AN ECONOMIC APPROACH TO SUSTAINABLE IRRIGATION MANAGEMENT: METHODS AND POLICY APPLICATIONS

BY

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A dissertation submitted to the Graduate School
in partial fulfillment of the requirements
for the degree
DOCTOR OF PHILOSOPHY

Major Subject: Water Science and Management

Minor Subject 1: Applied Statistics

Minor Subject 2: Agricultural Economics

New Mexico State University
Las Cruces, New Mexico
May 2013
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DEDICATION

I would like to dedicate this work to the memory of my father Abdelbaky Gohar and the souls of the martyrs of the great revolution of January 25 who sacrificed their lives in order to give us a better future of freedom and dignity.
ACKNOWLEDGMENT

I would like to express my sincere appreciation to my advisor, Professor Frank A. Ward, for his immeasurable advising, help, and inspiration that had guided me to the development of this work. His continued encouragement makes it possible for this work to see the light. In addition, I would like to thank my graduate committee: Professors Phillip King, Alexander Fernald, Steven Archambault, and David Daniel for their support and encouragement. Their innovative comments and suggestions improved the core scope of this dissertation.

I want to convey a special acknowledgment for Dr. Saud Amer for his academic and financial support of Afghanistan’s application of this work. His deep vision inspired the researcher to move this work to the implementation stage. I gratefully acknowledge the support of the Cultural Affairs and Missions Sector, Cairo, Egypt and the Egyptian Cultural and Educational Bureau, Washington D.C. that made this study possible. I am grateful to the South Valley University that helped to give me this great chance to study abroad. The deep acknowledgement for all faculties of the department of Agricultural Economics and Agricultural Business at New Mexico State University for their perseverance and encouragement has had a positive effect on my academic performance. Grateful thanks for Dr. Harb Ahmed at Elazhar University, Egypt and Mr. Omar Nasser for their support and helping me to obtain the important part of the data used in this dissertation.

Finally, I would like to extend my sincere thanks and gratitude to my family, who always provided me determination and strength to finish this work. My sincere
thanks to them for bearing strain, allowing time, and an appropriate environment for the completion of this hard work. I would like to send a special acknowledgment my lovely mother, brothers, and sisters in Egypt who have suffered with me the pain of separation in order to accomplish this mission. My great thanks also to my sincere wife engineer Nahed Hassan for sponsorship of our two beautiful boys; Hamza and Muaz and for her great efforts to bring a joy and warmth in our lives in order to create an appropriate environment to finish this work.
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ABSTRACT

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May 2013

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Water scarcity is a major concern for arid and semiarid regions around the world. Increasing population, growing food demands, living standards, and the potential impact of climate change pose additional challenges on the wise use of existing limited water resources. Therefore, better management that increases the economic efficiency, sustainability, and equity of water use to meet those needs is required. In Egypt’s part of the Nile Basin, the country historically faced those challenges with little attention given to economic principles of water use in the irrigation sector. Most previous research has ignored the regional interdependence of water, which makes it geographically, hydrologically, and economically limited. Another case of weak water institutions and poor infrastructure is found in the Balkh Basin, Afghanistan. In
addition to limited water supply, that basin lacks significant storage capacity that could be used for better management of irrigation water over sequential periods of drought and flood cycles. This dissertation addresses those gaps by developing an integrated basin management framework that improves the water economic efficiency and sustainability in both countries with possible application to other places. The integrated basin framework acknowledges the multidimensional aspect of the water by incorporating hydrology, economics, institutions, land use, policy applications, and water supply scenarios within a single unified framework. Using farm budget data, a dynamic non-linear programming framework is developed for each country that maximizes the national discounted net value of irrigation water. This framework is modified in the case of Afghanistan to maximize economic benefit from irrigation water and storage capacity for several proposed reservoir storage plans. Findings illustrate that the economic efficiency of irrigation water could increase for Egypt, while securing the country’ environmental, urban, and cultural needs through applying limited water trading instruments. When applied to Afghanistan, results show diminishing marginal impact of the additional reservoir capacity on regional and national farm income for the Balkh Basin. Our results provide insights for policymakers, farmers, farmer associations, and water managers to improve water use economic efficiency and sustainability. The framework has applicability for wide range of conditions in dry regions that face important challenges in the management of water resources.
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CHAPTER I

1.0. INTRODUCTION TO INTEGRATED BASIN FRAMEWORK MANAGEMENT

1.1. Overview

Freshwater is essential for both economic and ecological activities. Technological improvements in recent decades have made lives better and longer; however, freshwater is still essential. The power of water springs from the fact that it is fundamental for drinking, household uses, industrial activities, environmental assets, and transportation. Nevertheless, agricultural activities and food production is the largest single consumer for freshwater worldwide. Meanwhile, better water management is essential in arid and semiarid regions.

Several factors stress water resources in arid and semiarid regions. Growing population, food security, industrial activities, economic growth, environmental and ecological needs, climate change, and global warming pose large and growing pressure on limited water resources in those regions. Numerous efforts have been made in the last few decades toward better water resources allocation and management. Still, limitations posed by piecemeal management call for holistic management of freshwater. Holistic water management will draw on the principles of economic efficiency, sustainability, and equity associated with the development and use of water.

1.2. Integrated Basin Management Framework
The integrated basin management framework (IBMF) offers a promising tool for addressing complex water resources challenges. The main idea behind IBMF is to implement the economic concepts of economic efficiency and sustainability (Gallego-Ayala and Juizo, 2012; Grundmann et al., 2012). The economic efficiency of water refers to improved resource allocation in such way to make society better off economically as whole. That is, resources are employed in the economically best alternative uses that maximize their net total economic values. Measured economic efficiency of water use provides a framework for comparing different water use proposals and plans. While efficiency does not assure sustainability in general, sustainability can be defined measures that guard against declining future utilities resulting from current consumption of resources (Bishop, 1993).

1.2.1. Advantages

Water is a multidimensional resource and commonly gives rise to conflict among uses and locations. For example, freshwater can be used directly for drinking and household uses or indirectly for hydropower generation, irrigation, industrial production, and protecting the environment. In arid and semiarid regions where water scarcity presents major economic and political problems, there is ongoing competition among different users over scarce water. Another complexity caused by the natural movement of water is its downstream-upstream relationships. IBMF provides a comprehensive framework to simultaneously address uses of water such as hydropower, urban uses, irrigation, industrial production, and environmental
demands. IBMF combines economic, institutional, cultural, and agronomic dimensions. Moreover, participation of stakeholders in the process of policy design and evaluation to inform decision-making is critical for securing better outcomes of IBMF (Anokye and Gupta, 2012; Silva-Hidalgo et al., 2009).

The strength of the IBMF comes from its ability to comprehensively inform policy debate over large geographic areas and longtime spans. IBMF could be applied at a basin that contains several countries or at a much smaller scale represented by different users within one region or city (Zeng et al., 2012). The IBMF is an effective framework for mitigating transboundary conflicts over shared water basins (Karimov et al., 2012; Karki et al., 2011; Rahaman and Varis, 2009). Furthermore, this framework could include surface water along with groundwater. Within the IBMF, several sectors can be incorporated; therefore, an entire basin or any number of sub-basins could be studied as one unit over different water suppliers and users. Unifying a basin as one unit allows for better spatial and sectorial tracking of water. Therefore, better understanding of upstream downstream tradeoff could be used to inform superior decision-making.

The potential threat and consequences of climate change has received worldwide attention since the 1990s. The potential impact of climate change on water resource supply and food security has been investigated and debated worldwide. In recent years, the potential impact of the climate change has become an important motivation for integrated basin management investigations (Horlemann and
Dombrowsky 2012). The potential impact of climate change is an important factor for economic development that depends directly on the availability of water (Prodanovic and Simonovic, 2010). Integrated basin water management is a state-of-the art approach to address the issue of climate change under different water storage capacities and water inflow scenarios (Eum and Simonovic, 2010).

1.2.2. Challenges

The major challenge for IBMF rises from its multidimensional, multipurpose, and multi-objective potentials (Horlemann and Dombrowsky, 2012; Biswas, 2004). When stakeholders are involved, lacking an efficient and effective method of communication can weaken the performance of IBMF (Marimbe and Manzungu, 2003). Integrating a wide range of perspectives of diverse interests in water management is a large challenge (Grigg, 1999; Yevjevich, 1995; Merrett, 2004).

Another technical challenge for applying IBMF is the quantity and quality of data required for modeling. Comprehensive water management models require large amount of data that are usually collected from a range of different sources and are associated with high uncertainty (Blind and Refsgaard, 2007). Integrating those data requires high levels of programming skill in addition to high levels of computer capacity (Teodosiu et al., 2009). While the IBMF is mostly a long run management tool for water planning and implementation, a rising concern for short and medium run project appraisal has increased interest in IBMF in recent years (Allan, 2012).
While some progress has been made in the literature implementing the concepts of economic efficiency and sustainability, more efforts need to be taken in future for application of the concept of equity as an important part of integrated framework modeling. Many social and political indicators are associated with the concept of equity when addressing water allocation. The problem becomes more complicated when water is allocated among several countries that share the waters of single basin. The Nile River Basin is a good example of such ongoing conflict between the downstream and upstream countries. Even within the same country, the idea of water allocation equity raises several political and cultural challenges.

1.3. Objectives

The general objective for this research is to present a new application to increase the water resource use efficiency and sustainability for irrigation with special attention given to institutional and environmental requirements at the basin and sub-basin level. An integrated basin scale framework is formulated to be applied to Egypt’s part of the Nile Basin. The second application for the integrated basin scale is the Balkh Basin, Afghanistan. The overarching objective of this dissertation is divided into three sub-objectives, where one peer-reviewed journal article has already been published for each sub objective. The first sub objective is to examine measures for improving the efficiency and sustainable use of Egypt’s Nile River water resources for irrigation, while respecting urban, environmental cultural, political, and historical water requirements. The objective of the second paper is to study the
potential for two institutions, intraregional water trading and interregional water trading, to improve the economic efficiency of water use in Egyptian agriculture. The third objective is to investigate economic returns associated with a range of storage capacity expansions on farm income and food security. Both the first and second sub objectives are applied for the Egypt case and the third objective is applied for the Balkh Basin of Afghanistan.

The main body of this dissertation is composed of three standalone journal publications. However, two chapters have been added, one before and one after those three journal publications. Chapter one is the current chapter. The second chapter investigates the gain from improving the irrigation water use efficiency in Egypt. The third chapter presents an analysis to the gains from expanding irrigation water trading in Egypt. The fourth chapter applies the integrated basin framework to Afghanistan to estimate the potential economic performance of water storage capacity expansion for the food security. The last chapter concludes.

1.4. References


CHAPTER II

2.0. GAINS FROM IMPROVED IRRIGATION WATER USE EFFICIENCY IN EGYPT

2.1. Abstract

Egypt’s fortunes turn on the Nile. However, little research to date has evaluated economic efficiency improvements that could be achieved by altering Egypt’s agricultural water use patterns. This study develops an integrated catchment scale framework to identify potential economic benefits that can be supported by Egypt’s irrigation water use. An optimization framework is developed to identify improvements in national farm income that can be produced with current water supplies that are compatible with Egypt’s hydrologic, environmental, and institutional constraints. Results suggest that limited water trading across locations and seasons can increase national farm income by up to 28 percent. The methods used provide a framework for informing decisions on sustainable use of land and water for improved rural livelihoods in the developing world’s irrigated areas.

2.2. Background

Egypt’s long history of economic, political, and cultural achievement has been tied to the Nile. Egypt’s agriculture has had a long history of high productivity because of its moderate and uniform climate. Irrigated agriculture still occupies a central place in Egypt’s economy, contributing about 17 percent to GDP, and

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employing about 31 percent of the labor force (Attia, 2004; CAPMS, 2008).

Agriculture is characterized by scattered land holdings (Elarabawy et al., 1998; Elarabawy and Toswell, 1998; Kandil, 2003), and contains a large drainage area, covering about 2 million hectares (Ali et al., 2001; Wichelns, 2002a; Strzepek et al., 2008; Abu-Zied and El-Shibini, 1997; Wahba et al., 2005). Irrigated agricultural consumes about 85% of Egypt’s freshwater. Additionally, the Nile’s waters in Egypt are an important source of electric power production, fishing, and navigation to support tourism and barge traffic.

Since the late 1800’s, several agreements and protocols have established water-sharing arrangements among the various Nile Basin countries. To date, the ten Nile Basin countries are still attempting to forge a mutually acceptable solution to sharing the Nile’s water. One ongoing attempt, the Nile Basin Initiative (NBI), is step towards basin-wide cooperation. One signature historic achievement was the 1959 Agreement between the Sudan and Egypt for Full Control and Utilization of the Nile Waters. The quantity of average annual Nile flow was agreed at 84 billion cubic meters measured at the High Aswan Dam (HAD). It assigned the average annual flow of the Nile to be shared between Sudan and Egypt at 18.5 and 55.5 billion cubic meters, respectively. Annual water losses due to evaporation have been estimated at about 10 billion cubic meters (Nasser and Allam, 2007; Wichelns, 2004; Allen, 1992; Hefny and Amer, 2005).
Despite the progress achieved by the NBI, ongoing debates remain between the basin’s downstream users (Egypt and Sudan) and its upstream countries, especially Ethiopia. Many of these debates revolve around the distribution of the basin’s water use and its associated economic benefits (Mekonnen, 2010; El-Fade et al., 2003; Drake, 1997; Kung, 2003; Cascão, 2009). A recent proposal is Cooperative Framework Agreement (CFA). In May 2010, five upstream states signed that agreement to seek more water from the River Nile - a move strongly opposed by Egypt and Sudan. Much discussion among the Nile Basin countries deals with water reallocation (Laki, 1998; Mason, 2005). The Basin’s countries have not yet realized potential benefits from joint cooperation and development of more efficient water management policies (Wu and Whittington, 2006; Laki, 1998; Hefny and Amer, 2005; Swain, 2005).

Upstream countries call for larger shares of the basin’s water with greater opportunities to develop and use hydropower. The downstream countries see this proposal as a threat to their historical use (Arsano and Tamrat, 2005; Hamad and El-Battahani, 2005). Increased conflict among Nile basin countries adds uncertainty to the reliability of water supplies for all Basin countries. Ongoing conflict poses continued challenges to all the basin countries’ policy makers, while highlighting the importance of more efficient and sustainable water management.

Growing population, food security issues, increased urban use, and potential impacts of climate change increase the attention given to more efficient and
sustainable water management in Egypt. All these factors point to the continued challenges of guarding against Egypt’s water demands outpacing its supplies (Allen, 1992; Wichelns, 2004; Elarabawy and Toswell, 2000). Policy alternatives to water pricing are examined by He and Siam (2004) that could improve Egypt’s irrigation water allocation efficiency. Simonovic et al. (1997) used an object oriented framework to build a simulation model of Egypt’s use of the Nile with all major sources and uses of water considered. Malashkhia (2003) examined irrigation water saving measures that could be applied in Egypt with special attention given to water pricing and improved efficiency measures. Wichelns (2002b) conducted an economic analysis of investments in improved irrigation drainage to mitigate problems of waterlogging and salinization in Egypt.

Despite the achievements of these works, we are aware of no policy analysis to date that takes a national view that comprehensively analyze outcomes for alternative policies that could be implemented for Egypt’s use of the Nile. For this reason, the objective of this paper is to examine measures for improving the agricultural economic efficiency and sustainability of Egypt’s Nile River water use, while respecting cultural, hydrologic, environmental, and institutional constrains on urban and environmental uses. Its uniqueness lies in the formulation and application of an integrated catchment scale analysis of the sources and uses of water in Egypt with a special emphasis on irrigated agriculture.
2.3. Methods and Materials

2.3.1. Overview

This study formulates and applies an integrated basin-scale framework to improve the economic productivity of uses of Egypt’s Nile River for irrigated agriculture while respecting numerous other constraints that limit the size and economic value of its water’s reallocations. Using data on national agricultural water supplies and demands, an optimization framework is developed to identify maximum total agricultural benefits subject that can be achieved that also respect important hydrologic, environmental, and institutional constraints unique to Egypt. The model is written in GAMS (Brooke et al. 1988). Sustainability was enforced by constraining terminal period reservoir storage to be at least as high as its starting values.

A major logistical challenge posed by this study was to unify data from different sources to consistently inform a range of water management decisions. Another challenge is that the land in Egypt cultivated in three seasons each year, making it difficult to assemble consistent data on crop production, crop water use, and gauged flows on the Nile throughout the river’s entire length in Egypt. The three cropping seasons in Egypt are Winter, November to May; Summer, May to September; Nili, September to November (FAO, 1995). Farm budget data were obtained from the Ministry of Agricultural and Land Reclamation (MALR). This data included irrigated land, yield, cost of production, and prices by crop, season, and
district. These data are available in different volumes published yearly by the Department of Economic Affairs in (MALR).

Additional important data were for gauged river flows, which came from the Ministry of Water Resources and Irrigation (MWRI). These data describe the varying crop water use requirements by season and by location in the country. MWRI has data on river flows at all the major Nile River gauges in Egypt. MWRI also collects data on storage volume for the main reservoirs in Egypt, including Lake Nasser as well as the original Nile Lake created by the Low Aswan Dam. The two major data sources were merged as well as could be done, while recognizing the difficulties of merging data from different ministries, a common challenge faced in developing countries.

About 3 months was invested in merging data from these different sources to ensure reliability and compatibility of the data. For purposes of this study, the data are classified by the main irrigation district instead of by the administrative districts. The complete database for year 2006 included three irrigation seasons, fourteen crops, thirteen major irrigated areas, and total seasonal river flow at each of ten river gauges. An important task was the development of farm enterprise budgets for the base year.

2.3.2. Integrated Basin Framework Management

The analysis at the basin scale treats the entire Nile catchment within Egypt as a single unit, which offers many advantages over analyzing separate political,
hydrologic, and administrative boundaries. It accounts for upstream and downstream interactions throughout the country in different time periods. Accounting for these interactions comprehensively ensures consistent treatment of alternative water allocation and management plans (Wegerrich, 2004; Allen, 1992; Prairie, 2006). The basin framework integrates hydrology, land use, agronomy, economics, and institutions to support improved policy design, implementation, and evaluation (Ward and Velazquez, 2008; Gohar and Ward, 2010; Rosegrant et al., 2000; Ringler, 2001; Mainuddin et al., 2007). Where possible, a basin framework should include stakeholders, to improve the perceived sustainability of water resources management (Mouratiadou and Moran, 2007).

2.3.3. Approach to Modeling

This study formulated an integrated framework of Egypt’s Nile Basin that accounted for recent historical water uses for the nation’s three major irrigated regions: Upper, Middle, and Lower Egypt. We constructed a catchment scale integrated mathematical model, accounting for hydrologic, economic, agronomic, institutional, and environmental dimensions of Egypt’s use of the Nile. We also calibrated the model so that its predicted gauged flows were close to actual data at all major river gauges. Calibration presents numerous challenges for hydrologic and watershed analysis, many of which continue to be debated. A short list of celebrated papers published since the 1990's dealing with watershed calibration include the works of Janssen and Heuberger (1995), Yapo et al. (1998), Karvonen et al. (1999);
Sophocleous et al. (1999), Madsen et al. (2002); Singh and Woolhiser (2002). Other more recent papers include those of Doherty and Johnston (2003), Legesse et al. (2003), Butts et al. (2004), Merz and Bloschl (2004), and Muleta and Nicklow (2005).

Our idea behind the calibration was have the model’s predicted base year streamflows being close to observed flows at all major gauges from Lake Nasser to the Mediterranean. To achieve this we started by constraining the model to irrigate the observed amount of land in production by crop, season, and irrigated area. This required a fair amount of experimentation. We started the calibration at the HAD. Beginning from that point, we adjusted crop water use’s patterns at an irrigated region for each of the three seasons, so that the predicted gauged river flow matched actual gauged measurements. When predicted flows were too high, we increased crop water use’s coefficients so that more would be taken from the river for irrigation.

As we proceeded downstream, observed gauged flows were progressively less than flows predicted by the model. When the deviation became large, we concluded that there was unmeasured use being taken from the river. That unmeasured use consisted of several possible sources. These included unmeasured groundwater pumping, unmeasured river evaporation, and unmeasured diversions for urban use, an amount that became larger as the Nile approached the Giza and Cairo urban areas. Differences between observed and model-predicted river flow were resolved by defining the concept of “unmeasured river division” associated with each major agricultural use region. For this reason, the final piece of our calibration exercise was
to calculate this unmeasured use. This use was defined by defining unmeasured river
diversions so that predicted river flows matched actual gauged flows even at the
lower end of the basin. We calibrating the program in this way so that under the base
policy characterizing actual crop production and water use patterns, observed and
predicted streamflows were close. The complete program code written in GAMS as
well as data used and program output are available from the authors on request as
well as being posted at http://agecon.nmsu.edu/fward/water/.

