^f	Average factor price
$WFSUB_r^{ff}$	Subfactor price
$RGDP_r$	Real GDP
$GDPVA_r$	Value-added in market prices GDP

Production Block

E_r^i	Exports
M_r^i	Imports
X_r^i	Armington's composite goods
XD_r^i	Domestic goods supply
XXD_r^i	Domestic sales
FS_r^f	Factor supply
$FDSC_r^{i,f}$	Factor demand by sectors
QVA_r^i	Value added input
INT_r^i	Intermediates input demand by sectors
$SUBFS_r^{ff}$	Subfactor supply
$SUBF_r^{i,ff}$	Subfactor demand
$WFDIST_r^{i,f}$	Factor market distortion variable

Parameters

$tm_r^i =$ import tariff rate

$te_r^i =$ Export subsidy rate

$tva_r^i =$ Production taxes

$tq_r^i =$ Sectoral tax rate

$a_r^{i,ff} =$ Land and water Leontief production coefficient

Price Equations

$$PM_r^i = PWM_r^i.(1+tm_r^i).EXR_r \qquad (1)$$

$$PE_r^i = PWE_r^i.(1+te_r^i).EXR_r \qquad (2)$$

$$P_r^i = PD_r^i.XXD_r^i + PM_r^i.M_r^i / X_r^i \qquad (3)$$

$$PX_r^i = PD_r^i.XXD_r^i + PE_r^i.E_r^i / XD_r^i \qquad (4)$$

$$PX_r^i(1-ta_r^i)XD_r^i = PVA_r^i QVA_r^i + PINT_r^i.INT_r^i \qquad (5)$$

$$WF_r^{LAD}.WFDIST_r^{i,LAD} = \sum_{ff} a_r^{i,ff}.WFSUB_r^{ff} \qquad (6)$$

$$PC_r = GDPVA_r / RGDP_r \qquad (6.1)$$

Production Equation with sub factors

Parameters

α_r^i Shift parameter for aggregate production function (CES)
δ_r^i Share parameter in the aggregate production function (CES)
ρ_r^i Aggregate production substitution parameter
β_r^i Shift parameter for aggregate factor output CES function
$\phi_r^{i,f}$ Share parameter in the aggregate factor output CES function
$\varepsilon_r^{i,f}$ Aggregate factor output substitution parameter
γ_r^i Shift parameter for output transformation function (CET)
θ_r^{ie} Share parameter for the output aggregation function (CET)
τ_r^{ie} Output transformation function exponent
λ_r^i Shift parameter for the Armington function
ω_r^{im} Share parameter for the Armington function
υ_r^{im} Armington function substitution parameter
io_{is} Input-output flow coefficients of industries in the ith sector

$$XD_r^i = \alpha_r^i (\delta_r^i . QVA_r^{-\rho_r^i} + (1-\delta_r^i) INT_r^{-\rho_r^i})^{-\frac{1}{\rho_r^i}} \tag{7}$$

$$QVA_r^i = \beta_r^i \left(\sum_{f \in F} \varphi_r^{i,f} (FDSC_r^{i,f})^{-\varepsilon_r^{i,f}} \right)^{-\frac{1}{\varepsilon_r^{i,f}}} \tag{8}$$

$$WF_r^f . WFDIST_r^{i,f} = PVA_r^i (1 - tva_r^i) . QVA_r^i \left(\sum_{f \in F} \varphi_r^{i,f} (FDSC_r^{i,f})^{-\varepsilon_r^{i,f}} \right)^{-1} . \phi_r^{i,f} (FDSC_r^{i,f})^{-\varepsilon_r^{i,f} - 1} \tag{9}$$

$$SUBF_r^{i,ff} = a_r^{i,ff} FDSC_r^{i,LAD} \tag{10}$$

$$INT_r^i = \sum_i io_{is} * XD_r^i \tag{10.1}$$

$$XD_r^i = \gamma_r^i (\theta_r^{ie} E_r^{i^{-\tau_r^{ie}}} + (1-\theta_r^{ie}) XXD_r^{i^{-\tau_r^{ie}}})^{-\frac{1}{\tau_r^{ie}}} \tag{11}$$

$$X_r^i = \lambda_r^i (\omega_r^{im} M_r^{i^{-\upsilon_r^{im}}} + (1-\omega_r^{im}) XXD_r^{i^{-\upsilon_r^{im}}})^{-\frac{1}{\upsilon_r^{im}}} \tag{12}$$

$$E_r^i = XXD_r^i \left(\frac{PE_r^i}{PD_r^i} . \frac{1-\theta_r^{ie}}{\theta_r^{ie}} \right)^{\frac{1}{\tau_r^{ie}} - 1} \tag{13}$$

$$M_r^i = XXD_r^i \left(\frac{PD_r^i}{PM_r^i} . \frac{\omega^{im}}{1-\omega^{im}} \right)^{\frac{1}{1+\upsilon_r^{im}}} \tag{14}$$

$$XD_r^i = E_r^i + XXD_r^i \tag{15}$$

$$X_r^i = M_r^i + XXD_r^i \quad (16)$$

Institutional Block

YF_r^f Factor income

YF_r^{ff} Subfactor payment

$YIF_r^{A,f}$ Institutional factor incomes

tf_r^f Direct factor tax rate

$shif_r^{A,h}$ Share of domestic institutional income

EH_r^h Household consumption expenditure

$shii_r^{A,h}$ Household consumption shares

MPS_r^h Household marginal propensity to save

$TINS_r^h$ Exogenous direct tax rate for households

YI_r^h Household income

$trnsfr_{row}^f$ Transfer of factor income to the rest of the world

$\psi_r^{i,h}$ Subsistence consumption of marketed sectoral commodity by households