2.3.3.1. Economics

Hydrologic data were assembled on water diverted, cropping patterns, and
crop water use by region, crop, and season. These data were combined with farm
production details that accounted for crop prices, costs of production, and crop yields.
Net income per unit of land and total land in production by irrigated region, crop, and
season were identified. Net income from any single crop was defined as price
multiplied by yield minus the sum of all input costs including both variables and fixed
costs. Variable costs contain all costs that change with the level of output. These
include the various costs of cultivation, such as expenses associated with land
preparation, harvesting, fertilizers, labor, and irrigation. Fixed costs typically do not
vary with the level of output. Examples include depreciation, taxes, interest, and land
rent.

Net farm income per unit land was calculated by region, crop, and season. The
constrained optimization framework was designed to examine ways to allocate water
throughout Egypt’s share of the Nile Basin to maximize net discounted farm income summed over crops, seasons, time periods, and locations. This discounted net present value was maximized over a five-year planning period, with a time step consisting of three seasons per year as described above. It was also designed to account for various hydrologic, cultural, or institutional constraints that could limit potential water reallocations compared to existing water use patterns.

2.3.3.2. Hydrology

The long history of Egyptian irrigation has produced a complex and intricate irrigation system. The schematic shown in Figure 1 shows a highly simplified view of the current sources and uses of water for agriculture. Additional details on the pattern of Egypt’s canals are in Hvidt (1998). The entire irrigation system shown in the schematic includes three major regions in Egypt. Starting from Lake Nasser, Upper Egypt contains five main canals. Asfon, Kelabia, East Naghammadi, and West Naghammadi divert the water from the Nile, while the Toshka canal takes water directly from Lake Nasser. Middle Egypt includes two main canals: the Ibrahimia canal, which divides its water between many sub canals to serve numerous areas in the Assiut Region. These canals include El-Minia, Beni Suef, Fayoum, and Giza.

The second main canal in Middle Egypt region is Ismailia canal that provides irrigation water to the Suez canals regions and part of Elshrkia. Finally, at Lower Egypt, downstream of the Delta gauge, the Nile River splits into two branches called Rosetta and Damietta, creating the Nile Delta.
Fig 1. Schematic of Nile Basin, Egypt
The Rosetta branch includes the Menufia, Beheira, Nasser, and Mahmodia canals, while the Damietta branch includes the Tawfikia and Alsalam canals, which as well includes numerous sub canals.

2.4. Policy Analysis

2.4.1. Without Water Trading

Despite the fact that surface water is free in Egypt (Malashkhia, 2003; He and Siam, 2004), there can be considerable costs for pumping where surface water is conveyed to fields lying above irrigation canals. Moreover, until 1999, Egypt’s water management policy attempted to meet all irrigation water demands regardless of water’s opportunity cost or the cost of other resources consumed in the process of using water (Simonovic et al., 1997; Elarabawy and Toswell, 2000). The opportunity cost of water is the economic benefits displaced by taking water from another use, location, or time period. More recently, Egypt has formulated The National Water Resources Plan (NWRP, 2005). A partial list of measures for implementing this strategy includes:

- Cooperating with other Nile Basin countries to increase effective supplies.
- Monitoring, development, and increasing water from various sources, including shallow, deep, and brackish groundwater, in addition to harvesting floodwaters as well as desalination in coastal area.
• Making better use of existing water resources, including the improvement of irrigation efficiencies by maintaining canals and using modern irrigation technology, and improving the drainage efficiency by expanding drainage water reuse.

• Water allocation with the cooperation of water user associations at the mesqa level, and water boards at the irrigation district level. Water would be allocated based on equal opportunities, with upper bounds on use per unit land, which would limit certain high water-using crops.

For purposes of this paper, an analysis of ‘without water trading’ and ‘with water trading’ was conducted. Without water trading was simulated by constraining the basin model to reproduce historical water use, streamflow, land in production, and cropping patterns to match observed values for 2006, the only year for which we were able to assemble consistent and reliable data.

2.4.2. With Water Trading

A parallel analysis was conducted to reflect results of a policy that would permit more widespread water trading within irrigated agriculture than is currently practiced in Egypt. We examined the potential for greater total national agricultural income by testing whether it was possible to increase the total economic value of Egypt’s farm income compared to income achieved under baseline historical conditions. The ‘with trading’ policy scenario reflected a search for potential income gains that could be achieved by reallocating water through limited trading to produce greater total economic benefits over irrigated areas, crops, and seasons.
Our ‘with trading’ proposal falls under the National Water Resources Plan’s principle of making better use of existing water (NWRP, 2005). Our implementation of that principle increases land available for production to the maximum expected arable land in Egypt, currently estimated at 4.62 million hectares, which is 1.05 million hectares more than current land in production in the base year. Although more land could be brought into production, no additional water supplies overall would be made available for irrigated agriculture under the ‘with trading’ proposal. That is, total water available for irrigation was constrained to be no greater than the total actual historical base year use in Egypt of Nile River water in farming.

Under the ‘with trading’ scenario, small reductions of water use for any irrigated area were permitted. However, water use reductions through reductions in irrigated land could be no more than 10% of the base year’s historical land in production. Even if Egyptian agriculture would benefit nationally from large water supply trades from a water exporting area to a water importing area, high volumes of water exports may be politically and culturally unacceptable. Several changes were considered in the analysis of water use under the ‘with trading’ policy. Under ‘with trading,’ all constraints on the Nile’s gauged flows throughout Egypt were removed. That is, gauged flows could depart from observed flows in any way needed to increase national farm income, consistent with the upper bound on irrigated land reductions described above.
Reservoir storage volume was also considered as part of the package defined by ‘with trading’. Storage volumes at both major Nile Basin reservoirs, Lake Nasser and Lake Nile, were constrained. That constraint was established so that in the terminal period of the five-year planning horizon, both reservoirs had at least as much water in storage as actually occurred at the beginning of the base year. By imposing this constraint on terminal period reservoir storage, we assured a sustainable water use pattern, under both the ‘without trading’ and ‘with trading’ policy. In addition, environmental flows at the two Nile delta gauges into the Mediterranean Sea (Edfina and Zifta) were constrained to be at least as high as their base year outflows. This constraint was imposed to assure adequate flow levels in the Nile to support tourism demands and to protect the irrigation environment by guarding against saltwater intrusion.

2.4.3. Cap and Trade

Cap and trade systems are becoming increasingly common in water resources management as a water trading mechanism to encourage water to move to a higher valued use when it exists. A recent paper by Speed (2009) described efforts by Chinese water planners who are starting to take steps down this path with the development of a new water rights transfer system.

A market institution that promotes water reallocation such as cap and trade should meet three criteria to be acceptable. It should reduce water consumption in low valued water uses, be perceived as equitable, and signal water’s real scarcity. Any
water trading institution requires a water rights system to be in place before the full power of the market can be harnessed in moving water to higher valued uses in ways that benefit both water buyers and water sellers (Gohar and Ward, 2010). Egypt currently has no legal foundation supporting well-defined, secure, and transferable water rights assigned to individual farmers. Water rights and the rules governing their use and transfer need to be clearly defined for a cap and trade system to work.

A cap and trade water transfer program in Egypt, if established, could provide elements of all three criteria. It could be a culturally acceptable way to reduce water use by sending the right water price signals to Egypt’s irrigators. Under the program all farmers could be assigned a water entitlement per unit land irrigated, namely the cap. The cap could be established with the idea of an equitable base right in mind. For example, something like 4 meters depth per hectare per year could be assigned as a base irrigation water right. For example, that base right could be assigned to every farmer that demonstrated historical irrigation for a set amount of recent years. While the details obviously need to be worked out carefully, the amount chosen could be based on the full yield flood irrigation requirements of all but the most water intensive crops like sugar cane or rice. A higher cap could be possibly assigned to farmers in irrigated area where higher temperatures produced higher evaporation and greater crop ET.

Under a cap and trade arrangement, any water use in excess of the cap would be legal, but would require a trade of cash for water from a willing seller. Ward and
Gohar (2010) describe in detail some of the challenges surrounding trades of water for cash in Egypt. A cap and trade program avoids the most undesirable effects of government-administered prices, namely that administered prices can be unjust as well as rarely signaling the real scarcity of water. Who would be willing water suppliers under a cap and trade program in Egypt? Those supplies would come from irrigators who used less than their assigned cap. Some supplies would also come from irrigators who exceeded their capped use at the time of the assigned cap, but who later invested in conservation measures to reduce water use to lower than capped levels. Conservation could come from on farm water conserving measures like deficit irrigation, land leveling, shifting crops, and spreading water more uniformly over time or space. Sellers could also be farmers who fallowed part of their land, permitting them to irrigate with full supplies to meet crop requirements associated with maximum yields applied to remaining lands.

Under such a cap and trade arrangement, market forces and not government edict would establish the price of water. The market price of tradable water would vary from time to time as the scarcity of water or its economic value changed. These changes could be brought about from any adjustments that affected any crop’s price, yield, or production costs. It could also fall with advances in plant genetics or irrigation engineering that reduced any crop’s water use or application requirements. Variability from time to time in water’s price would signal changes in water scarcity, providing immediate economic incentives that reward farmers who adjust their
behavior quickly to changes in water scarcity. Changes in water scarcity could be brought about by outside forces like climate change or new agreements for sharing the Nile’s supplies throughout the entire basin. Higher prices for tradable water would reward conservation, while lower prices would reward farmers who take advantage of its reduced scarcity.

2.5. Results and Discussion

2.5.1. Overview

Results are described for each of two policy scenarios: (1) water use without trading and (2) water use with trading, subject to the cultural, institutional, and hydrologic constraints described above. Results for each policy scenario are shown for their impacts on water stocks, water flows, irrigated land, cropping patterns, and farm income.

2.5.2. Water Stocks and Flows

Streamflows are shown for ten mainstem Nile gauges located in Egypt from the HAD to the Mediterranean Sea. Reductions in gauged flow between any two gauges indicate how much water is depleted in the irrigated area between the gauges including depletions based on the calibration exercise described previously. Table 2.1 shows results of streamflows by stream gauge, season, and policy. This table reveals several messages. It shows reduced winter flows in Upper and Middle Egypt as well as increased summer flows in the upper and middle part of the country that would occur under a ‘with trading’ policy. It also shows reduced flows throughout Egypt in
the Nili season that would occur under the ‘with trading’ policy. The table shows a
general reallocation of river flows from Lower to Middle and Upper Egypt in order to
support higher valued patterns of irrigation water use in Middle and Lower Egypt
under the water trading policy. In all cases, the column indicating change in flow
shows the difference in flows between the without water trading and with water
trading policy. A positive (negative) entry indicates that greater (less) gauged flow
would occur under a with water trading policy at a given stream gauge compared to
the without trading policy.

Table 2.1 also shows that the ‘with trading’ policy results in small increases in
gauged flow from the Upper and Middle Egypt to Lower Egypt and from Winter and
Nili to Summer. In comparing the without trading and with trading policy, a positive
change in gauged flow can only occur with reduced agricultural use or increased
reservoir releases or a combination of the two. For a given level of total supply of
water into Lake Nasser, higher reservoir releases reduce reservoir storage volume.
Outflows at the Zifta and Edfina gauges match flows that occurred during the base
period, both with and without water trading, ensuring that with ‘with trading’ policy
protected environmental values associated with outflows to the Sea.
### Table 2.1. Nile River Flow by Gauge, Season, and Policy, Egypt, in Million Cubic Meters per Season, 5 Year Average

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Region in Egypt</th>
<th>Winter Without Trading</th>
<th>Winter With Trading&lt;sup&gt;1&lt;/sup&gt;</th>
<th>% Change</th>
<th>Summer Without Trading</th>
<th>Summer Without Trading</th>
<th>% Change</th>
<th>Nili Without Trading</th>
<th>Nili With Trading</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aswan High Dam</td>
<td>Upper</td>
<td>15,900</td>
<td>15,488</td>
<td>-3</td>
<td>36,650</td>
<td>37,147</td>
<td>1</td>
<td>4,700</td>
<td>4,593</td>
<td>-2</td>
</tr>
<tr>
<td>City of Aswan</td>
<td>Upper</td>
<td>15,900</td>
<td>15,522</td>
<td>-2</td>
<td>36,600</td>
<td>37,097</td>
<td>1</td>
<td>4,286</td>
<td>4,179</td>
<td>-2</td>
</tr>
<tr>
<td>Esna</td>
<td>Upper</td>
<td>15,100</td>
<td>14,751</td>
<td>-2</td>
<td>35,500</td>
<td>36,103</td>
<td>2</td>
<td>3,200</td>
<td>3,098</td>
<td>-3</td>
</tr>
<tr>
<td>Naghammadi</td>
<td>Upper</td>
<td>13,500</td>
<td>13,277</td>
<td>-2</td>
<td>32,700</td>
<td>33,588</td>
<td>3</td>
<td>3,100</td>
<td>3,003</td>
<td>-3</td>
</tr>
<tr>
<td>Assiut</td>
<td>Middle</td>
<td>10,800</td>
<td>10,741</td>
<td>-1</td>
<td>25,500</td>
<td>26,742</td>
<td>5</td>
<td>2,300</td>
<td>2,254</td>
<td>-2</td>
</tr>
<tr>
<td>Delta</td>
<td>Lower</td>
<td>10,800</td>
<td>10,754</td>
<td>0</td>
<td>23,400</td>
<td>24,651</td>
<td>5</td>
<td>600</td>
<td>554</td>
<td>-8</td>
</tr>
<tr>
<td>Rosetta</td>
<td>Lower</td>
<td>1,468</td>
<td>1,584</td>
<td>8</td>
<td>3,177</td>
<td>4,479</td>
<td>41</td>
<td>90</td>
<td>83</td>
<td>-8</td>
</tr>
<tr>
<td>Demitta</td>
<td>Lower</td>
<td>3,800</td>
<td>3,881</td>
<td>2</td>
<td>7,400</td>
<td>7,362</td>
<td>-1</td>
<td>1,100</td>
<td>1,097</td>
<td>0</td>
</tr>
<tr>
<td>Edfina outflow</td>
<td>Lower</td>
<td>500</td>
<td>500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zifta outflow</td>
<td>Lower</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>1</sup> With trading refers to limited trades of water for cash or other assets. Results of ‘with trading’ are produced in the model by a constrained optimization model of agricultural water use throughout Egypt. The model searches for the crop water use patterns in irrigated agriculture throughout Egypt's part of the Nile Basin that maximize discounted net present value of farm income, while respecting existing constraints described in the text. Constraints are written to also sustain water use patterns for urban and environmental demands.
Table 2.2 presents water use (ET) in irrigation by district, season, and policy for a five year average. Overall, the table shows that higher flows associated with a water trading policy are incurred to support higher crop water use from that policy, especially for the Behera and Mahmodia Districts. Moreover, that increased crop water use is especially pronounced during summer. The table shows a decrease in agricultural water use of about 10 percent averaged over the seasons for Upper and Middle Egypt occur under a water trading policy. This reduction in water use occurs because of a typically lower economic value of water use in Upper and Middle Egypt farming compared to the value of water used for irrigation in Lower Egypt.

For Lower Egypt, water use under a water trading policy decreased by about 10 percent in the Nili season for most areas compared to historical water use patterns. However, during winter, water use increased for Nasser, Mahmodia, and Alsalam areas, while it decreased for the rest of the areas under the water trading policy compared to without trading base condition. The largest increase in water use under water trading occurred at the Alsalam and Mahmodia areas, increasing by 122, and 49 percent in winter and summer respectively. Mahmodia and Alsalam Districts are major supply sources for fresh produce exported to European markets, as well as supplying fresh food for mega cities like Cairo and Alexandria. These regions produce much higher farm income per unit of land and water than income produced in other regions or seasons. Water use increases are shown for Nasser, Behera, and Mahmodia Districts, all major fresh produce irrigating areas, under with trading
policy during summer. Water use decreased for the remainder of irrigated areas at this region during summer.

Table 2.3 shows patterns of water storage volumes for Lake Nasser, Egypt’s largest reservoir, for the same two policy comparisons. It shows water storage volume as well as evaporation by season, year, and policy. Overall, higher reservoir storage volumes are required to support with water trading policy in the nili and winter seasons. These higher storage volumes are carried over to support higher summer crop water use throughout the country. Under with trading policy water is allocated to crop production and away from evaporation that would have otherwise been brought about by high summer reservoir storage.

Table 3 shows that with water trading policy has no major effect on the storage volume level of water in Lake Nasser for any season or year. Storage volumes for the much smaller Lake Nile are not shown. Each of the two reservoirs was constrained to have a terminal period storage volume at least as high in each year and season under trading water policy as actually occurred for the same year and season for the base policy. In general, results showed reduced overall evaporation by very small increases in water storage in winter compared to summer and Nili. Table 2.3 also shows estimated evaporation for Lake Nasser by year, season, and policy. These results illustrate small changes in evaporation losses at Lake Nasser over time from without water trading to with water trading management for all seasons.
Table 2.2. Nile River Water Use in Agriculture by Irrigation District, Season, and Policy, Egypt, in Million Cubic Meters, 5 Year Average

<table>
<thead>
<tr>
<th>Irrigation District</th>
<th>Region in Egypt</th>
<th>Winter Without Trading</th>
<th>Winter With Trading</th>
<th>% Change</th>
<th>Summer Without Trading</th>
<th>Summer With Trading</th>
<th>% Change</th>
<th>Nili Without Trading</th>
<th>Nili With Trading</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toshka</td>
<td>Upper</td>
<td>110</td>
<td>99</td>
<td>-10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>8</td>
<td>-11</td>
</tr>
<tr>
<td>Asfon</td>
<td>Upper</td>
<td>165</td>
<td>148</td>
<td>-10</td>
<td>775</td>
<td>698</td>
<td>-10</td>
<td>31</td>
<td>28</td>
<td>-10</td>
</tr>
<tr>
<td>Kelabia</td>
<td>Upper</td>
<td>123</td>
<td>111</td>
<td>-10</td>
<td>286</td>
<td>257</td>
<td>-10</td>
<td>19</td>
<td>17</td>
<td>-11</td>
</tr>
<tr>
<td>W_Nagh.</td>
<td>Upper</td>
<td>789</td>
<td>710</td>
<td>-10</td>
<td>2,054</td>
<td>1,849</td>
<td>-10</td>
<td>30</td>
<td>27</td>
<td>-10</td>
</tr>
<tr>
<td>E_Nagh.</td>
<td>Upper</td>
<td>468</td>
<td>421</td>
<td>-10</td>
<td>795</td>
<td>716</td>
<td>-10</td>
<td>18</td>
<td>16</td>
<td>-11</td>
</tr>
<tr>
<td>Ibrahimia</td>
<td>Middle</td>
<td>2,303</td>
<td>2,138</td>
<td>-7</td>
<td>3,845</td>
<td>3,491</td>
<td>-9</td>
<td>507</td>
<td>456</td>
<td>-10</td>
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<tr>
<td>Ismailia</td>
<td>Middle</td>
<td>132</td>
<td>119</td>
<td>-10</td>
<td>90</td>
<td>82</td>
<td>-9</td>
<td>7</td>
<td>6</td>
<td>-14</td>
</tr>
<tr>
<td>Nasser</td>
<td>Lower</td>
<td>629</td>
<td>653</td>
<td>4</td>
<td>1,168</td>
<td>1,326</td>
<td>14</td>
<td>84</td>
<td>76</td>
<td>-10</td>
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<td>Behera</td>
<td>Lower</td>
<td>1,094</td>
<td>1,074</td>
<td>-2</td>
<td>1,345</td>
<td>1,592</td>
<td>18</td>
<td>83</td>
<td>75</td>
<td>-10</td>
</tr>
<tr>
<td>Menufia</td>
<td>Lower</td>
<td>1,405</td>
<td>1,331</td>
<td>-5</td>
<td>3,182</td>
<td>2,908</td>
<td>-9</td>
<td>97</td>
<td>87</td>
<td>-10</td>
</tr>
<tr>
<td>Mahmodia</td>
<td>Lower</td>
<td>1,065</td>
<td>1,181</td>
<td>11</td>
<td>2,640</td>
<td>3,942</td>
<td>49</td>
<td>68</td>
<td>62</td>
<td>-9</td>
</tr>
<tr>
<td>Tawfikia</td>
<td>Lower</td>
<td>2,750</td>
<td>2,577</td>
<td>-6</td>
<td>5,187</td>
<td>5,044</td>
<td>-3</td>
<td>99</td>
<td>89</td>
<td>-10</td>
</tr>
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<td>Alsalam</td>
<td>Lower</td>
<td>67</td>
<td>149</td>
<td>122</td>
<td>379</td>
<td>342</td>
<td>-10</td>
<td>25</td>
<td>23</td>
<td>-8</td>
</tr>
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<td>Years</td>
<td>Winter</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>Without Trading</td>
<td>With Trading</td>
<td>% Change</td>
<td>Without Trading</td>
<td>With Trading</td>
<td>% Change</td>
<td>Without Trading</td>
<td>With Trading</td>
<td>% Change</td>
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<td>140,000</td>
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<td>0.4</td>
<td>144,967</td>
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<td>142,859</td>
<td>142,977</td>
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<tr>
<td>5</td>
<td>145,520</td>
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<td>0.4</td>
<td>146,190</td>
<td>146,190</td>
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<td>144,070</td>
<td>144,176</td>
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<table>
<thead>
<tr>
<th>Lake Nasser Volume</th>
<th>Winter</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Trading</td>
<td>With Trading</td>
<td>% Change</td>
<td>Without Trading</td>
<td>With Trading</td>
<td>% Change</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2,241</td>
<td>2,241</td>
<td>0.0</td>
<td>4,508</td>
<td>4,510</td>
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<td>2</td>
<td>2,265</td>
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<td>4,556</td>
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<tr>
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<td>2,287</td>
<td>2,298</td>
<td>0.5</td>
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<td>0.0</td>
<td>1,496</td>
</tr>
<tr>
<td>4</td>
<td>2,309</td>
<td>2,319</td>
<td>0.4</td>
<td>4,640</td>
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<td>0.0</td>
<td>1,509</td>
</tr>
<tr>
<td>5</td>
<td>2,329</td>
<td>2,339</td>
<td>0.4</td>
<td>4,680</td>
<td>4,680</td>
<td>0.0</td>
<td>1,522</td>
</tr>
</tbody>
</table>
Total evaporation per year is about 8.388 billion cubic meters under both policy alternatives, slightly less than existing estimates.

2.5.3. Land in Production

Table 2.4 presents results of cropland by irrigation region, season, crop class, and policy. In general, it emphasizes the importance of water reallocated to increased fresh produce supply with water trading policy. Under that policy, greater amounts of water pass through Upper and Middle Egypt to make way for additional water delivered to Lower Egypt. Grains, fiber, and other crops show a general decline throughout Egypt under the water trading policy. This pattern again reflects the reduced economic value of water when used for staples, compared to a considerably higher value of water used to grow fruits and vegetables.

Results illustrate that irrigated land cultivated for grains and fiber decrease for all regions under water trading policy. The decrease occurred for all districts across Egypt and did not exceed 10 percent. For fruit crops, the change in irrigated cropland under the water trading policy was much different. While some regions would see a significant increase in irrigated cropland under with water trading arrangement, others show a reduction in irrigated cropland. The greatest increase in irrigated cropland occurred in Mahmodia and Meunfia both by about 50 and 45 percent respectively. Moreover, the Lower Egypt districts showed large gains in irrigated land in production under water trading management, with the exception of the Tawfikia region, which showed a small reduction in irrigated land mentioned policy. In
contrast, all Middle and Upper Egypt’ districts experience 10 percent reductions in irrigated cropland under the water trading policy.

For vegetables, irrigated land decreased for all Upper Egypt districts with the water trading policy. The decrease occurred by 10 percent at all regions. In the Middle Egypt districts, while vegetable land increased slightly in Ibrahimia, it decreased by 9 percent at Ismailia under the water trading policy. Some districts gained considerably for irrigated vegetable production in Lower Egypt. The highest increase occurred at Mahmodia District, followed by smaller amounts at Behera, Tawfikia, Nasser, and Meunfia Districts, while 7 percent reduction occurred at Alsalam District.

Cropland in production by season and policy are shown also in Table 2.5. It shows a general pattern of reduced cropland in production in winter under water trading, making way for much larger summer cropland under production for the Lower Egypt with special emphasis on the importance of the heavy produce suppliers of Behera and Mahmodia Districts. The table’s results illustrate that the change in irrigated land in production varies widely by season and region. Irrigated land decreased for all regions during the nili season under water trading arrangement. Those reductions occurred by similar percentages, about 10 percent, for all seasons in Upper and Middle Egypt. The irrigated land decreased for all seasons under the improved policy compared to the base year, where the farmers mostly irrigate low
valued crops such as grain and fiber, and clover crops. The reduction in irrigated land ranged from between 6 and 10 percent for most areas under water trading policy.

In Lower Egypt, some irrigated regions showed increases in irrigated land under water trading policy, while others showed a reduction in irrigated land for both winter and summer seasons. Growth in irrigated land ranged from between 81 percent for Alsalam District and 4 percent for Mahmodia District during winter. This increase in cropped land could be explained by the domination of high valued crops like fruits and vegetables at these areas.

### 2.5.4. Farm Income

Table 2.5 presents results of farm income by irrigation district, crop class, season, and policy. Overall, the table reveals similar messages as shown in Tables 2.1-2.4. This message reaffirms the significance of with water trading policy that would encourage growth in Lower Egypt for fresh produce, with an attendant reduction in water allocated to staples throughout the country. The table shows that Lower Egypt is to be very productive for fruits and vegetables, and with water trading policy in this region has considerable potential to produce large increases in Egypt’s farm income.

Table 2.5 also shows farm income split out by season rather than by crop class. Results show that farm income under water trading policy would decrease by almost 10 percent for most of Upper Egypt’s areas for all seasons. For Middle Egypt, farm income would decrease for all season except for a slight increase for Ibrahimia.
District in winter. For Lower Egypt, farm income would decrease by 10 percent in the Nili season for all districts under water trading arrangement. However, farm income increases for both winter and summer seasons for all nodes except Alsalam District in summer, which decreased by almost 10 percent under trading policy implication.

2.6. Policy Implications

Flexible management of water resources is essential to sustain culture and economic activity in the world’s dry regions. The economic and cultural future the Nile Basin’s residents inside and outside Egypt will turn on the development of resilient institutions for adapting to unexpected changes in future water supplies or demands. These institutions will be needed to smooth the adaptation to future climate change, growing population, and emerging agreements on the sharing of the Nile Basin’s waters.

Irrigators who are armed with better information on price of tradable water can make more informed decisions on crop selection, water application rates on cropped areas, irrigation technology, as well as the type and use of non-water inputs like fertilizers, new crop varieties, capital, and labor. For climate and political reasons, Egypt is likely to receive no more than its current 55.5 billion cubic meters per year of the Nile’s waters for the foreseeable future. Therefore, despite its growing population, movement to democracy, and growing industrial base, Egypt faces the challenge of making better use of its existing water supplies. The methods used for our analysis of Egyptian water policy provide promising tools to inform future policy
debates. The integrated basin framework presents a comprehensive approach for tracking water use among locations, time periods, and crops. Moreover, it has the potential to be a versatile framework for addressing water use and water policy where there are multiple competing uses, such as hydropower, urban use, irrigation, and environmental uses. Our catchment scale framework considers all irrigation water users and seasons in Egypt. The framework accounts for the storage volume for the main reservoirs as well. Moreover, our framework is accounts for some of Egypt’s most important hydrological, institutional, urban, and environmental constraints.

Our results illustrate the importance of water trading as a low cost measure to increase national farm income produced by existing irrigation water used in Egypt. Findings from our analysis indicate that limited adjustments to existing irrigation water use patterns motivated by mutually beneficial trades among buyers and sellers could raise the efficiency by which water is used in irrigated agriculture. Requiring that 90 percent or more of current land in production stay in production in the face of water trading protects all regions’ agriculturally related industry while increasing national income from farm production by 28 percent per year. Both sellers and buyers of traded water stand to benefit. Water buyers increase their farm income by moving water from lower to higher valued crops. Those who trade water for cash gain from the value of the traded water exceeding the current value in irrigated agriculture. Some of those receipts could be invested in water-conserving irrigation technologies.
Table 2.4. Land in production by Irrigation District, Crop Class, Season, and Policy, Nile River Basin, Egypt, 1000 ha/ year, 5 years average.

<table>
<thead>
<tr>
<th>Irrigation District</th>
<th>Region in Egypt</th>
<th>Winter</th>
<th>Summer</th>
<th>Nili</th>
<th>Vegetables</th>
<th>Fruits</th>
<th>Grains and Fiber and Other Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toshka</td>
<td>Upper</td>
<td>20 -10</td>
<td>0 0</td>
<td>2 -10</td>
<td>1 -10</td>
<td>0 -10</td>
<td>21 -10</td>
</tr>
<tr>
<td>Asfou</td>
<td>Upper</td>
<td>32 -10</td>
<td>55 -10</td>
<td>5 -10</td>
<td>16 -10</td>
<td>3 -10</td>
<td>73 -10</td>
</tr>
<tr>
<td>Kelabia</td>
<td>Upper</td>
<td>24 -10</td>
<td>30 -10</td>
<td>3 -10</td>
<td>13 -10</td>
<td>2 -10</td>
<td>42 -10</td>
</tr>
<tr>
<td>W. Nagh.</td>
<td>Upper</td>
<td>137 -10</td>
<td>271 -10</td>
<td>4 -10</td>
<td>113 -10</td>
<td>14 -10</td>
<td>286 -10</td>
</tr>
<tr>
<td>E. Nagh.</td>
<td>Upper</td>
<td>84 -10</td>
<td>110 -10</td>
<td>3 -10</td>
<td>41 -10</td>
<td>0 -10</td>
<td>156 -10</td>
</tr>
<tr>
<td>Ibrahimia</td>
<td>Middle</td>
<td>495 -6</td>
<td>479 -9</td>
<td>96 -10</td>
<td>174 4</td>
<td>57 -10</td>
<td>839 -10</td>
</tr>
<tr>
<td>Ismailia</td>
<td>Middle</td>
<td>28 -10</td>
<td>10 -10</td>
<td>1 -10</td>
<td>4 -9</td>
<td>4 -10</td>
<td>31 -10</td>
</tr>
<tr>
<td>Nasser</td>
<td>Lower</td>
<td>165 -1</td>
<td>158 19</td>
<td>18 -10</td>
<td>98 41</td>
<td>87 2</td>
<td>156 -10</td>
</tr>
<tr>
<td>Behera</td>
<td>Lower</td>
<td>275 -4</td>
<td>210 20</td>
<td>19 -10</td>
<td>78 76</td>
<td>39 20</td>
<td>387 -10</td>
</tr>
<tr>
<td>Menufia</td>
<td>Lower</td>
<td>340 -7</td>
<td>320 -8</td>
<td>21 -10</td>
<td>42 12</td>
<td>17 45</td>
<td>622 -10</td>
</tr>
<tr>
<td>Mahmodia</td>
<td>Lower</td>
<td>260 4</td>
<td>323 71</td>
<td>16 -10</td>
<td>137 184</td>
<td>53 50</td>
<td>409 -10</td>
</tr>
<tr>
<td>Tawfikia</td>
<td>Lower</td>
<td>673 -7</td>
<td>651 0</td>
<td>22 -10</td>
<td>139 45</td>
<td>75 -2</td>
<td>1,132 -10</td>
</tr>
<tr>
<td>Alsalam</td>
<td>Lower</td>
<td>16 81</td>
<td>45 -10</td>
<td>5 -10</td>
<td>9 -7</td>
<td>47 20</td>
<td>9 -10</td>
</tr>
</tbody>
</table>
Our results showed that under limited water trading, water at some locations and crops in Upper and Middle Egypt move toward more economically productive crops and regions in Upper Egypt. In addition, a water trading program will move water from low valued grains and fiber crops to higher commercially valued crops, such as vegetables and fruits. Our findings highlight the urgent need for more innovative measures that could reduce the planting of highly water using crops like rice and sugar cane crops that dominate Upper Egypt and parts of Lower Egypt. Nevertheless, despite the potential gains from water trading, Egypt’s current water distribution system is not well-suited to implement water trading. Volumetric pricing of water supported by a more efficient physical distribution system could reduce important currently existing constraints to water trading in Egypt (NWRP, 2005).

Integrated river basin management (IRBM) tools such as the one developed for this paper, are a powerful way to analyze proposals for reallocating the Nile’s flows among the Nile Basin countries. Put into the right hands at the right time, IRBM could support the discovery of mutually beneficial water development, allocation, or trading proposals of the kind currently under debate among Basin’s countries. The IRBM framework, currently limited to Egypt, could be expanded to include other countries as a step for national Basin cooperation, helping to mitigate conflicts in the basin.

The analysis described in this paper has several limits. All point to the need for continued work. Economic benefits from water uses outside agriculture are not
directly measured in the analysis. These uses include hydropower, urban and domestic use, recreation, groundwater recharge, and environmental uses, all of which are important. This study also performed no analysis of the technical, financial, or institutional requirements needed to establish or sustain water trading. It also did not directly address the methods to communicate to stakeholders the gains from water trading. Egyptians are demanding a growing voice in the nation’s future. Egyptian water stakeholders will need to be consulted before water trading can be initiated on a large scale.

Looking to the future, a more detailed analysis of the potential benefits of reclaimed land currently not being used for agriculture would address a number of questions currently being posed in Egypt (NWRP, 2005). Additional constraints that address Egypt’s food security and employment should be examined. Water reallocations resulting from the implementation of water trading will likely reduce domestic production of food staples that will otherwise need to be imported into Egypt. For farmers who reduce their water use by trading it for cash, income earned from agricultural production will decline, even though their total income increases because of water sold, rented, leased, or lent. Especially in Upper Egypt for high water-using crops, regional income and employment generated from food production can be negatively affected by water exports. A more comprehensive analysis than the one conducted for this paper would support a more powerful policy analytic capacity.
<table>
<thead>
<tr>
<th>Irrigation District</th>
<th>Region in Egypt</th>
<th>Seasons Categories</th>
<th>Crops Categories</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Without Trading</td>
<td>% Change With Trading</td>
</tr>
<tr>
<td>Toshka</td>
<td>Upper</td>
<td>20</td>
<td>-10.62</td>
</tr>
<tr>
<td>Kelalia</td>
<td>Upper</td>
<td>30</td>
<td>-10.08</td>
</tr>
<tr>
<td>Ibrahimia</td>
<td>Middle</td>
<td>558</td>
<td>0.78</td>
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<tr>
<td>Ismailia</td>
<td>Middle</td>
<td>30</td>
<td>-9.83</td>
</tr>
<tr>
<td>Nasser</td>
<td>Lower</td>
<td>147</td>
<td>37.84</td>
</tr>
<tr>
<td>Behera</td>
<td>Lower</td>
<td>252</td>
<td>19.17</td>
</tr>
<tr>
<td>Menfouia</td>
<td>Lower</td>
<td>350</td>
<td>5.85</td>
</tr>
<tr>
<td>Mahmudia</td>
<td>Lower</td>
<td>292</td>
<td>53.20</td>
</tr>
<tr>
<td>Tawfikia</td>
<td>Lower</td>
<td>679</td>
<td>1.52</td>
</tr>
<tr>
<td>Alsalam</td>
<td>Lower</td>
<td>29</td>
<td>246.99</td>
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<tr>
<td><strong>Total/Average</strong></td>
<td></td>
<td>2,669</td>
<td>12.38</td>
</tr>
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There is potential for improvements in our methods of analysis. While not known for certain, it appears that Egypt’s irrigation policymakers can be better informed by the use of a new method of analysis known as ‘positive mathematical programming’ (PMP). Use of PMP outperforms conventional optimization methods in predicting current crop production, crop yields, farm income, and water use. It also avoids unexpected large changes in predicted crop production and crop water uses in the face of the kinds of changes in policies or water supplies that are likely to occur in future years.

Integrating hydropower, recreation, urban, and environment uses into a single framework makes for a more comprehensive analysis of policy proposals. There is great promise from the use of integrated basin framework as a tool to communicate among all the Bing’s countries as they debate their future economic and development process (DCTANBC, 2007). Financial, trade, and infrastructure policy could be included in the future models to evaluate the potential benefits and consequences of wider cooperation among the Nile Basin countries.

2.7. Conclusions

Worldwide, the potential amount of water that could be conserved in agriculture and the best measures to achieve that conservation are matters of long standing debate. Water conservation strategies in Egypt typically avoid promotion of water-conserving irrigation technologies like sprinkler or drip irrigation, because widespread implementation of these measures will reduce return flows to the river
and may even increase overall water consumed in irrigation as a result of their higher crop yields. Rather most irrigation conservation measures in Egypt address the problem that when farmers lack control of the timing, duration, and amount of water supply, they irrigate too early and over apply water. In fact, over-irrigation can be an economically rational measure to reduce the risk of future supplies coming at the wrong time or in the wrong quantity. A bank of water stored in the soil profile is an on-farm measure to guard against the risk of unreliable future surface supplies.

The aim of this study was to identify economic and hydrologic impacts of potential adjustments in Egypt’s water and land use patterns in irrigated agriculture that could occur under a policy of limited water trading. Like other analyses of ways to improve the performance of irrigation water management conducted in recent years, our findings indicate that water re-allocation over time, space, and crops could increase overall economic performance of Egyptian irrigated agriculture. The goals were achieved by examining the economic potential that could arise from a special form of water conservation in Egyptian irrigated agriculture. It identified potential gains in national farm income that could result from a better use of existing Nile River water supplies in Egypt for crop irrigation. It reached several conclusions:

- Better allocation of water among crops, seasons, and locations in Egypt has the potential to increase national farm income by about 28 percent per year with existing water supplies and with no change in existing irrigation technologies.
The increased potential economic earned in irrigated agriculture could be achieved with no irrigated region exporting any more than ten percent of its current water use for cash in any time period.

We were not able to identify which policies or institutions provide the best road map to improve the economic performance of Egypt’s crop irrigation. However, water trading is one institution that could establish the right incentives to move water from current to higher valued uses in irrigation.

A system of water rights must be in place for water trading to be successful in moving water to higher valued uses. Lacking a formal system of adjudicated water rights consistently administered throughout Egypt, a cap-and-trade like arrangement such as the one described by Speed (2009) has the potential to perform important functions. It could serve the dual roles as the beginnings of a workable water right system as well as a mechanism to move water from lower-valued to higher-valued times, locations, and crops.

By accounting for all major sources and uses of water for Egypt’s share of the Nile River, this study has taken a modest first step at a comprehensive hydrologic and economic framework that can be used by water managers and policy makers. The methods and results described in this analysis can inform water policy makers in Egypt and elsewhere in the search for policies consistent with economic goals that are compatible with hydrologic, cultural, and environmental constraints.
2.8. References


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Wichelns, D., 2004. The role of virtual water in efforts to achieve food security and other national goals, with an example from Egypt. Agricultural Water Management. 49(2), 20-50.


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http://agecon.nmsu.edu/fward/water
CHAPTER III

3.0. GAINS FROM EXPANDED IRRIGATION WATER TRADING IN EGYPT: AN INTEGRATED BASIN APPROACH²

3.1. Abstract

Economic development and population growth in Egypt continue to increase the demands for water. Meeting these demands places increasing stress on Egypt's water institutions to support the country's need for food, urban, industrial, and environmental water uses. Many studies have examined measures to increase Egypt's effective water supplies or reduce its water demands. However, no research to date has examined economically efficient and culturally acceptable water institutions for improving the economic performance of Egyptian agricultural water use. The aim of this study is to examine the potential for irrigation water trading as a measure to improve the economic efficiency of Egyptian agricultural water use of the Nile River. Using data on Egyptian land, water, and agriculture, a catchment scale framework is developed to characterize hydrologic and economic impacts of limited water trading by irrigated agriculture while respecting hydrologic, environmental, food security, and institutional constraints. Results suggest that expanded water trading among Egyptian farmers could raise the economic performance of Egypt's irrigation water use. That improved performance could increase national farm income by 6.3 to 7.9% annually with little or no loss in water-related benefits outside agriculture.

Worldwide, solutions to safeguard food production are needed fast. Institutionalizing currently informal water trading arrangements could be a prototype for measures to promote food and water security in Egypt and in other countries with similar water management challenges.

3.2. Introduction

The Nile and its use have always been the most important resource limiting or promoting Egypt's economic development. Growing population, food security challenges, an emerging industrial sector, and the potential threat of climate change elevate the attention given to efficient and sustainable water management in Egypt. These factors point to the continued challenges of guarding against Egypt's water demands exceeding its supplies (Allan, 1992; Wichelns, 2004; Elarabawy and Toswell, 2000).