$b_r^{i,h}$ Marginal share of consumption expenditure

A = Institutions (domestic and rest of the world)

$$YF_r^f = WF_r^K.FDSC_r^{i,K} + WF_r^L.FDSC_r^{i,L} + WF_r^{LAD}.FDSC_r^{i,LAD} \quad (17)$$

$$YF_r^{ff} = WF_r^{LAD}.FDSC_r^{i,LAD} \quad (18)$$

$$WF_r^{LAD}.FDSC_r^{i,LAD} = \sum_{ff} WFSUB_r^{ff}.FSUB_r^{i,ff} \quad (18a)$$

$$YIF_r^{A,f} = shif_r^{A,f}(1 - tf_r^f).YF_r^f - trnsfr_{row}^f.EXR_r \quad (19)$$

$$EH_r^h = \left(1 - \sum_{h \in A} shii_r^{A,h}\right).(1 - MPS_r^h).(1 - TINS_r^h).YI_r^h \quad (20)$$

$$PX_r^i.QH_r^{i,h} = PX_r^i \psi_r^{i,h} + b_r^{i,h}(EH_r^h - \sum_i PX_r^i \psi_r^{i,h}) \quad (20.1)$$

Investment demand and government consumption

$QINV_r^i$ Quantity of sectoral investment demand

YG_r Government revenue

$TINS_r^A$ Direct tax rate for institutions

$IADJ_r$ Investment adjustment factor

$GADJ_r$ Government consumption adjustment factor

QG_r^i Government consumption demand for commodity

qg_r^i Base-year quantity of government demand

EG_r Government expenditure

$$QINV_r^i = IADJ_r.qinv_r^i \quad (21)$$

$$QG_r^i = GADJ_r.qg_r^i \quad (22)$$

$$YG_r = \sum_A TINS_r^A.YI_r^A + \sum_{f \in F} tf_r^f.YF_r^f + \sum_{i \in I} tva_r^i.PVA_r^i.QVA_r^i$$

$$+ \sum_i tm_r^i.pwm_r^i.M_r^i.EXR_r + \sum_{i \in I} te_r^i pwe_r^i.E_r^i.EXR_r \quad (23)$$

$$+ \sum_i tq_r^i PX_r^i X_r^i + \sum_{f \in F} YIF_r^{f,gov} + trnsfr_r^{gov,row}.EXR_r$$

$$EG_r = \sum_i PX_r^i.QG_r^i + \sum_A trnsfr_r^{A,gov}.PC_r \quad (24)$$

System block

W_r^i Sectoral water supply

TW_r Total water supply (allocation)

$QH_r^{i,h}$ Sectoral quantity consumed by households

$qdst_r^i$ Quantity of stock changes

$FSAV_r$ Foreign savings

$GSAV_r$ Government savings

$TABS_r$ Total nominal absorption (GDP at market prices)

$Invshr_r$ Investment share in nominal absorption

$govshr_r$ Government consumption shares in nominal absorption

Factor market equilibrium

$$\sum_i FDSC_r^{i,f} = FS_r^f \quad (25)$$

$$\sum_i SUBF_r^{i,ff} \leq SUBFS_r^{ff} \quad (26)$$

Water equilibrium conditions

$$\sum_i SUBF_r^{i,water} \leq W_r^i \quad (27)$$

$$\sum_i SUBF_r^{i,water} + W_r^i \leq TW_r \quad (28)$$

Commodity Market equilibrium

$$X_r^i = INT_r^i + QH_r^{i,h} + QG_r^i + QINV_r^i + qdst_r^i \quad (29)$$

$$PWE_r^i = PMW_{rr}^i \qquad \forall_{i,r} \neq rr \quad (29.1)$$

$$E_r^i = M_{rr}^i \qquad \forall_{i,r} \neq rr \quad (29.2)$$

Saving, Investment and GDP equations

$$PWM_r^i M_r^i + \sum_{f \in F} trnsfr_r^{f,row} = PWE_r^i . E_r^i + trnsfr_r^{i,row} + FSAV_r \quad (30)$$

$$YG_r = EG_r + GSAV_r \quad (31)$$

$$MPS_r^A (1 - TINS_r^A) . YI_r^A + GSAV_r + EXR_r . FSAV_r = PX_r^i QINV_r^i + PX_r^i qdst_r^i + walras_r \quad (32)$$

$$GDPVA_r = PVA_r^i . QVA_r^i + indirect\ tax_r + tariff_r \quad (33)$$

$$TABS = QH_r^i PX_r^i . QH_r^i + PX_r^i . QG_r^i + PX_r^i QINV_r^i + PX_r^i qdst_r^i \quad (34)$$

$$Invshr_r . TABS_r = PX_r^i . QINV_r^i + PX_r^i . qdst_r^i \quad (35)$$

$$govshr_r . TABS_r = PX_r^i . QG_r^i \quad (36)$$