Despite these challenges facing Egypt's policymakers and water managers, Egypt's share of the Nile's waters has historically been allocated with little attempt to harness the joint power of economic principles and hydrologic science applied at the catchment scale. He and Siam (2004) examined policy alternatives to water pricing that could improve economic efficiency of water allocation in Egypt's share of the Nile's waters. Whittington and McClelland (1992) and Wu and Whittington (2006) analyzed basin scale policy options for improved management of the Nile from its headwaters to the Mediterranean. Simonovic et al. (1997) built a simulation model of Egypt's water use that accounted for its major sources and uses of water. Strzepek et
al. (2008) estimated the value of the High Aswan Dam to the Egyptian economy. Malashkhia (2003) examined irrigation water saving measures that could be applied in Egypt with special attention given to water pricing measures. Wichelns (2002a,b) conducted economic analyses of investments in improved irrigation drainage to address problems of waterlogging and salinization in Egypt.

Establishing institutional innovations in Egyptian water management is important due to the nation's high rate of population growth and increased water demands from all sectors. In Egypt, special attention has been given in recent years to increasing the economic benefit produced by water, in order to improve institutional resilience and economic efficiencies of water allocation and use. Irrigation water trading has the potential to raise the productivity of the country's water. While irrigation water trading is not widespread in Egypt, it can occur at a small scale (Badawy, 2005).

It is widely recognized that irrigation water trading has considerable potential to increase the economic productivity of water by encouraging its movement from low to higher valued uses where there is sufficient physical and institutional flexibility in the system to permit crop diversification. With that flexibility, the allocation of water and crop planting choices respond to changing scarcity values of water, and water trading can occur where it is compatible with existing water laws, institutions, and regulations. Examples of recent studies include works in the western USA by Michelsen (1994) and Zilberman et al. (1994), Australia by Bjornlund and
McKay (1998) and Brennan and Scoccimarro (1999), Texas USA by Characklis et al. (1999) and McCarl et al. (1999), Spain by Garrido (2000), and California and Colorado USA by Carey and Sunding (2001). More recent work has been published for Australia by Tisdell (2001), Bjornlund (2006), Qureshi et al. (2007), and Brooks and Harris (2008). Better known examples from developing countries include works from the Middle East by Dinar and Wolfe (1994 a, b), Becker (1996), India and Bangladesh by Kilgour and Dinar (2001), Central Asia by Cai et al. (2003), Chile by Rosegrant et al. (2000a,b), Tunusia by Zekri and Easter (2005), Morocco by Roe et al. (2005), and for several countries by Rosegrant et al. (2009).

Despite the potential offered by water trading to improve the performance of irrigated agriculture, Egypt's water use patterns occur under a geographically complex maze of river locations, conveyance facilities, cropping patterns, and seasons. So a basin scale integrated framework would be of considerable help in the design or evaluation of a range of irrigation water trading proposals. That broad framework would be especially useful where proposed water trading could occur over large distances. A good part of this complexity comes from the fact that the main source of Egypt's River water use lies at a single release point at the Aswan High Dam, about 1000 km from the river's mouth. These large distances make any adjustments to existing spatial water delivery patterns fraught with logistical challenges produced by a large number of interdependent calculations required to secure a hydrologic balance while examining impacts of water trading.
Nearly 30 years ago, Haynes and Whittington (1981) issued an important challenge by stating that in Egypt, integrated hydrologic and economic research at the basin scale has done little to live up to their potential in generating informed debate for use of Egypt's waters of the Nile. Their challenge still faces Egypt today (Kandil, 2003; Nasser and Allam, 2007). The challenge elevates the importance of formulating a basin scale framework to identify economically efficient irrigation institutions in Egypt. To our knowledge, no research to date has examined comprehensively the potential for more economically efficient water use throughout Egypt that could occur from institutional changes. For these reasons, the objective of this paper is to examine the potential of one institution, namely water trading, to improve the economic efficiency of water use in Egyptian agriculture. The paper achieves that objective by formulating and applying an integrated basin scale model. The model is used to test for economic efficiency gains that could be achieved by intra-regional and interregional water trading among farmers in Egypt. In the model, the potential for economic efficiency gains in agriculture is examined while also protecting demands placed on the river by other water uses, the environment, farm labor, agribusiness, and food security.

3.3. Methods and Materials

3.3.1. Overview

Using information on the basin's water supplies and demands, a framework was developed and applied to predict impacts of two water trading institutions on
national farm income that could be earned with water available from Egypt's use of the Nile waters. In all cases, the model was formulated to maximize total farm income in Egypt's Nile Basin subject to numerous hydrologic, environmental, and institutional constraints that limit water reallocations. Our analysis examines irrigation water trading. Its implementation is a constrained maximization of a single objective, total Egyptian farm income. While the geographic scope, number of crops, river distances, and quantities of water used are large, the objective is limited. It seeks ways to expand the income of irrigated agriculture in Egypt while protecting its other water uses and users, an example of improved Pareto Efficiency. Policymakers have an ongoing interest in pursuing multiple objectives such as efficiency, equity, sustainability, employment, and tax revenues. To address these more comprehensive objectives, multiple criteria decision making (MCDM) is an attractive tool for policy analysis of water resource systems. A good example of an application of MCDM to a Vermont USA watershed is presented in the work of Hermans et al. (2007). The MCDM society (International Society on MCDM, 2010) has seen growing international membership interested in approaching complex water management decisions at the river basin scale through the use of MCDM approaches.

One baseline and two alternative water trading arrangements were considered as measures to improve the economic performance of irrigation water use. The baseline institution was implemented in the model by constraining irrigation in Egypt's Nile Basin to reproduce base year (2006) water use, streamflow, reservoir
levels, reservoir releases, land in production, and cropping patterns. The first alternative institution was intra-regional water trading, in which farmers in a given district would trade water for cash. Water could be traded for cash, but more often it would be traded for other assets. While recognizing the importance of noncash assets, this paper usually refers to cash as what is traded for water. We also considered a second alternative institution, namely interregional trading. Under that arrangement, farmers in different farming regions of the country could trade limited amounts of water. All three institutions are described in greater detail in a subsequent section of the paper. In our study, no Egyptian farmers were surveyed to discover their willingness to engage in water trading. For our results to be applied, communication with farmers and other water stakeholders are highly recommended.

Constraints were established that accounted for several important characteristics of the water, environment, and culture of Egypt. Furthermore, all reservoir storage levels in the last period were constrained to be at least as high as their starting values. We also required all non-agricultural users to use no less water under either alternative institution as they used under the baseline.

3.3.2. Data

Data on cropped area, yield, and cost were obtained from the Egyptian Ministry of Agricultural and Land Reclamation (2008). Data on gauged water flows came from the Ministry of Water Resources and Irrigation (2008). The complete data set for the base year included three irrigation seasons, 22 crops, 13 major irrigated
areas that account for the bulk of Egypt's crop production, and total seasonal river flow of the Nile at each of 10 stream gauges. Representative farm cost and return budgets were also developed and applied for the base year for each crop and area for 3 seasons. Table 3.1 shows a small part of that database, cropland in production by region, season, and crop class for the base year. Remaining base year data are available from the authors. Table 3.2 places the base year in a larger view, showing land in production as well as reservoir levels and reservoir outflows from Nasser Lake from 1983–2006.

3.3.3. Basin Scale Framework

Our basin scale analysis treats as a unit the entire Nile basin within Egypt. Written in GAMS (Brooke et al. 1988), the framework accounts for base year irrigation water uses for Upper, Middle, and Lower Egypt. Our basin analysis accounts for upstream and downstream interactions for different parts of the country in different time periods, which ensures consistent treatment of alternative water allocation and management plans (Wegerrich, 2004). The basin framework also allows for a comprehensive analysis of policies, which could address efficient, equitable, and sustainable water resources use (Allan, 1992). Our basin framework
Table 3.1. Land in Production by Region, Season, and Crop Class, Nile Basin, Egypt (2006), 1000s of Hectares

<table>
<thead>
<tr>
<th>Irrigation District</th>
<th>Region in Egypt</th>
<th>Food Staples</th>
<th></th>
<th>Vegetables</th>
<th></th>
<th>Other Crops</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>winter</td>
<td>summer</td>
<td>nil</td>
<td>winter</td>
<td>summer</td>
<td>nil</td>
</tr>
<tr>
<td>Toshka</td>
<td>Upper</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Asfon</td>
<td>Upper</td>
<td>20</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Keladia</td>
<td>Upper</td>
<td>14</td>
<td>10</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>W Nagh.</td>
<td>Upper</td>
<td>68</td>
<td>69</td>
<td>2</td>
<td>18</td>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>E Nagh.</td>
<td>Upper</td>
<td>53</td>
<td>36</td>
<td>2</td>
<td>6</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>Ibrahimia</td>
<td>Middle</td>
<td>253</td>
<td>230</td>
<td>63</td>
<td>64</td>
<td>79</td>
<td>17</td>
</tr>
<tr>
<td>Ismailia</td>
<td>Middle</td>
<td>14</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Nasser</td>
<td>Lower</td>
<td>105</td>
<td>16</td>
<td>8</td>
<td>28</td>
<td>54</td>
<td>5</td>
</tr>
<tr>
<td>Behera</td>
<td>Lower</td>
<td>171</td>
<td>123</td>
<td>7</td>
<td>18</td>
<td>38</td>
<td>4</td>
</tr>
<tr>
<td>Menufia</td>
<td>Lower</td>
<td>179</td>
<td>236</td>
<td>20</td>
<td>13</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Mahmodia</td>
<td>Lower</td>
<td>152</td>
<td>144</td>
<td>8</td>
<td>25</td>
<td>77</td>
<td>2</td>
</tr>
<tr>
<td>Tawfikia</td>
<td>Lower</td>
<td>383</td>
<td>468</td>
<td>14</td>
<td>61</td>
<td>39</td>
<td>2</td>
</tr>
<tr>
<td>Alsalam</td>
<td>Lower</td>
<td>5</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>1,430</td>
<td>1,339</td>
<td>134</td>
<td>248</td>
<td>437</td>
<td>35</td>
</tr>
</tbody>
</table>

Data Source: Egyptian Ministry of Egyptian Ministry of Agricultural and Land Reclamation (2008)
integrates hydrology, land use, agronomy, economics, and institutions to support improved policy design, implementation, and evaluation (Ward and Pulido-Velazquez, 2008a,b). Numerous excellent basin scale analyses have been completed and published in recent years. Three of the better known examples include the works of Rosegrant et al. (2000a,b) for the Maipo Basin in Chile, Ringler (2001) for the Mekong Basin, and Mainuddin et al. (2007) for Australia's Murray Basin. Furthermore, the basin framework can provide a consistent and comprehensive tracking of water (Prairie, 2006) as well as better communication with stakeholders (Mouratiadou and Moran, 2007).

Models of water supply and use typically require calibration. Good examples are described by Janssen and Heuberger (1995), Singh and Woolhisier (2002), Madsen et al. (2002), and Yapo et al. (1998). We calibrated the model so that its predicted flows matched observed gauged flows at each river gauge on the Nile for which we had base year data. Our calibration involved defining unmeasured water use or unmeasured water supply. Each can come from several sources. Unmeasured use comes from underestimates of crop water use, groundwater pumping, river evaporation, and urban diversions. Unmeasured supply includes overestimates of crop water use, upstream return flows from crop irrigation reaching the river. It also includes unmeasured discharge from aquifers to the river. What this means is that the model's pre-calibrated river flows did not match actual gauged flows. The maximum error varied by gauge and season. In winter, the maximum error was less than 70
million cubic meters at the Aswan Dam outflow, falling to a low of less than 15 million cubic meters at the Edfina outflow. Errors were slightly larger in summer and slightly lower in the nili season.

For both policy alternatives to the current policy, all unmeasured use, and unmeasured supply were held constant at their base calibrated level. This procedure assured that any changes brought about by a new policy would permit no additional supplies or uses of water compared to base levels. An abbreviated mathematical treatment is attached as an Appendix. The complete program code written in GAMS as well as data used and program’s output are available from the authors on request and is also posted on internet (Gohar and Ward, 2010).

3.3.3.1. Economics

Egypt's irrigation from the Nile occurs in three cropping seasons (FAO, 1995): winter, November to May; summer, May to September; and nili, September to November. Hydrologic data on streamflows, water diversions, and crop water use were combined with farm production details that accounted for crop prices, costs of production, and crop yields. Net income produced by any single crop was defined as price multiplied by yield minus all input costs, including both variable and fixed costs. Variable costs are incremental costs incurred by production like those associated with planting and harvesting. Fixed costs typically remain the same within a production period and do not vary with the level of output. They include depreciation, taxes, interest on investment, and land charges. For political and
historical reasons there is currently no charge for surface irrigation water in Egypt. However, where water trading would be permitted, the cost to an irrigator of using water for a low-valued crop is the opportunity cost that could be earned by trading that water for cash.

Net farm income per unit land was calculated by region, crop, season, and year. The model was designed to examine ways to allocate water and land under two water trading arrangements different from arrangements in place for the base year. For each trading arrangement the model allocated water to maximize net discounted farm income summed over crops, seasons, time periods, and locations, subject to a series of cultural, economic, food security, and environmental constraints. Where water could be reallocated to increase farm income, the model adjusted whatever change in land was needed to accompany the change in water. So, our approach treats water and not land as the limiting resource. Discounted net present value at a 0% discount rate was maximized over a five year planning period, with a time step consisting of three seasons per year as described above. The economic analysis accounted for several constraints that could limit potential water reallocations under water trading. Even if water trading institutions emerged that secured an economic benefit to both a supplier and a user, one would expect considerable resistance by affected communities to proposed large scale water transfers, especially by communities that would export water.
Table 3.2. Lake Nasser Storage and Reservoir Outflows and Irrigated Land in Production, Egypt, 1983-2006

<table>
<thead>
<tr>
<th>Year</th>
<th>Reservoir Outflow (Million Cubic Meters)</th>
<th>Reservoir Storage (Thousand Hectares)</th>
<th>Food Staples (Thousand Hectares)</th>
<th>Vegetables (Thousand Hectares)</th>
<th>Other Crops (Thousand Hectares)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>57,190</td>
<td>96,088(^a)</td>
<td>1,944</td>
<td>272</td>
<td>1,067</td>
</tr>
<tr>
<td>1984</td>
<td>57,307</td>
<td>72,059(^a)</td>
<td>1,869</td>
<td>268</td>
<td>1,078</td>
</tr>
<tr>
<td>1985</td>
<td>55,837</td>
<td>74,003(^a)</td>
<td>1,835</td>
<td>289</td>
<td>1,134</td>
</tr>
<tr>
<td>1986</td>
<td>55,234</td>
<td>67,845(^a)</td>
<td>1,797</td>
<td>333</td>
<td>1,189</td>
</tr>
<tr>
<td>1987</td>
<td>54,403</td>
<td>56,397(^a)</td>
<td>1,880</td>
<td>326</td>
<td>1,166</td>
</tr>
<tr>
<td>1988</td>
<td>52,142</td>
<td>91,824</td>
<td>1,916</td>
<td>337</td>
<td>1,208</td>
</tr>
<tr>
<td>1989</td>
<td>50,100</td>
<td>96,173(^a)</td>
<td>2,045</td>
<td>308</td>
<td>1,213</td>
</tr>
<tr>
<td>1990</td>
<td>54,055</td>
<td>85,112(^a)</td>
<td>2,246</td>
<td>297</td>
<td>1,176</td>
</tr>
<tr>
<td>1991</td>
<td>53,750</td>
<td>93,558</td>
<td>2,442</td>
<td>297</td>
<td>1,136</td>
</tr>
<tr>
<td>1992</td>
<td>54,733</td>
<td>100,395</td>
<td>2,481</td>
<td>275</td>
<td>1,202</td>
</tr>
<tr>
<td>1993</td>
<td>55,235</td>
<td>117,712</td>
<td>2,443</td>
<td>323</td>
<td>1,221</td>
</tr>
<tr>
<td>1994</td>
<td>54,613</td>
<td>131,522</td>
<td>2,531</td>
<td>336</td>
<td>1,125</td>
</tr>
<tr>
<td>1995</td>
<td>55,671</td>
<td>125,876</td>
<td>2,727</td>
<td>407</td>
<td>1,136</td>
</tr>
<tr>
<td>1996</td>
<td>54,889</td>
<td>140,568</td>
<td>2,561</td>
<td>422</td>
<td>1,237</td>
</tr>
<tr>
<td>1997</td>
<td>56,608</td>
<td>140,807(^a)</td>
<td>2,720</td>
<td>434</td>
<td>1,224</td>
</tr>
<tr>
<td>1998</td>
<td>65,510</td>
<td>152,713</td>
<td>2,642</td>
<td>470</td>
<td>1,216</td>
</tr>
<tr>
<td>1999</td>
<td>67,160</td>
<td>156,642(^a)</td>
<td>2,669</td>
<td>536</td>
<td>1,246</td>
</tr>
<tr>
<td>2000</td>
<td>64,147</td>
<td>151,685(^a)</td>
<td>2,701</td>
<td>551</td>
<td>1,209</td>
</tr>
<tr>
<td>2001</td>
<td>67,197</td>
<td>149,256</td>
<td>2,578</td>
<td>516</td>
<td>1,308</td>
</tr>
<tr>
<td>2002</td>
<td>61,822</td>
<td>132,892(^a)</td>
<td>2,669</td>
<td>548</td>
<td>1,261</td>
</tr>
<tr>
<td>2003</td>
<td>56,630</td>
<td>134,308</td>
<td>2,689</td>
<td>583</td>
<td>1,194</td>
</tr>
<tr>
<td>2004</td>
<td>57,808</td>
<td>117,897(^b)</td>
<td>2,710</td>
<td>576</td>
<td>1,287</td>
</tr>
<tr>
<td>2005</td>
<td>57,015</td>
<td>118,128</td>
<td>2,931</td>
<td>600</td>
<td>1,281</td>
</tr>
<tr>
<td>2006</td>
<td>57,646</td>
<td>128,552</td>
<td>2,902</td>
<td>721</td>
<td>1,804</td>
</tr>
</tbody>
</table>

\(^a\) Storage volume at Lake Nasser related to surface elevation by a fourth order polynomial regression. Percentage of variance explained by the equation > 99.9

\(^b\) Estimated, original data missing

Data sources for Water: Egyptian Central Agency for Public Mobilization and Statistics (2009)
Data sources for Land: FAO (2010)
3.3.3.2. Hydrology

Egypt has a spatially complex irrigation system. The schematic shown in Fig.1 presents a highly simplified view of Egypt's sources and uses of irrigation water from the Nile. The system hierarchy begins with the mainstem of the Nile. Principal canals receive water directly from the Nile, then deliver to the branch canals and distributary canals. Private canals known as mesqas receive water from the branch canals or distributary canals, and then deliver the water either directly to the fields or into smaller marwas, which are private deliveries from mesqas that convey water to fields located at a distance from the mesqa (Hvidt, 1998).

The main canal diversions shown in the schematic include Asfon, Kelabia, East Naghammadi, and West Naghammadi in Upper Egypt, while the Toshka canal takes water directly from Lake Nasser (Water Technology, 2010). Middle Egypt has two main canals. The Ibrahimia canal divides its water among many canals to serve irrigation in the Assiut region. The Ismailia canal irrigates the Suez and Elshrkia regions (Egyptian Ministry of Public Works, 2010). In Lower Egypt, downstream of the Delta gauge, the Nile splits into two branches Rosetta and Damietta, creating the Nile Delta. The Rosetta branch includes the Menufia, Beheira, Nasser, and Mahmodia canals, while the Damietta branch includes the Tawfikia and Alsalam canals. There are about 30,000 km of public canals, 80,000 km of mesqas and drains, and 670 large pumping stations for irrigation (Hvidt, 1998). For the current study, details on the pump stations and smaller canals were ignored to keep the analysis manageable. Fig.1
summarizes the essential characteristics of the Egyptian irrigation and hydrologic complex used for our analysis.

3.3.4. Policy Analysis

3.3.4.1. The national water resources plan

A large number of water management and policy strategies are described in the 2005 Egyptian National Water Resources Plan (Egyptian Ministry of Water Resources and Irrigation, 2005). Four strategies include (1) developing additional water, (2) making better use of existing water, (3) protecting public health and the environment, and (4) institutional and financial reform. The analysis in this paper focuses on one policy alternative to the baseline under (2) above. For that alternative, opportunities are examined for making better use of existing water.

3.3.4.2. Market Measures

Water trading offers a potential for reallocating water from lower to higher valued uses if approached carefully and with sensitivity to cultural requirements (Hellegers and Perry, 2006). The benefits of water trading have been discovered in recent years under water trading programs established in both Chile and Australia. Any market institution that promotes water conservation or reallocation should meet three criteria to be politically acceptable. It should reduce the consumption of low-valued water uses, be perceived as equitable, and signal water's real economic scarcity.
3.3.4.3. Water Rights and Water Trading in Egypt

An existing water rights system, with a well-defined and enforceable right to use water, is needed for water trading to occur. Two foundations of an irrigation water right are seen in Egypt (Badawy, 2005). The first is the right held by a group of farmers whose land is served by a canal owned and operated by the group (mesqa), to which the government delivers water from larger canals. A second type of water right can accrue, namely the right to use water earned in proportion to labor contributed to developing the water supply. A good example is labor invested in developing a well, which can produce a water right that is passed down to future members of the developer's family.

Water rarely reaches the mesqa at a convenient time for all farmers. After water is delivered to the mesqa, each farmer has the right to begin irrigation at a set point in time (the turn). The farmer also has the right to apply a given quantity of water on his land for a set time duration (the quota). The quota is based on the quantity of land the farmer owns as a proportion of the total lands the mesqa supplies. Within a mesqa, a farmer's quota is typically independent of the crop grown. So where a water saving crop could be planted, deficit irrigation practiced, land fallowed, or modern irrigation technology adopted, there would be unused water available for trading.

Where informal irrigation water trading occurs in Egypt, it can consist of farmers arranging to trade a turn or quota or both (Badawy, 2005). Trading turns
improves a farmer's flexibility by altering the time at which irrigation begins. For example a woman unable to irrigate at night may exchange her turn with a man who can. Quota trading involves exchange of irrigation durations. A farmer with a larger quota may trade with one whose quota is smaller in exchange for cash. Alternatively, two or more farmers can pool their individual quotas and distribute it among themselves for mutual benefit. While Islamic law does not prohibit trading private irrigation water for cash, it's more common in Egypt to trade water for in-kind resource, such as farm tools, animals, or future water.

Islamic law recognizes three classes of water use: (1) private good, (2) restricted public good, and (3) public good. For the first, a user who develops the water through measures such as wells or canals has the right to continue using the water. For the second, where several landowners share water, outsiders need permission from the owners to use the water. The third applies to public waters like lakes and rivers. For it, potential water users must avoid damages to others or the environment. For all three classes, no potential water user can be deprived of water for drinking (Hefny, 2009) and Beaumont (2005).

3.3.4.4. Baseline Management

For our analysis, a base policy framework was defined to replicate water supply and demand conditions that occurred in the base year. It was implemented by constraining irrigation in Egypt to reproduce base year water use, streamflow, reservoir levels, reservoir outflows, land in production, and cropping patterns. That
was the only year for which we could assemble a consistent dataset with all economic, agronomic, and hydrologic data.

3.3.4.5. Intra-regional Water Trading

Water trading among irrigators benefits both traders. Water moves to higher valued crop production, the seller receive more cash than is currently earned in agriculture while the buyer receives use of water of a higher economic value than the cash cost of the water. Despite the benefits of water trading, farm labor, regional agribusiness and communities whose income streams depend on irrigated agriculture may suffer when water is exported as a result of water trading. With this in mind, our analysis formulated a policy that would limit water trades to buyers and sellers who farm in the same region. We label this arrangement “intra-regional water trading”.

This policy would ensure five protections.

First, limited water trading would capture many of the benefits of national trading across regions while limiting undesirable external costs associated with water exports. Second, the policy is designed to protect the food security of each crop-producing region in Egypt: total water irrigating each staple is restricted so that water allocated to each staple is no less than in the base year. Third, the water trading arrangement protects crop price security. Each vegetable crop in each district is constrained to allocate no more than 110% of base levels of water under the water trading arrangement. Without this constraint, large amounts of water could be reallocated from existing crops into higher income vegetables, reducing vegetable
prices significantly. Next, for all non-staple crops, at least 90% of existing crop water allocations is constrained to remain at current levels for each district. This constraint assures viability of income earned under base water conditions for farm labor, food processors, and related agribusiness. Finally, no water can be exported from the region. An intra-regional water trading program with these constraints satisfied could promote a Pareto Improvement, in which water traders are made better off while few others are made worse off.

3.3.4.6. Interregional Water Trading

An analysis parallel to intra-regional water trading was conducted to reflect interregional water trading. It, too, is directly comparable with base year water use patterns. Under this trading scenario, modest reductions of water use in any of the 14 irrigation regions were permitted that would result from water trades among farmers in different regions. However, a constraint was imposed so that for each region and season, water use reductions could be no more than 10% of base year water use. There was an important reason for establishing this upper bound on water use reductions. Even if Egyptian farmers would benefit overall from large water trades in which water moved across regions to a higher valued use, large water exports may be politically unacceptable for all the reasons described above.

3.3.4.7. Trading Under Both Scenarios
Compared to the base policy several changes were considered in the analysis of water use under both water trading policies. For both alternatives to the baseline, all constraints on gauged flows throughout Egypt were removed. That is, under each alternative policy, gauged flows could depart from observed flows in any way needed to increase national farm income, consistent with the constraints on adjustments in water use described above. Reservoir storage volume was also addressed for both water-trading scenarios. Storage volume at Lake Nasser and Lake Nile was both constrained to be at least as high at the end of the planning horizon as volumes that occurred at the end of the base year in those reservoirs. By imposing this constraint on terminal period reservoir levels, we guaranteed equally sustainable water supplies and uses under both alternative policies as those that occurred under the base policy.

In addition, river flows at the two Nile delta gauges into the Mediterranean (Edfina and Zifta) were constrained to be at least as high as base year measured flows. This constraint was established to assure adequate flow levels in the Nile to support tourism demands for river flows and to protect the environment by guarding against saltwater intrusion. Interregional water trading does not produce an actual Pareto Improvement. While water traders can be made better off under interregional trading, there would be some losses to third parties as a consequence of water exports. Still, establishing an upper bound of 10% water use reduction from any existing region was designed to control these third party losses.
3.4. Results

3.4.1. Overview

Our findings illustrate several important economic forces that can be harnessed if irrigation water trading is introduced in Egypt. Trading allows water buyers to offer a price for water that enable them to increase their water use beyond their existing water rights by taking advantage of high valued water uses in irrigation. Water sellers transfer water from existing low-valued uses at the margin to buyers' higher valued uses. As the geographic scope for water trading widens from intra-regional to interregional trading, the overall volume of water traded rises nationally. Water exporting regions export more while importing regions import greater amounts under this wider geographic scope.

A rising price of water resulting from introduced trade provides incentives for both water exporters and water importers to adjust their behavior. Water exporters substitute land for water in two ways: (1) shifting from water intensive to water saving crops, and (2) fallowing land. Both substitutions occur because a rising price of water raises the opportunity cost of continuing to grow water intensive crops for which the economic value of water is low at the margin. Water importing irrigators find that the opportunity to purchase water is cheaper than seeking water from an alternative source. For our analysis, the alternative source is to reduce irrigation of an existing high valued crop because of water supply constraints. So, for the importer, the price of water made available when trade opens up is lower than the cost of
having access to no additional water. Importers substitute water for land in two ways: shifting from existing to more water intensive crops and bringing new land into production currently fallowed for a lack of water. Two potentially important adjustments in Egypt were not examined in this study: (1) reduced water use by adopting water conserving technologies such as sprinkler or drip irrigation, and (2) stressing crops by reduced water applications per unit land where yield losses are small.

3.4.2. Water Flows and Use

Tables (3.3–3.5) show water flow and use patterns throughout Egypt for the base and both water trading alternatives. For each alternative, Table (3.3) shows streamflows at the 10 major Nile River gauges. Note that results of intra-regional trading show no change in the Nile's gauged flows compared to the base year. This is expected because no interregional trading would occur, so no irrigated area would send or receive additional water. As expected, interregional trading shows modest changes in the Nile's gauged flows. Where interregional trading sends water from an upstream to a downstream region, hydrologic balance requires increased flows to occur in the intervening reach. Where a trade sends water from a downstream to upstream location, gauged flows decrease in the intervening river reach. Notice that winter interregional trading produces slightly higher winter flows at the Assiut gauge in Middle Egypt and at the three gauges in Lower Egypt, Delta, Rosetta, and Demitta. It also produces higher gauged summer flows at the two contiguous gauges Assiut
and Delta. Finally, it produces no change in flows in the nili season, since interregional water trading would produce minimal water use changes in that season.

The capacity to systematically track and predict river flows for policies not yet implemented is an important reason for spending large amounts of time and money to build and use a hydrologically balanced model. Without a mechanism to enforce a physical water balance, neither water trades among regions nor other complex water policy proposals can be evaluated comprehensively. This is, an ancient and widely recognized problem facing those who would propose changes in water laws or other policies that affect water use patterns.

Table 3.4 presents irrigation water use by season, district, and policy. Compared to the base policy, intra-regional water trading shows no change in overall irrigation water use at any region or season. This finding is consistent with the institutional constraint that all water trades are limited to trades within the same region. The table also shows considerable changes in water use patterns under winter interregional trading. Major increases in water use with that trading would occur in Mahmodia, with a 32% water use increase, and Alsalam, with a 62% increase. This trading occurs because of the potential to increase profits from additional palm and aromatic plant production, profits that are currently unrealized under historical water use patterns. Table 3.4 also shows that the summer season has the largest adjustments to existing water use patterns in most of the irrigated regions when faced with interregional trading.
Table 3.3. Nile River Flow, Egypt, by Gauge, Season, and Policy, in Million Cubic Meters per Season, Five Year Average

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AHD</td>
<td>Upper</td>
<td>17,849</td>
<td>0</td>
<td>0</td>
<td>38,686</td>
<td>0</td>
<td>0</td>
<td>1,073</td>
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<td>0</td>
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<tr>
<td>Aswan</td>
<td>Upper</td>
<td>17,685</td>
<td>0</td>
<td>0</td>
<td>38,367</td>
<td>0</td>
<td>0</td>
<td>1,088</td>
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<td>0</td>
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<tr>
<td>Esna</td>
<td>Upper</td>
<td>16,754</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>1,005</td>
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<td>0</td>
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<td>Naghammadi</td>
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<td>0</td>
<td>34,648</td>
<td>0</td>
<td>0</td>
<td>962</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Assiut</td>
<td>Middle</td>
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<td>0</td>
<td>2</td>
<td>26,058</td>
<td>0</td>
<td>1</td>
<td>710</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Delta</td>
<td>Lower</td>
<td>11,732</td>
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<td>2</td>
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<td>0</td>
<td>1</td>
<td>691</td>
<td>0</td>
<td>0</td>
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<td>Rosetta</td>
<td>Lower</td>
<td>8,031</td>
<td>0</td>
<td>4</td>
<td>17,392</td>
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<td>0</td>
<td>470</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Demitta</td>
<td>Lower</td>
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<td>1</td>
<td>7,694</td>
<td>0</td>
<td>0</td>
<td>196</td>
<td>0</td>
<td>0</td>
</tr>
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<td>Edfina outflow</td>
<td>Lower</td>
<td>134</td>
<td>0</td>
<td>0</td>
<td>307</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zifta outflow</td>
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<td>974</td>
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<td>0</td>
<td>2,190</td>
<td>0</td>
<td>0</td>
<td>46</td>
<td>0</td>
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</tr>
</tbody>
</table>

Data For Gauged Flows without Trading: Egyptian Ministry of Water Resources and Irrigation
Table 3.4. Water Use in Agriculture by Region, Season, and Water Trading Policy, Nile Basin, Egypt, in Million Cubic Meters Per Season, Five Year Average*

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
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<tr>
<td>Upper</td>
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<td>110</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>-4</td>
<td>9</td>
<td>0</td>
<td>-10</td>
</tr>
<tr>
<td>Asfon</td>
<td>Upper</td>
<td>165</td>
<td>0</td>
<td>-4</td>
<td>775</td>
<td>0</td>
<td>-8</td>
<td>31</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Kelibia</td>
<td>Upper</td>
<td>123</td>
<td>0</td>
<td>-4</td>
<td>286</td>
<td>0</td>
<td>-3</td>
<td>19</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>W Nagh.</td>
<td>Upper</td>
<td>789</td>
<td>0</td>
<td>-5</td>
<td>2,054</td>
<td>0</td>
<td>-2</td>
<td>30</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td>E Nagh.</td>
<td>Upper</td>
<td>468</td>
<td>0</td>
<td>-5</td>
<td>795</td>
<td>0</td>
<td>-1</td>
<td>18</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Ibrahimia</td>
<td>Middle</td>
<td>2,303</td>
<td>0</td>
<td>-5</td>
<td>3,845</td>
<td>0</td>
<td>-4</td>
<td>507</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ismailia</td>
<td>Middle</td>
<td>132</td>
<td>0</td>
<td>-6</td>
<td>90</td>
<td>0</td>
<td>-5</td>
<td>7</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Nasser</td>
<td>Lower</td>
<td>629</td>
<td>0</td>
<td>0</td>
<td>1,168</td>
<td>0</td>
<td>-8</td>
<td>84</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Behera</td>
<td>Lower</td>
<td>1,094</td>
<td>0</td>
<td>0</td>
<td>1,345</td>
<td>0</td>
<td>-3</td>
<td>83</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Menufia</td>
<td>Lower</td>
<td>1,405</td>
<td>0</td>
<td>-5</td>
<td>3,182</td>
<td>0</td>
<td>-2</td>
<td>97</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mahmoda</td>
<td>Lower</td>
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<td>0</td>
<td>32</td>
<td>2,640</td>
<td>0</td>
<td>-1</td>
<td>68</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Tawfikia</td>
<td>Lower</td>
<td>2,750</td>
<td>0</td>
<td>-4</td>
<td>5,187</td>
<td>0</td>
<td>10</td>
<td>99</td>
<td>0</td>
<td>-1</td>
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<tr>
<td>Alsalam</td>
<td>Lower</td>
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<td>62</td>
<td>379</td>
<td>0</td>
<td>-10</td>
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<td>0</td>
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<tr>
<td>Total</td>
<td></td>
<td>11,101</td>
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<td>21,747</td>
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<td>0</td>
<td>1,076</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Negative entries are water supplies, positives are water demands

Data for Water Use in Agriculture without Trading: Egyptian Ministry of Water Resources and Irrigation (2008)
Table 3.5. Water Use in Irrigation by Region, Crop Class, and Water Trading Policy, Nile Basin, Egypt, Millions of Cubic Meters/Year, 5 Year Average*

<table>
<thead>
<tr>
<th>Irrigation District</th>
<th>Region in Egypt</th>
<th>Food Staples**</th>
<th>Vegetables</th>
<th>Other Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without Water Trading</td>
<td>Intra-regional Water Trading</td>
<td>Inter-regional Water Trading</td>
</tr>
<tr>
<td></td>
<td></td>
<td>water use</td>
<td>% change</td>
<td>water use</td>
</tr>
<tr>
<td>Toshka</td>
<td>Upper</td>
<td>59</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Asfon</td>
<td>Upper</td>
<td>145</td>
<td>0</td>
<td>113</td>
</tr>
<tr>
<td>Kelibia</td>
<td>Upper</td>
<td>150</td>
<td>0</td>
<td>88</td>
</tr>
<tr>
<td>W Nagh.</td>
<td>Upper</td>
<td>782</td>
<td>0</td>
<td>737</td>
</tr>
<tr>
<td>E Nagh.</td>
<td>Upper</td>
<td>500</td>
<td>0</td>
<td>272</td>
</tr>
<tr>
<td>Ibrahimia</td>
<td>Middle</td>
<td>3,012</td>
<td>0</td>
<td>903</td>
</tr>
<tr>
<td>Ismailia</td>
<td>Middle</td>
<td>89</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>Nasser</td>
<td>Lower</td>
<td>494</td>
<td>0</td>
<td>447</td>
</tr>
<tr>
<td>Behera</td>
<td>Lower</td>
<td>1,317</td>
<td>0</td>
<td>321</td>
</tr>
<tr>
<td>Menufia</td>
<td>Lower</td>
<td>3,301</td>
<td>0</td>
<td>79</td>
</tr>
<tr>
<td>Mahmodia</td>
<td>Lower</td>
<td>1,989</td>
<td>0</td>
<td>563</td>
</tr>
<tr>
<td>Tawfikia</td>
<td>Lower</td>
<td>5,304</td>
<td>0</td>
<td>461</td>
</tr>
<tr>
<td>Al Salam</td>
<td>Lower</td>
<td>37</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>17,179</td>
<td>0</td>
<td>4,029</td>
</tr>
</tbody>
</table>

* Negative entries are water supplied, positives are water demands

** Food staples: wheat, sorghum, barley, maize, corn, rice, beans, and potatoes. Vegetables: sesame, onion, garlic, tomatoes. Other crops: flax, cotton, sugar beets, sugar cane, clover, aromatic and medicinal plants, palms, orchards.
Ibrahimia (144 MCM reduced water use) and Nasser (92 MCM reduction) have the largest predicted water exports induced by the trading opportunity. Tawfikia region shows the largest summer water importation at more than 500 MCM, mostly to support increased aromatic and medicinal plant production. For Tawfikia, these are high valued but water intensive crops, for which there is too little water available to grow under base water right limits. The short nili season presents the least opportunity for gains from water trading.

Table 3.5 presents the same results as shown in Table 3.4, but sorts the findings by district and crop class for each policy scenario. All 22 crops analyzed are shown at the bottom of this table. The three crop classes include food staples, vegetables, and a residual of “other crops.” One interesting finding is the very low water importation induced by trading for food staples for either trading arrangement. Food staples are typically marginal (but predictable) income earners in Egypt. If it were not for the food security requirement, food staple production would fall considerably in the face of water trading opportunities. For this reason, it is important for policymakers to find mechanisms to protect production of food staple crops to accompany the introduction of water trading.

Vegetables show large increases under both kinds of water trading, because of their high-income earning capacity as long as that production avoids expanding by enough to reduce prices significantly. In absolute terms, water brought into vegetable production is the highest for West Naghammadi in Upper Egypt, at 65 MCM more
use, and Ibrahimia in Middle Egypt, at 69 MCM more. The largest water imports occur for ‘other vegetables’ (tomatoes) because of their high but currently unrealized profitability per unit water consumed. The ‘other crop’ class typically shows heavy water exports compared to base water use when intra-regional trading opens up. However, two important exceptions occur for which there would be large imports of water for palms in Lower Egypt's Mahmodia and Tawfikia regions. This crop only becomes sufficiently profitable to use imported water when the scope for trading widens from intra-regional to interregional imports. Without interregional trading, there would be too little water in either region to irrigate that crop profitably.

3.4.3. Land in Production

Tables (3.6) and (3.7) show the pattern of land in production by irrigated region, season, and policy. Typically, the land adjustments parallel water trading results as shown in Tables (3.4) and (3.5). Interestingly total national land use changes with interregional water trading follow slightly different patterns than total water use. Where total national water use was constrained under both trading patterns to be no larger than for the base policy, total land use can increase, reflecting the fact that when water is made available, additional land can be cheaply brought into production by the Egyptian farmer. Water is the limiting resource for irrigation in Egypt, not land. Notice that total land in production would fall in the winter if intra-regional water trading opens up. While total water use in each region does not increase, farmers would grow more water intensive but higher income earning crops
in this season. Total winter land in production nationally would fall by an estimated 13,000 ha with intra-regional trading, while only falling by 2000 ha with interregional trading.

Table 3.7 presents results of cropland by irrigation region, crop class, and policy. The table shows the impact on land use associated with water trades that would occur for both alternative policies. Results for food staples mirror the findings from Table 5: no major changes in land use occur for either policy. This result occurs because food staples are the most marginal income earners. As was the case for both vegetable and ‘other crops’ shown in Table 3.5, Table 3.7 shows the impacts on land use associated with the considerable water trading activities. It shows that while water applied to other crops would fall under both water-trading arrangements, land in production will increase. This increase occurs because of the general substitution of land for water in the face of higher water prices from water trading opportunities, again because water is more limiting than land in Egypt.

3.4.4. Farm Income

Table 3.8 shows results for farm income by region, season, and water trading policy. All changes in farm income exclude water-trading revenues for water exporting regions as well as water charges paid by water importing regions. Farm income totals for the country do account for the price of water, since the sum of water trading revenue equals water-trading cost.
Table 3.6. Land in Production by Season, Region, and Water Trading Policy, Nile Basin, Egypt, in 1000 Hectares/Season, Five Year Average

<table>
<thead>
<tr>
<th>Irrigation District</th>
<th>Region in Egypt</th>
<th>Winter Without Water Trading</th>
<th>Intra-regional Water Trading</th>
<th>Inter-regional Water Trading</th>
<th>Summer Without Water Trading</th>
<th>Intra-regional Water Trading</th>
<th>Inter-regional Water Trading</th>
<th>Nili Without Water Trading</th>
<th>Intra-regional Water Trading</th>
<th>Inter-regional Water Trading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>land use</td>
<td>% change</td>
<td>% change</td>
<td>land use</td>
<td>% change</td>
<td>% change</td>
<td>land use</td>
<td>% change</td>
<td>land use</td>
</tr>
<tr>
<td>Toshka</td>
<td>Upper</td>
<td>20</td>
<td>-1</td>
<td>-3</td>
<td>0</td>
<td>0</td>
<td>-3</td>
<td>2</td>
<td>0</td>
<td>-10</td>
</tr>
<tr>
<td>Asfon</td>
<td>Upper</td>
<td>32</td>
<td>0</td>
<td>-3</td>
<td>55</td>
<td>9</td>
<td>-6</td>
<td>5</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Kelabia</td>
<td>Upper</td>
<td>24</td>
<td>0</td>
<td>-3</td>
<td>30</td>
<td>2</td>
<td>-2</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>W Nagh.</td>
<td>Upper</td>
<td>137</td>
<td>-1</td>
<td>-4</td>
<td>271</td>
<td>1</td>
<td>-1</td>
<td>4</td>
<td>2</td>
<td>-3</td>
</tr>
<tr>
<td>E Nagh.</td>
<td>Upper</td>
<td>85</td>
<td>-1</td>
<td>-3</td>
<td>110</td>
<td>0</td>
<td>-1</td>
<td>3</td>
<td>0</td>
<td>-1</td>
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<tr>
<td>Ibrahimia</td>
<td>Middle</td>
<td>495</td>
<td>-1</td>
<td>-4</td>
<td>479</td>
<td>2</td>
<td>-3</td>
<td>96</td>
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<tr>
<td>Ismailia</td>
<td>Middle</td>
<td>28</td>
<td>-2</td>
<td>-5</td>
<td>10</td>
<td>3</td>
<td>-5</td>
<td>1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Nasser</td>
<td>Lower</td>
<td>165</td>
<td>0</td>
<td>0</td>
<td>158</td>
<td>12</td>
<td>-7</td>
<td>19</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Behera</td>
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<td>210</td>
<td>4</td>
<td>-1</td>
<td>19</td>
<td>-2</td>
<td>-2</td>
</tr>
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<td>Menoufia</td>
<td>Lower</td>
<td>340</td>
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<td>-4</td>
<td>320</td>
<td>3</td>
<td>-2</td>
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<td>0</td>
</tr>
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<td>21</td>
<td>323</td>
<td>3</td>
<td>-1</td>
<td>16</td>
<td>-1</td>
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</tr>
<tr>
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<td>3</td>
<td>30</td>
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<td>-2</td>
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<tr>
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<td>18</td>
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</table>

Data for Land in Production without Trading: Egyptian Ministry of Agricultural and Land Reclamation (2008)
<table>
<thead>
<tr>
<th>Irrigation District</th>
<th>Region in Egypt</th>
<th>Food Staples</th>
<th>Vegetables</th>
<th>Other Crops</th>
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<tbody>
<tr>
<td></td>
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<td>Intra-regional Water Trading</td>
<td>Inter-regional Water Trading</td>
</tr>
<tr>
<td></td>
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<td>land use</td>
<td>% change</td>
<td>land use</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
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</tr>
<tr>
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<td>0</td>
</tr>
<tr>
<td>E Nagh.</td>
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</tr>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nasser</td>
<td>Lower</td>
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<td>0</td>
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<td>Behera</td>
<td>Lower</td>
<td>301</td>
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<td>0</td>
</tr>
<tr>
<td>Menfia</td>
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<td>0</td>
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<td>Mahmodia</td>
<td>Lower</td>
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<td>Tawfikia</td>
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<td>0</td>
</tr>
<tr>
<td>Alsalam</td>
<td>Lower</td>
<td>9</td>
<td>0</td>
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<td>Total</td>
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</table>
Overall, the table shows increased farm income under the intraregional water trading policy of about 6.3% compared to the baseline. A slightly larger increase of about 7.9% occurs under the interregional water trading policy. Total national annual average farm income under the base policy is an estimated $US 7.92 billion: 3.36 for winter plus 4.31 billion for summer plus 0.25 billion for nili. Intra-regional water trading produces average annual farm income of $US 8.42 billion: 3.61 billion in winter plus 4.55 billion in summer plus 0.25 billion for nili. For interregional water trading, total average farm income per year is estimated at $US 8.54 billion. The Mahmodia region is the largest beneficiary of winter water trading, with an estimated gain of $US 311 million. Tawfikia gains the most from summer trading, at $US 294 million. Consistent with the earlier results, these findings show that by far the largest part of the gains from water trading can be had without the need to trade water among regions.

Table 3.9 shows farm income by irrigation region, crop class, and policy. Overall, the table reveals similar findings as shown in previous tables. Nationally, incomes earned from staple crops are unchanged under both trading arrangements, since the trading has no effect on staple crop production from a base of $US 2.275 billion. Much more income is earned for vegetables under trading, increasing from $US 2.79 billion without trading to $US 2.98 billion with intra-regional trading and to $US 2.94 billion under interregional trading.
<table>
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<th>Irrigation District</th>
<th>Region in Egypt</th>
<th>Winter Without Water Trading</th>
<th>Winter Inter-regional Water Trading</th>
<th>Winter Inter-regional % change</th>
<th>Summer Without Water Trading</th>
<th>Summer Inter-regional Water Trading</th>
<th>Summer Inter-regional % change</th>
<th>Nili Without Water Trading</th>
<th>Nili Inter-regional Water Trading</th>
<th>Nili Inter-regional % change</th>
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<td>-2</td>
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<tr>
<td>E Naj.</td>
<td>Upper</td>
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<td>-5</td>
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<td>6</td>
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<td>-2</td>
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<td>-3</td>
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<td>5</td>
<td>-1</td>
<td>108</td>
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<td>-6</td>
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<td>110</td>
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<td>-10</td>
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<td>Vegetables</td>
<td>Other Crops</td>
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<td>Interregional Water Trading</td>
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</tr>
<tr>
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<tr>
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<td>-1</td>
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<td>6</td>
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</tr>
</tbody>
</table>

Million/Year, 5 Year Average
That slight reduction in vegetable income under interregional trading is much more than offset with a growth in ‘other crop’ income from $US 3.16 billion to $US 3.33 billion.

While not shown in the tables, the scarcity value of water (shadow price) is consistent with farm income. With rising farm income, water becomes less scarce as the scope for water trading widens. For the baseline scenario, water's shadow price is $US 0.18 per cubic meter averaging over the seasons. For intra-regional trading, water's shadow price falls slightly as expected, since that trading increases farm income while reducing the scarcity value of water to $US 0.17 per cubic meter. Finally, for the interregional trading scenario, water's shadow price falls to a much lower $0.08 per cubic meter, reflecting the greater opportunities realized for raising farm income.

3.5. Discussion

This study's findings and its implications regarding adjustments in water institutions are constructive, practical, flexible, and pro-active. Especially relevant to address future climate change conditions, our methods present a comprehensive approach for dealing with impacts of future changes in water supply. Our results could provide insights into the design of adaptation measures to improve water institutional resilience in arid and semi-arid countries.

Our findings illustrate several important outcomes associated with a policy that would permit limited water trading among irrigators in Egypt. Adjusting baseline
water use patterns through limited water trading provides flexibility in response to changes in crop economic conditions. This increased flexibility can encourage water trading, even within a single irrigated region, by opening opportunities for exchange where they are valued economically by both sides to a water trade.

Where water trading by irrigators occurs, water flows to uses where its marginal economic value in irrigation is the highest. Where trades are voluntary, the water seller receives an income in place of the previous water use in agriculture that has a higher economic value than the seller's current use. This income can be used in part to finance water conservation investments or other infrastructure improvements that could maintain crop yields while reducing current water use. The water buyer receives water whose economic value is larger than the cash paid for the water and is larger than the economic costs currently incurred by lack of access to the purchased water. Communities in areas that export water may experience reduced populations, reduced payments to farm labor, and falling local spending. Communities in regions importing water could see increased populations but may not always have adequate infrastructure and services to serve the new residents in the short run.

Water trading by irrigators gives farmers greater flexibility in making decisions about their priorities for water use. It also offers a way to manage cash flows, and facilitates regional agricultural business growth and development dependent on those crops. Without water trading, farmers in Egypt who grow crops with a lower economic value per unit of water use, such as cotton, sorghum, and
sugar cane, will fare much worse than will be the case with water trading because of the lost opportunity to earn more cash by trading than by irrigating. Without water trading farmers who grow crops with a higher value per unit of water, such as garlic, tomatoes, and palms, would also fare worse without than with the trading because of considerable losses in potential income. The presence of water markets, even where limited in scope, gives farmers greater opportunity to take advantage of unexpected changes in crop prices, yields, and production costs. Finally, water trading provides a mechanism for adjusting for past decisions in irrigation development that are no longer economically justified, such as continuing to irrigate less economically productive land.

3.6. Conclusions

Economic development, population growth, growing food demands, climate change, and ongoing debates over the allocation of the Nile's waters among its ten Basin countries continue to increase the threat of growing water scarcity in Egypt. Flows from the Nile River currently supply an average of 55.5 billion cubic meters per year that support virtually all Egypt's water demands. The 2005 Egyptian National Water Resources Plan identified four policy measures for improving management of Egypt's water supplies: (1) developing additional water, (2) making better use of existing water, (3) protecting public health and the environment, and (4) institutional and financial reform.
Our aim was to identify economic and hydrologic impacts of potential adjustments in Egypt's water and land use patterns in irrigated agriculture resulting from the second strategy in the National Plan, making better use of existing water through water trading. It identified potential economic gains from two potential water trading policies. Adjustments were examined that would increase economic benefits from irrigation water supplies, while respecting food security, hydrologic balance, crop marketing limits, institutions, and community economic security needs that limit the size and scope of water reallocations.

We found that increases in net economic benefits for Lower Egypt would improve total annual net farm income for the Nile River basin as a whole, from an annual average of $US 7.92 billion under the baseline policy to $US 8.42 billion with intra-regional water trading to $US 8.54 billion with interregional water trading allowed. While numerous simplifying assumptions were made in the face of very considerable data limits, this study has taken a modest first step at a comprehensive hydrologic, economic, and institutional framework to inform decisions by water managers and policy makers.

This work has several important limits. Agriculture is the only water use analyzed for which we have estimated economic values. There is no treatment of hydroelectric, urban, or environmental values. All economic values in agriculture are based on private revenues and costs to farmers, with no adjustment for social or public values of water in agriculture. Compared to base year water allocations, only
two policy alternatives for managing Egypt's Nile Basin waters in agriculture are analyzed among the many being debated. In addition, we were only able to secure a detailed description of land in production by crop and region for a single base year, 2006. A longer time series would make for a much better analysis with stronger policy implications.

Our research describes only the potential gains associated with two kinds of water trading. It presents no detailed insights on the best way to carry out this trading. Some important questions remain: How would other water trading arrangements, such as inter-seasonal trading, compare to the ones we examined? How would a water trading policy be received by Egypt's wide range of stakeholders?

Those stakeholders will need to be consulted. How would water trading be set up so that potential gains from trading could be translated into income earning opportunities? Market forces surrounding private irrigation economics would set the prices. Those marginal values of water can adjust to changing future conditions caused by changes in water supply, crop prices, crop production costs, and technological advances. Water volumes at the farm gate are rarely measured in Egypt with sophisticated stream gauges but by the irrigation duration for a farm canal of a given size and shape. So considerable work will be required to improve or more effectively use the existing hydrometric network to adequately support water trades by measuring water volumes traded.
Yet, despite these limits, the analysis described in this article could inform Egyptian water management and policy in the search for policies that are consistent with national economic goals while respecting environmental, political, and cultural requirements. For example, when irrigation water supplies are threatened by aging irrigation infrastructure, rising prices produced by increased water scarcity could help signal collective action to repair and maintain primary canal networks by providing an economic return to owners and employees. While on the surface, water trading is little more than trades in water volumes at the margin, it carries larger policy implications. Water trades induced by price signals have a considerable potential to tackle water policy challenges surrounding the need for increased water use efficiency through measures like canal lining, land leveling and improved water distribution.
Appendix A. Integrated Framework for Egypt’s Nile River

A.1. Overview
This appendix presents a mathematical documentation of an integrated hydro-economic framework for policy evaluation for Egypt’s part of the Nile Basin. The GAMS code is available (Gohar and Ward, 2010). The framework was developed to support analysis of how water trading can affect the use of the water resources of the Egypt's Nile Basin for irrigated agriculture. Constraints are imposed to account for hydrology, culture, food security, and the environment.

A.2. Hydrology
The essential principle of the hydrology is mass balance, both for surface flow interactions and reservoir levels. The hydrology uses mass balance principles to account for headwater flows, river flows, reservoir levels, water from surface applied to various uses, and the impact of surface flows on current and future reservoir storage levels.

A.2.1. Headwater Runoff
Inflows into Egypt’s part of the Nile basin are defined as total seasonal flows into Lake Nasser. Inflow at \( h \)-th headwater gauge \( (h = 1 \text{ for Egypt}) \) and year \( t \), \( X_{ht} \), equals total source supplies. All water supplies are measured in million cubic meters per season.

\[
(A1) \; X_{ht} = Source_{ht}
\]

A.2.2. River Flow
Figure 1 shows that in Egypt, the Nile River has several gauges, indicated by boxes. River flow at each \( v \)-th river gauge in period \( t \), \( X_{vt} \), equals the sum of flows over any upstream node whose activities directly influence that flow. These include: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; (5) upstream reservoir releases; (6) upstream unmeasured water use. Total flows, which cannot be negative, are defined for each of those six types of nodes, respectively, as:

\[
(A2) X_{vt} = \sum_{h} B_{hv} X_{ht} + \sum_{v} B_{vv} X_{vt} + \sum_{d} B_{dv} X_{dt} + \sum_{r} B_{rv} X_{rt} + \sum_{m} B_{mv} X_{mt} + \sum_{l} B_{lv} X_{lt}
\]
Where the set $v$ defines all river gauges, and $X_{vt}$ is the river flow at any river gauge node (element of the set $v$). Each of the six vectors of $B$ coefficients takes on values of 0 for non-contributing upstream sources, 1 for sources that add flow, and -1 for sources that reduce flow. So, positive signs in an equation (+) require adding flows, and subtractions (-) occur whenever a $B$ coefficient is negative. For example, the first term sums contributions over the set $(h)$ of headwater nodes. The vector $B_{hv}$ contains 1s for all immediately upstream headwater gauges that contribute to a river's flow and 0 otherwise, where $X_{ht}$ are flows at all headwater gauges. The second right-hand side term sums contributions over the set $(v)$ of relevant upstream river gauge elements. The vector $B_{vv}$ typically contains a single 1, and the rest zeros. The third term sums river flow reductions over the set $(d)$ of upstream diversion nodes. By accounting for upstream diversions, the $B_d$ coefficients are 0 for non-diverting locations and for diversions that do not affect the given node’s flow, but -1 where upstream diversions directly reduce that flow. The last three terms similarly account for; upstream surface return flows in the set $(r)$, unmeasured use required to calibrate the model in the set $(m)$, and upstream reservoir releases in the set $(L)$ that affect river flows.

### A.2.3. Water Diverted

Agriculture diverts water from the Nile. There is little groundwater pumping for irrigated agriculture in Egypt. The following equation, a ‘wet water’ condition, requires that no diversion exceeds available river flow at the point of diversion. That is, each diversion must be less than the sum of all six classes of upstream sources that contribute to flow at that point: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; (5) upstream unmeasured use; (6) upstream reservoir releases. A diversion ($d$ subscript), which cannot be negative, is:

$$
(A3) X_{vt} \leq \sum_h B_{hv} X_{ht} + \sum_v B_{vv} X_{vt} + \sum_d B_{dv} X_{dt} + \sum_r B_{rv} X_{rt} + \sum_m B_{mv} X_{mt} + \sum_l B_{lv} X_{lt}
$$
The right hand side terms are the various contributions to flow at the point of diversion from upstream sources. The various \( B \) terms indicate presence (1) or absence (0) of upstream flow sources for a given node, and are used to configure a basin’s unique geometry.

### A.2.4. Water Applied

Like diverted water, total water applied to crops at any node in period \( t \), \( X_{at} \), is a choice variable, influenced by the institution or policy being debated. Water applied can come from two sources: a stream diversion, \( X_{dt} \) or water pumped, \( X_{pt} \). Pumping in the current implementation is constrained to be zero following the findings of Kim and Sultan (2002), but can be made active. Total water applied is:

\[
(A4) \quad X_{at} = \sum_d B_{da} X_{dt} + \sum_p B_{pa} X_{pt}
\]

Both sets of coefficients \( B_{da} \) and \( B_{pa} \) are identity matrices to conform like nodes in the basin.

For each agricultural node in the basin, total water applied to farmlands is expressed as:

\[
(A4a) \quad X_{at} = \sum_d B_{ac} \sum_u B_{ua} L_{uct}
\]

Total irrigation water applied from at each \( a\)-th water application node in the \( t\)-th year equals total water demands. These demands are summed over crops \( (c) \) based on known water application amounts per hectare by crop, \( B_{ac} \). The result is multiplied by an identity matrix, \( B_{ua} \), that conforms nodes and the number of hectares irrigated in Egypt at the \( u\)-th use node by the \( c\)-th crop in the \( t\)-th year, \( L_{uct} \). The optimal solution of a single run determines the total quantity of irrigated land, \( L_{uct} \). That quantity of irrigated land determines the total demand for irrigation water applications, \( X_{at} \).

### A.2.5. Water Consumed

Any node’s consumptive use, \( X_{au} \), is an empirically determined proportion of total water applied, \( X_{at} \). For irrigation, consumptive use is the quantity of water lost through plant evapotranspiration (ET) to any future use in the system. That use, which cannot be negative, is measured as:
\((A5)\) \[ X_{ut} = \sum_a B_{au} X_{at} \]

The parameters \(B_{au}\) are elements indicating the proportion of total water applied that is used consumptively. For agricultural nodes, water use is measured as:

\[(A5a)\] \[ X_{ut} = \sum_c B_{uc} \sum_u B_{uu} L_{uct} \]

Irrigation ET at the \(u\)-\(th\) agricultural node in the \(t\)-\(th\) year is derived from total hectares of land in production. That water use is measured as the sum over crops \((c)\) of empirically estimated ET amounts per hectare by node, crop and \(B_{uc}\), times an identity matrix, \(B_{uu}\) that conforms nodes. The result is multiplied by the hectares of land irrigated. The quantity of land irrigated by use, crop, season, and time for each of the two alternative policies described in the text is determined by the program’s (constrained) optimal solution.

A.2.6. Surface Returns to River

For each agricultural node, total surface returns to the river are measured as:

\[(A6)\] \[ X_{rt} = \sum_c B_{cs} \sum_u B_{uu} L_{uct} \]

Where \(B_{cr}\) is the \(c\)-th crop’s return flow coefficient and \(B_{uu}\) is an identity matrix as described above.

A.2.7. Evaporation

Egypt has hot summers and moderate winters. Reservoir evaporation is measured as:

\[(A7)\] \[ X_{et} = \sum_r B_{re} Z_{at} \]

That is, any period’s evaporation from a reservoir equals the evaporation rate per hectare of water exposed, \(B_{re}\), multiplied by the average surface area in hectares exposed at the reservoir that period, \(Z_{at}\). The pan evaporation rate increases for both Egypt’s Nile basin reservoirs in summer season due to the higher temperature rate in comparison to winter and nili seasons. The evaporation rate in winter is half the summer rate. The rate in nili season is one-third the summer rate, partly because of its shorter season length. Recent estimates of evaporation losses at Nasser Lake are about 10 billion cubic meters per year, just under 20 percent of Egypt’s annual supply (Sadek et al., 1997).
Measures that could reduce that evaporation, such as raising storage in winter and reducing it in winter, have a considerable potential to increase Egypt’s economic benefits.

A.3. Land Use

Land use patterns affect the irrigation demand for water. For irrigated agriculture, total land in production is expressed as:

\[
\sum_c L_{uct} < RHS_{ut}.
\]

That is, irrigated land in production by node, crop, season, and time, summed over crops cannot exceed available land \((RHS_{ut})\) by node, season, and period. We used the current irrigated land in production for each node as the upper limit on available land. However, in the longer term, more irrigated land could become available if greater long-term water supplies could be secured, water-conserving technologies could be adopted, or if water-conserving crops become economically attractive.

The baseline policy analysis is constrained to replicate historical irrigated land by irrigation district and crop for the base year. For the two alternative policies, those constraints are removed by allowing water trading to occur, either within a single or among irrigated areas. Either policy permits existing water to be reallocated to higher economic valued water uses where the economics would support such a reallocation.

A.4. Institutions

A.4.1. Historical Patterns

The model was hydrologically balanced to match the actual river flow for the Egypt’s entire use of the Nile River for the base year, as described in the text. It was constrained to reproduce historical gauged flow for all Egypt’s stream gauges for which we had data. We achieved this balance by creating a variable named net loss. Net loss is calculated for each irrigation district and season. It was always typically but not always found to be positive, indicating positive net losses from additional uses outside irrigated agriculture. Starting from Lake Nasser, predicted flows at all eleven gauges in the basin were calibrated to be within a small amount of actual gauged flows for the year 2006.
As stated in the text, these net losses include groundwater pumping, river evaporation, unmeasured urban uses as well as unmeasured crop return flows and aquifer discharge to the river. Calibration presents numerous challenges for hydrologic and watershed analysis, many of which continue to be debated. A short list of celebrated papers published since the 1990's dealing with watershed calibration include the works of Janssen and Heuberger (1995), Yapo, et al. (1998), Karvonen et al. (1999), Sophocleous et al. (1999), Madsen et al. (2002), Singh and Woolhiser (2002). Other more recent papers include those of Doherty and Johnston (2003), Legesse et al. (2003), Butts et al. (2004), Merz and Bloschl (2004), and Muleta and Nicklow (2005).

A.4.2. Water Reallocation Constraints

For each of the two alternative policies, we allowed a decrease in water for irrigation in each district of either nothing (intraregional water trades) or up to 10 percent (interregional trades) for each irrigated area. The irrigated land constraint for the interregional water trading scenario is:

\[
(A9) \quad X_{uct} \geq 0.90 X^*_{uct}
\]

Where \(X_{uct}\) is the water used in irrigation for each \(u-th\) node, \(c-th\) crop, and \(t-th\) period, in the interregional trading scenario, and the \(X^*_{uct}\) is historically observed water irrigated by node and crop for the base year. For the intraregional water trading policy, the coefficient 0.90 was replaced by 1.00, indicating that no water use reductions in any irrigation district are permitted.

A.4.3. Total Agricultural Water Use

In each of the two alternative policy frameworks, Egypt’s total water available for use in irrigated agriculture is set to be the same as occurred for the base year. This means that there is no available water for use in irrigation under the improved policy not also used in the base year. That constraint is written as:

\[
(A10) \quad \sum_u X_{u} = \sum_u X^*_{u}
\]

Where the left hand term is total water use over the basin for each alternative water policy, while the right hand term is actual observed use for the base year. Likewise, net losses for each \(m-th\)
node, and \( t \)-th period in the improved policy analysis set to equal base net losses and are expressed in
the following algebraic form:

\[
(A11) \quad X_{mt} = X_{mt}^* \\
\]

For which the left term is net water losses under each given water policy proposal, and the
right term is net loss measured for the base year. This constraint assures that no policy either
manufactures water or loses water.

A.5. Environmental Constraints

Flows at two important outflow gauges can be operated to guard against saltwater intrusion
into the Nile Delta. To meet this environmental requirement, stream flows at both outflow gauges,
Edfina gauge and Zifta gauge are constrained in both alternative policy runs to meet or exceed
outflows under the base year. This constraint is enforced in the program by requiring minimum
outflows delivered to the Mediterranean. Those environmental constraints are expressed in the
following form:

\[
(A12a) \quad X_{Zifta,t} > X_{Zifta,t}^* \\
(A12b) \quad X_{Edfina,t} > X_{Edfina,t}^* \\
\]

The Zifta and Edfina subscripts refer to the Zifta and Edfina gauged outflows for the \( t \)-th
period under each alternative policy scenario.

A.6. Economics

Economic benefits from irrigated agriculture in Egypt’s Nile Basin are produced by water
depletions for irrigated agriculture at thirteen nodes located from the High Dam to the Mediterranean.
For future implementations of the program, we plan to include environmental, urban, recreational, and
environmental values of flows and stocks of water, all of which have growing importance for Egypt.
A.6.1. Benefits and Costs

For the current implementation of the Egyptian Nile Basin model, all nodes that produce an economic benefit use water. Each node produces what we describe as a “use-related” benefit. For each irrigated agricultural nodes, the economic benefit is measured as net farm income, defined as:

\[ Y_{uct} = (P_c \times Yield_{uct} - Cost_{uct}) \times L_{uct} \]

That is, net farm income at the \( u \)-th basin node for the \( c \)-th crop, the \( t \)-th period equals net income per feddan multiplied by the number of feddans. Annual net income per unit land, \( Y_{uc} \), equals crop price, \( P_c \), times crop yield, \( Yield_{uc} \), minus total production costs, \( Cost_{uc} \). For any given agricultural use node, net benefits for the entire node are obtained by summing net farm income over all crops in production:

\[ XB_{ut} = \sum_c Y_{uct} \]

Where \( XB_{ut} \) is the total economic benefit for nodes and time periods summed over crops.

A.6.2. Discounted Net Present Value

The overall objective function is discounted net present value of irrigated farm income over nodes and time-periods, which includes all crops in each district’s actual or potential crop mix. It is expressed in its standard algebraic form:

\[ NPV = \sum_u \sum_t \frac{XB_{ut}}{(1 + r_u)^t} \]

This says that the net present value of total water-based farm income for all nodes in Egypt’s part of the Nile Basin sums income over districts and time-periods, which discounts future incomes more heavily when there is a higher discount rate. The current model implementation uses a zero discount rate. There are several decision variables. These include land in irrigated agriculture by crop, irrigated area, and time period. They also include water diverted from the Nile by crop, irrigated area, and time period as well as reservoir storage levels at Lake Nasser and Lake Nile for three seasons per year for a five year period.
3.7. References


Wichelns, D., 2004. The role of virtual water in efforts to achieve food security and other national goals with an example from Egypt. Agricultural Water Management 49, 20–50.


CHAPTER IV

4.0. ECONOMIC PERFORMANCE OF WATER STORAGE CAPACITY EXPANSION FOR FOOD SECURITY

4.1. Abstract

Continued climate variability, population growth, and rising food prices present ongoing challenges for achieving food and water security in poor countries that lack adequate water infrastructure. Undeveloped storage infrastructure presents a special challenge in northern Afghanistan, where food security is undermined by highly variable water supplies, inefficient water allocation rules, and a damaged irrigation system due to three decades of war and conflict. Little peer-reviewed research to date has analyzed the economic benefits of water storage capacity expansions as a mechanism to sustain food security over long periods of variable climate and growing food demands needed to feed growing populations. This paper develops and applies an integrated water resources management framework that analyzes impacts of storage capacity expansions for sustaining farm income and food security in the face of highly fluctuating water supplies. Findings illustrate that in Afghanistan’s Balkh Basin, total farm income and food security from crop irrigation increase, but at a declining rate as water storage capacity increases from zero to an amount equal to six times the basin’s long term water supply. Total farm income increases by 21%, 41%, and 42% for small, medium, and large reservoir capacity, respectively, compared to 

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the existing irrigation system unassisted by reservoir storage capacity. Results provide a framework to target water infrastructure investments that improve food security for river basins in one of the world’s dry regions with low existing storage capacity that faces ongoing climate variability and increased demands for food security for a growing population.

4.2. Background

Continued climate variability, population growth, and rising food prices present ongoing challenges for achieving food and water security in poor countries that lack adequate water infrastructure. Undeveloped storage infrastructure presents a special challenge in northern Afghanistan, where food security is undermined by highly variable water supplies, inefficient water allocation rules, and a damaged irrigation system due three decades of war and conflict. Afghanistan is a developing Asian country with livelihoods heavily dependent on agriculture that has suffered ongoing consequences of military conflict since the late 1970s (figure 1). These conflicts have severely damaged the country’s irrigation infrastructure, institutions, and capacity to adapt to ongoing climate variability. Balkh province is located in the northern part of the country with total population around 1.12 Million (Torell and Ward, 2010). In that province, agricultural activities in the Balkh Basin (the Basin) are a major source of income, livelihoods, and food security. That region is an important producer for the country’s most important grain and staple food crops, especially
wheat (Reeling et al., 2012; Chabot and Dorosh, 2007). Runoff into the Basin is the main source for fresh water for irrigation in the Balkh Province.

Farmers in this province face highly fluctuating water supplies with no significant reservoir storage capacity, which places heavy stress on food production in dry years, especially in the low part of the watershed. Reliable water availability is a major determinant of the recovery and expansion of irrigated agriculture activities in Balkh Basin to its former high levels of the mid 1970s (Kugbei et al., 2005; Walters et al., 2012). In the Basin, weak water institutional capacity (e.g., rules for defining water rights) limits farmers’ ability to adapt to highly fluctuating flows supplied from runoff in the Balkh River and its tributaries. The average annual water supplies in the river are estimated at 1540 MCM per year (Torell and Ward, 2010). Moreover, the basin has a high fluctuation in yearly water supply that could be at times undergo severe drought like the period of 1998 to 2002 (Chabot and Dorosh, 2007).

Weak water institutions combined with virtually no reservoir storage capacity limits irrigators’ capacity to earn a sustainable income and sustain adequate food security in drought periods, especially in downstream areas. These weak water-sharing arrangements result in high fluctuations in food supply and production, and increasing the country’s dependence on national food aid and imports from neighboring countries like Pakistan. While foreign food aid and imports temporarily supplement grain needs in any given year, such aid causes reductions in domestic grain prices, reduces future production and more generally is not sustainable (Chabot
Moreover, high variability in water supply negatively influences the net farm income and food production in downstream agricultural production.

Numerous previous studies have examined irrigation, water institution, agricultural systems, and food security in Afghanistan. Many national and international projects intend to examine ways to improve and rehabilitate the irrigation infrastructures and agricultural system. Example includes studies aimed at estimating crop water consumption (Senay et al., 2007), agricultural productivity (Sharp et al., 2002), impacts of the 2008 Afghan Water Law (Wegerich, 2010). However, few existing studies have aimed to improve Balkh Basin’s water and irrigation institution capabilities. Torell and Ward (2010) investigated a water allocation framework that aimed to improve the water use and food security in the Balkh Basin. Reeling et al., (2012) applied a linear programming approach to investigate impacts of a range of reservoir and water right allocation systems on the basin’s agricultural activities. However, no previous work to our knowledge has systematically integrated the hydrological, economic, and institutional characteristics of the basin as a part of science-based policy assessment to improve food security and farm livelihoods.

In light of these gaps, this paper aims to investigate the economic returns associated with a range of storage capacity expansions that would benefit farm income and food security in the Balkh Basin, Afghanistan. Using available data, an integrated basin framework is developed and applied that addresses the Basin’s
hydrology, economics, culture, and institutions using a dynamic mathematical optimization framework. Based on our integrated framework, results are examined for three reservoir capacity expansions: small, medium, and large. Impacts are identified for several outcomes: regional farm income, land use, and irrigated crop production. These results are compared to the base condition in the Basin, where no significant water storage currently exists.

4.3. Methodology

4.3.1. Data

With a history of more than three decades of military conflict, continuous research grade records of hydrological and agricultural data do not exist for our study area. This work employed the (very limited quality) available data on irrigated land, crop water use coefficients, and net revenue for fourteen canals in the Basin (Figure 2). Data used in this study, including average annual water inflow for the Balkh headwater were obtained from previous works of Torell and Ward (2010) and Reeling at al., (2012). Estimated available land for irrigation considered for this study, is 5762 paikals. Each paikal is a local measure of water that is sufficient to irrigate 80 hectares of land. Data on irrigated land, crop water use per ha, and net revenue show variability by sub-region (Figure 2). In this paper, eight of the Basin’s most important crops are included: wheat, alfalfa, rice, cotton, melon, potato, tomato, and pulses (a legume crop).
The fourteen canals that take water from the Balkh River are divided into three regions that have similar water supply reliability and economic conditions. The first region is the Upper Region, which contains four main canals: Aman Sahib, NahrShahi, Siagard, and Balkha canal. The second region is the Middle Region, which includes Mushtag, Chemtal, Dawlatabad, and Abdullah canal. The third region is the Lower Region that contains six canals: Charbulak, Murdian, Faizabad, Mingajik, Aqcha, and Khanaqah canal at the terminal of the basin (Figure 2). The future water supply is randomly distributed around the average annual volume of 1540 MCM per year with historic variance in flows for the years 1964-1978. These stochastic supplies reflect the forecast future year-to-year variation in water supply in the Basin.

4.3.2. Integrated Water Resources Management

4.3.2.1. Overview

In recent years, integrated water resources management has emerged as the state-of-the-arts approach for assessments of policy choices available at the basin scale. Integrated basin analysis has been used for policy design, implementation, and evaluation in the Rio Grande Basin in the USA; Maipo Basin in Chile; Mekong Basin; and Murray Basin in Australia (Ward and Pulido-Velazquez a, b, 2008; Rosegrant et al., 2000 a, b; Ringler, 2001; Mainuddin et al., 2007). Furthermore, integrated basin scale analysis provides a good chance for assessment of alternative water allocation schemes (Wegerich, 2004; Gohar and Ward, 2011). Another
advantage arising from the integrated basin framework methodology is its impressive record in tracking water supply and use patterns under a range of water supply variability and policy scenarios as well as investigating alternative water institution policies (Gohar and Ward, 2010).

The integrated basin framework is a comprehensive tool that encompasses agronomy, hydrology, economical, institutions, and environmental dimensions of the problem. Our study takes a first step to develop and apply an integrated basin framework that include hydrology, agronomy, land use, culture, economic, and water institution for Balkh Basin in Afghanistan. A brief mathematical framework is described at various places below. The complete mathematical framework and GAMS model code used for this research and study is available on http://agecon.nmsu.edu/fward/water/.

4.3.2.2. Hydrology

The Basin is an important watershed in Northern Afghanistan that includes 14 main canals (Figure 1). The basin’s runoff feeds the water supply for all fourteen canals used to irrigate a range of crops in the catchment. Our framework treats the entire basin as one unit, which allows for a unified tracking for surface water from the headwater to a range of locations lower in the catchment. The hydrologic balance accounts for headwater flows, river flows, reservoir storage volume, water diverted, water use, and water return flows at different locations and time scale within the basin. To complete the hydrologic balance, four (virtual) gauges are specified to track
total water diverted, used, and returned to the river’s mainstem at the three main regions and at the tail end of the watershed (Figure 2).

Total water use in any region is defined as the quantity of water lost through evaporation and evapotranspiration (ET), characterized by crop water use coefficients. Total water use for any given region and period is the estimated ET by crop multiplied by the irrigated land during period in given region. Annual total (stochastic) water inflow is set at an equal trajectory for all reservoir capacity scenarios. The main motivation behind the hydrology model is a desire to reflect mass balance, both for surface flow interactions and reservoir levels. The hydrology model described below uses mass balance principles to account for headwater flows, river flows, reservoir levels, water from surface applied to various uses at different locations, and the impact of surface flows and river diversions for land under irrigation by crop and region for both the current as well as for three alternative reservoir storage levels.

4.3.2.2.1. Headwater Runoff

The annual average water flow is stochastically generated for 20 years around the long run mean measured water inflow. Water Inflow at h-th headwater gauge (h = 1) and year t, $X_{ht}$, equals total source supplies:

$$X_{ht} = N \sim source_{ht}$$
Fig. 3 Schematic of Balkh River Canal System, Afghanistan
4.3.2.2.2. Gauged Streamflows

River flow at each \( v \)-th river gauge, reservoir capacity \( c \), in period \( t \), \( X_{vct} \), equals the sum of flows over any upstream node whose activities directly influence that flow. These include: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; and (5) upstream reservoir releases. Total flows, required to be nonnegative, are defined for each of those five types of nodes, respectively, as:

\[
X_{vct} = \sum_{h} B_{hv} X_{hct} + \sum_{v} B_{vv} X_{vct} + \sum_{d} B_{dv} X_{dct} + \sum_{r} B_{rv} X_{rct} + \sum_{L} B_{Ls} X_{Lct}.
\]

The set \( v \) defines all river gauges, and \( X_{vct} \) is the river flow at any river gauge node (element of the \( v \) set). Each of the five vectors of \( B \) coefficients takes on values of 0 for non-contributing upstream sources, 1 for sources that add flow, and -1 for sources that reduce flow. Thus, positive signs in an equation (+) require adding flows, and subtractions (-) occur whenever a \( B \) coefficient is negative. For example, the first term, \( \sum_{h} B_{hv} X_{hct} \), sums contributions over the set \( (h) \) of headwater nodes. The vector \( B_{hv} \) contains 1 for all immediately upstream headwater gauges that contribute to a river’s flow and 0 otherwise, where \( X_{hct} \) are flows at the one headwater gauge used for this study. The second right-hand side term, \( \sum_{v} B_{vv} X_{vct} \), sums contributions over the set \( (v) \) of relevant upstream river gauge elements. The vector \( B_{vv} \) typically contains a single 1, and the rest zeros. The third term \( \sum_{d} B_{dv} X_{dct} \), sums river flow reductions over the set \( (d) \) of upstream diversion nodes. By accounting for upstream diversions, the...
B_{d_v} coefficients are 0 for non-diverting locations and for diversions that do not affect the given node's flow, but -1 where upstream diversions directly reduce that flow.

The last two terms similarly account for; upstream surface return flows in the set (r), and upstream reservoir releases in the set (L) that affect river flows.

4.3.2.2.3. Water Diverted

Agricultural water use is supplied by direct stream diversions from the 14 canals that divert Balkh River water. Those canals are aggregated into three main regions: Upper, Middle, and Lower region. The following equation, a "wet water" condition, requires that no diversion exceed available river flow at the point of diversion. Therefore, for the river to be wet, each diversion must be less than the sum of all five classes of upstream sources: (1) headwater inflows; (2) upstream river gauges; (3) upstream diversions; (4) upstream surface return flows; and (5) upstream reservoir releases. A diversion (d subscript), which cannot be negative, is:

\[ X_{dct} \leq \sum_h B_{hd} X_{hct} + \sum_r B_{vd} X_{vct} + \sum_d B_{dd} X_{dct} + \sum_r B_{rd} X_{rct} + \sum_L B_{Ld} X_{Lct}, \]

The right hand side terms are the sum of all contributions to flow at the point of diversion from upstream sources. The various B terms, which indicate presence (1) or absence (0) of upstream flow sources for a given node, are used to configure the basin.

4.3.2.2.4. Water Applied
Like diverted water, total water applied for use at any node in period $t$, $X_{act}$, is a choice variable, where water applied come from stream diversion, $X_{dct}$. Total water applied is:

$$ (3) \quad X_{act} = \sum_d B_{da} X_{dct} $$

The coefficient $B_{da}$ is identity matrices to conform like nodes in the basin. For each agricultural node in the basin, total water applied to farmlands is expressed as:

$$ (4) \quad X_{act} = \sum_k B_{ak} \sum_u B_{ua} L_{ukct}. $$

Total irrigation water applied from surface flows at each $a$-th water application node and $c$-th reservoir capacity in the $t$-th year equals total water demands. These demands are summed over crops (k) based on known water application amounts per hectares by crop, $B_{ak}$. The result is multiplied by an identity matrix, $B_{ua}$, that conforms nodes and the number of hectares irrigated at the $u$-th use node by the $k$-th crop by $c$-th reservoir capacity in the $t$-th year, $L_{ukct}$. The optimal solution of a single model run determines the total quantity of irrigated land, $L_{ukct}$, which determines the total demand for irrigation water applications, $X_{act}$.

4.3.2.2.5. Water Consumed

Any use node's, consumptive use, $X_{uct}$, is an empirically determined proportion of total water applied, $X_{act}$. For irrigation, consumptive use is the quantity of water lost through plant evapotranspiration (ET) to any future use in the system. That use, which cannot be negative, is measured as:
The parameters $B_{au}$ are elements indicating the proportion of total water applied that is used consumptively. Setting $B_{au}$ at 1.00 for the current model implementation achieved the best hydrologic balance when comparing model-predicted use against actual river flows and land under irrigation. For agricultural nodes, water use is measured as:

\[
X_{act} = \sum_a B_{au} X_{act}.
\]

Irrigation ET at the $u$-th agricultural node under $c$-th reservoir capacity in the $t$-th year is derived from total hectares of land in production. That water use is measured as the sum over crops (k) of empirically estimated ET amounts per hectares by node, crop and $B_{uk}$, times an identity matrix, $B_{uu}$ that conforms nodes. The result is multiplied by the hectares irrigated. The quantity of land irrigated by use, crop, reservoir capacity, and time is determined by the model’s optimal solution.

4.3.2.2.6. Return Flows

For agricultural nodes, total surface returns to the river are measured as:

\[
X_{ret} = \sum_k B_{kr} \sum_u B_{ur} L_{uct}.
\]

In the case of the Basin, where there are little reliable data available for return water flow, so return flows were treated in this study as equal to zero. Our hope is to secure more data on these flows for future work.
4.3.3. Cultural characteristics: Water rights

The Balkh Basin lacks a formal water right system that controls water allocation and use to adapt to shortages in periods of drought. However, the basin water allocation and distribution relies on deep historical roots. The water allocation within each canal service area is highly organized by local communities called mirab, mirab bashis, and wakils. The mirab is a local farmer-elected leader at each canal who is responsible for water allocation and distribution within the canal service area. Each mirab attempts to resolve any conflict arise among the farmers regarding water allocation for his canal service area (Torell and Ward, 2010; Reeling et al., 2012). A Mirab bashi is a less common version of a mirab, for which a single canal master is responsible for managing water right issue that could include many mirabs. A wakil is a water district representative in urban areas (Lee, 2006; Rout, 2008).

In the Basin, the community based water allocation system has many aims. Those aims include distribution water for the purpose of social justice, maintaining water flows, and addressing conflicts arising among farmers within any given canal service area. Despite the consistent aims of the mirab system throughout the Basin, different water management practices are applied uniquely by canal service area and region. An important challenge of this community water allocation system has always been a limited and sometimes non-existent capacity to promote cooperation over water conflicts that can occur among mirabs, each of whom is responsible for a different canal. As a result, during drought years, upstream canals, by virtue of their
preferred location, have a default top priority to use water, with whatever water remains in the River’s mainstem available for use by downstream (Lee, 2006). In this paper, the water right priority system of an “upstream priority” arrangement is maintained. Under all inflow scenarios, upstream users have the top priority to use water.

4.3.4. Economics

Hydrologic data on water inflow, water diverted, and water use is combined with farm budget data that account for farm crop net revenue. A dynamic optimization framework that maximizes the discounted net present value of net farm income summed over crops and regions is developed. That framework is applied to assess consequences of alternative possible expansions of storage reservoir capacity levels. For any crop, the net revenue per unit land is equal to crop yield multiplied by the crop price minus costs of production by period and region. Net revenue per ha is calculated by crop and region. Total net revenue (farm income) for each region in the Basin is equal to the net revenue per ha for irrigated crops multiplied by the irrigated land from that crop at any period. For the water supply scenario used and storage capacity levels other than the baseline observed levels, irrigated land in production is an unknown and is solved for by the model. Results show four combinations of water supply scenarios and reservoir storage levels.

Water is allocated among the three regions based on the existing priority allocation system in the Balkh Basin: the top priority goes to the Upper region
remaining water, if any goes to the Middle Region, while the lowest priority is the Lower region (Figure 2). The Lower region receives water only if there is adequate streamflow, either from natural supplies or from reservoir releases to irrigate fully the top two regions. Each region receives its water defined in this way without optimization of income produced by water. That is, water is allocated among regions by priority rather than by economic performance. After water is allocated among regions in this way, each region’s water is allocated among its crops to produce the highest level of farm income with available water. Net income per ha is equal to crop price multiplied by crop yield minus production cost. The highest net revenue per ha is wheat because of its greatest importance for food security. A suitably high price (marginal benefit) is assigned to wheat so that wheat always has the highest net income per ha compared to other crops. After basic food security dietary calorie needs from wheat are met for a region, no more wheat is produced in that region. At that point, water is then allocated to the mix of remaining non-wheat crops that maximizes total income for the region.

For the current implementation of the Basin model, all regions that produce an economic benefit for agriculture use water. That is, each region produces what we describe as use-related benefits, a benefit for crop irrigation that requires water use. For each irrigated agricultural region, the economic benefits are measured as net farm income. For any given agricultural use node net under any reservoir capacity, benefits
for the entire region are obtained by summing net farm income over all crops in production:

\( (8) \quad XB_{ucl} = \sum_{k} Y_{ukct} \)

The term \( XB_{ucl} \) is the total economic benefit for nodes, reservoir capacity, and time periods summed over crops. Discounted net present value for each reservoir capacity over nodes and time-periods is expressed in its standard algebraic form:

\( (9) \quad NPV_{c} = \sum_{u} \sum_{t} \frac{XB_{ut}}{(1 + r_{u})^{t}} + \sum_{s} \frac{XB_{ct}}{(1 + r_{c})^{T}} \)

That is, the present value of total water-based farm income in the Basin sums income over regions and time-periods. The model discounts future incomes more heavily because of a positive discount rate. This is added to very small value \( XB_{ct} \) assigned to the water storage volume(s) at the last period of analysis (T), made available for future generations after the end of the normal planning period. This is a sustainability condition.

4.3.5. Institutional capabilities

An important objective for this study is to investigate the economic value to irrigated agriculture in the Basin of expanding storage reservoir capacity from the current level of zero to various alternative potential levels. The motivation for considering additional reservoir capacity rests with the well-known and very old problem that in this Basin: farmers have limited ability to utilize water from wet years.
when the inevitable dry year occurs. Additional storage capacity could be used to support livelihoods, food security, and farm income in dry years when irrigators would otherwise suffer from the long-repeated historical pattern of little capacity to adapt to low supplies. In normal water years, total available land brought under irrigation is estimated at 461,000 hectares, which uses about 1540MCM of water for the Basin. However, during drought years, farmers are unable to cultivate this amount of land. In contrast, during flood seasons, there is no reservoir capacity available, so farmers are not capable of storing otherwise unused water for future use.

4.3.5.1. Land Use

Land use patterns assigned to crop irrigation affect the demand for water. For irrigated agriculture, total land in production is expressed as:

\[ L_{ukct}^{first} = 1.0 \times RHS_{uk} \]  \hspace{1cm} (10)

\[ L_{ukct}^{later} \leq 3.0 \times RHS_{uk} \]  \hspace{1cm} (11)

\[ L_{ct} \leq 461000 \]  \hspace{1cm} (12)

Irrigated land for any given node and crop under any given reservoir storage capacity for the first year \( (t^{first}) \) is taken to be the same as the observed irrigated land in production for the base year (observed) condition. Similarly, irrigated land in production by node, crop, and reservoir capacity for later periods \( (t^{later}) \) cannot exceed three times the available land \( (RHS_{uk}) \) by node, and period, a constraint that reflects limited land capacity expansion by crop compared to existing...
observed levels. We used the maximum current irrigated land capability for the Balkh Basin, estimated at 461,000 hectares as the upper limit on total available land. However, more irrigated land could become available if greater long-term water supplies could be secured and if institutions could adjust to permit the extra water to be used by agriculture. The model keeps track of land use by node, crop, reservoir capacity available, if developed, by period.

4.3.5.2. Reservoir capacity

For the current work, we consider and evaluate the consequences of three different potential reservoir scales: small, medium, and large. A small reservoir is defined to hold 50% of the total average annual water inflows, estimated at 770 MCM. The second reservoir scale is the medium reservoir, assigned to hold 150% of average annual inflow, 2,310 MCM. The third reservoir capacity is large, for which storage capacity is 600% of average annual water inflow. The three alternative potential reservoir capacities are specified as:

\[(13)Z_{sc} = \beta * Source_h\]

Where the maximum reservoir capacity \(Z_{sc}\) for any storage volume \(s\), and reservoir scale \(c\), is each parameter described above, \(\beta\) multiplied by the average annual water inflow. The scale parameter takes the value of 0.5, 1.5, and 6.0 for small, medium, and large reservoir capacity, respectively.

4.3.5.3. Reservoir construction cost
There are many types of reservoirs that can be classified based on their purpose of use. Those types contain hydropower generation, flood control, irrigation, and multiuse reservoirs. The cost of reservoir construction is a major challenge that associated with different variables and subject to high fluctuation. The cost of establishing the reservoirs are affected by the type, purpose, size, design, geographical, and hydrological characteristics of the basin (Gaudette and Bulota, 2003; Mwea and Ngware, 1996). In the case if irrigation reservoirs, the reservoir site plays important role in determining the construction cost where the earthwork contribute by 80% of the construction cost of this type of reservoirs (Agueera et al., 2007). While the small reservoirs are more financially accomplishable and easy to be regulated especially with small river basins, large reservoirs found to be more economically efficient in the long run (Chiquito, 2012; Yazdi and Neyshabouri, 2012; Mushtaq et al., 2007). Other externalities could be correlated with reservoir construction that could include environmental and ecosystem cost. On contrast, multiple use reservoirs could provide economic development and create many jobs and employment in additional to secure water for irrigation (Tundisi et al., 2008).

For the purpose of this work, the average estimated construction cost per unit of stored water of some dams and reservoirs within the region are used as parameters to estimate the related construction cost of different proposed reservoir size. Available data from both Rogun and Dashtijum reservoirs at Tajikistan show that both reservoirs have volume capacity of 13.3 and 17.4 Billion Cubic Meter and cost
about 2.2 and 3.5 Billion USD respectively. The average construction cost is estimated to be $0.186 USD per one cubic meters of stored volume. The total construction cost of different reservoir sizes are incorporated in the model as a function of the construction cost of the unit of stored capacity volume. The following equation describes the relationship between the reservoir capacity and construction cost.

\[
(14) ConCost_{uc} = B_{uc} \ast Z_{uc}
\]

Where the construction cost (ConCost) associated with different proposed reservoir size (c) is equal to the construction cost per unit of stored water multiplied by the maximum storage volume of the reservoir (z).

4.3.6. Snow runoff scenarios

The data of snow runoff for the period of 1964 to 1979 is used to be the estimated annual long run water supply for 20 years analysis plan. The estimated average annual snow runoff is 1540 Million Cubic Meter. However, this annual average water supply is a subject to the impact of climate change that could reduce this annual inflow by different degrees. Three water supply scenarios are assumed to investigate the impact of proposed institutional capacities on the national farm income for Balkh Basin. Those scenarios are compared to the base condition where the average annual inflow is normally distributed. The first snow runoff is set to be 90% of the base condition annual water inflow. The second scenario represents a
moderate reduction in water supply to be 20% and the severe snow runoff is estimated to be 70% of the historical water inflow. Under all water supply reduction scenarios, the annual inflow is stochastically generated and distributed around decline average inflow over the 20 years span analysis. To investigate the impact of different water supply reduction on the net farm income, the stored water under small, medium, and the large water reduction scenarios is set to be the same of stored water under the historical water supply condition over the time.

4.4. Results

4.4.1. Overview

Results are shown to compare the three possible proposed reservoir capacity scenarios to the base situation, where there is no reservoir storage capacity available. The impact of alternative reservoir capacities on basin water use, water storage, and water not used (leaving the Basin at the bottom) - are described for 20 year the time span for this analysis. In addition, impacts of reservoir capacity on irrigated land, water consumption, and net farm income are illustrated. The tables show average values for the analyzed time scale.

4.4.2. Water supply, storage, use, and nonuse

Table 4.1 illustrates the Basin’s annual water supply generated by the stochastic inflow, storage water, water use, and water non-use by year and reservoir scenario, in MCM, for the Basin. The stochastic water supply is assigned to be the same under all reservoir capacities proposed. Results show high variability in annual
water supply. Furthermore, reservoirs under different capacities allowed storing the maximum storage capacity at the end of analysis period to sustain supplies for future generations that receive benefits after the end of the 20-year scenario considered here. Annual water supply ranges from a high of 4485 MCM, such as shown for year 15 to as low of 295 MCM in year four. The Basin has a history of producing flashy supplies, in which supplies from one year to another show considerable fluctuation. This high variation in water supply reflects the natural of flood and drought pattern associated with the Basin.

Over all reservoir capacities, maximum average water use for irrigation is 1465 MCM yearly, which is nearly enough to irrigate the total available land in the Basin. In the case of no reservoir storage at all, which represents the current situation, farmers use the maximum amount of available water in an average year’s inflow. However, where inflow exceeds 1465 MCM, excess water has no use due to zero storage capacity for use in future years. Table 4.1 shows that 3020 MCM of supply has no use in year 15 for example, which equals more than twice average inflows, an amount that could be used for irrigation in future dry years.

Developing a small reservoir storage capacity, with 770 MCM of capacity, is equivalent to 50% of average annual inflow. Table 1 shows that the availability of small reservoir allows water users to benefit from stored 770 MCM in the third year and reallocate this amount of water for the subsequent drought years. The small reservoir storage also increases average water use from 885 MCM in the base
condition to 1036 MCM. However, the basin’s nonuse of water still happens from
time to time, especially in those years where water inflow exceeds the small reservoir
storage capacity. This situation repeatedly occurs in year 2, 3, 8, 15, 19, and 20. The
average yearly amount of nonuse water declines, however, from 486 MCM to 296
MCM under small reservoir, so less water passes downstream out of the Basin to non-
use because of inadequate storage capacity.

If a medium storage, capacity is developed reservoir storage increases up to
2310 MCM. Increasing the reservoir capacity to that level considerably enhances the
ability to reallocate stored water from wet to dry years. Table 4.1 shows that average
annual water use for irrigation increases under this reservoir scale increases to 1209
MCM, an increase of 37 percent from the long run average water use level of 885
MCM without any reservoir storage capacity. Medium storage capacity increases
average water use by making more available for dry years that would have otherwise
gone unused. Unused water (nonuse) decreases to zero for all years except years
15 and 19, where the water inflow is very high and exceeds irrigated land capacity.
In contrast, the average nonuse water decreases to be 46 MCM under medium
reservoir capacity. Finally, large-scale reservoir capacity can capture up to 6 times
average estimated inflow, an amount of water equal to 9240 MCM. This large
capacity increases the ability to store for later use all water inflows even in very wet
years. The high reservoir capacity reduces nonuse (spills) to zero for all 20 years.
Results in Table 4.1 show that water stored and released for later years increases the ability of putting all water to beneficial use in irrigated agriculture and reduces the level and economic damages with the attendant tragic consequences for food security suffered by shortfalls in a series of very dry years. Moreover, a large reservoir stores 2525 MCM that can be used in the future. Nevertheless, for the years analyzed and considering those sequential years of drought, even a large reservoir cannot hold enough amount of water to use when water users face a sequence of extremely dry years, such as could occur under a future climate change scenario. The large reservoir, however, provides more sustainability on the long run due to the reservoir’s capacity to store larger volume of water in very wet years for use in extreme drought years.

4.4.3. Water use

Average water use by crop, region, and reservoir storage capacity is shown in Table 4.2 for the Basin. In Afghanistan as with many irrigated basins outside the western world, water users at the higher end of watersheds typically default to the highest priority of water use when there is no water rights administration assigned and enforced by the central government. Average water use, especially in the lower parts of the watershed, increases as the reservoir capacity increases. Total average water use increases from 885 MCM in base condition of zero storage to 1036, 1209, and 1244 MCM for Small, Medium, and Large reservoir capacity respectively.
<table>
<thead>
<tr>
<th>Year</th>
<th>No Reservoir Capacity</th>
<th>Small Reservoir Capacity</th>
<th>Medium Reservoir Capacity</th>
<th>Large Reservoir Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>1,465</td>
<td>0</td>
<td>1,465</td>
<td>0</td>
</tr>
<tr>
<td>02</td>
<td>2,065</td>
<td>963</td>
<td>1,465</td>
<td>1,102</td>
</tr>
<tr>
<td>03</td>
<td>2,276</td>
<td>1,465</td>
<td>0</td>
<td>812</td>
</tr>
<tr>
<td>04</td>
<td>295</td>
<td>295</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>05</td>
<td>417</td>
<td>417</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>06</td>
<td>308</td>
<td>308</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>07</td>
<td>943</td>
<td>943</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>08</td>
<td>3,009</td>
<td>1,465</td>
<td>0</td>
<td>812</td>
</tr>
<tr>
<td>09</td>
<td>374</td>
<td>374</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>1,556</td>
<td>1,465</td>
<td>0</td>
<td>91</td>
</tr>
<tr>
<td>11</td>
<td>309</td>
<td>309</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>2,090</td>
<td>1,465</td>
<td>0</td>
<td>626</td>
</tr>
<tr>
<td>13</td>
<td>525</td>
<td>525</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>799</td>
<td>799</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>4,485</td>
<td>1,465</td>
<td>0</td>
<td>3,020</td>
</tr>
<tr>
<td>16</td>
<td>434</td>
<td>434</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>303</td>
<td>303</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>302</td>
<td>302</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>2,053</td>
<td>1,465</td>
<td>0</td>
<td>588</td>
</tr>
<tr>
<td>20</td>
<td>3,402</td>
<td>1,465</td>
<td>0</td>
<td>1,937</td>
</tr>
<tr>
<td>Average</td>
<td>1,371</td>
<td>885</td>
<td>0</td>
<td>486</td>
</tr>
</tbody>
</table>
Results illustrate that under the current zero reservoir capacity, total average water use is 885 MCM allocated among the sub basins as 211, 299, and 374 MCM for the Upper, Middle, and Lower region respectively. Wheat, melon, rice, and tomato crops consume a significant amount of water comparing to other cultivated crops. In general, the Lower Region farmers consume large amount of water when available given the fact that this region contains large number of canals and irrigated land. Under small reservoir capacity, Middle Region farmers could increase their water use for melon crop almost by 55% comparing to base condition, while no increase occurred for other crops. Respectively, additional reservoir storage retrieves more water to Lower Region cultivators of wheat, melon, tomato, and pulses. Moreover, the average available water for rice decreases under small reservoir comparing to no reservoir capacity.

Under a medium reservoir development plan, melons in the Middle Region can still obtain a modest increase of water use comparing to small reservoir condition. In addition, the lower region users can increase their water used to irrigate wheat, melon, and tomato in addition to a modest increase in water to irrigate pulses crops. In contrast, a significant decrease in the water allocated to rice crops occurred under the medium reservoir capacity for this region. Moving to large reservoir size, no much change will be happen in water allocation comparing to the medium reservoir size scenario. Under this institutional capacity, only the water allocated to rice producers increases, while the cultivator of pulses crops could practice a small
decrease that keep the allocated water at higher level comparing to both no reservoir and small reservoir.

### 4.4.4. Irrigated land

The impact of a reservoir up-scaling on average irrigated land by crop and region in the Basin is presented in Table 4.3. This table reflects the same information as discussed in the earlier tables but is presented in land units. With no reservoir capacity, farmers are not able to use surplus water in high supply years. On average, farmers irrigate just over 313692 hectares, considerably less than available land for irrigation. Wheat, melons, and tomatoes are heavy cultivated crops in all regions, while rice is an important crop in the Lower Region. Developing a small reservoir capacity allows farmers to irrigate more land in total than with no capacity. Total average irrigated land is increased to just over 378196 ha, with a gain equivalent to 21% of the total cultivated land. The increasing in irrigated land occurs for melon crops at Middle region, while in Lower Region can increase their irrigated land from wheat, melon, tomato, and pulses with considerable decrease from cultivated land of rice crop.

Developing a medium reservoir storage capacity adds more land in production due to the ability to store more water from wet years. The total average irrigated land increased by 19% comparing to small reservoir capacity. The increased irrigated land occurs in Middle Region for melon crop, while wheat, melon, tomato, and pulses irrigated land in Lower Region. Expanding to large reservoir scale slightly increases
irrigated land by 0.7% comparing to medium reservoir scale. All increased land in production takes place in Lower region for rice crop, while the irrigated land from pulses crops practice a small decline.

4.4.5. Farm income

The major advantage of up-scaling reservoir storage capacity is allowing more irrigation water for farming more cropland in drought years that would otherwise cause considerable hardship in food security and farm livelihoods. The net farm income by crop, region, and reservoir capacity in the Basin is presented in Table 4.4 Results show that farmers in the three regions can gain in average around $ US 144 million per year. Gains from wheat, melon, and tomato contribute the main source of income in the Basin compared to incomes produced without any reservoir capacity available.

Farmers increase their income by having access to the fruits of a small reservoir, seeing returns increase by 21%. The growing net income occurs in both the Middle and Lower Regions, regions that would otherwise shoulder the greatest burden of adapting to dry year shortages. The highest increase in net farm income takes place in the Middle Region for melon cultivators, where the net income rises by 55% comparing to no reservoir situation. In Lower Region, the income for the irrigators of wheat, melon, tomato, and pulses increases by 16%, 41%, 32%, and 23% respectively, while rice cultivators sustain negative gains of 24%. 

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Table 4.2. Water use by crop, region, and reservoir capacity for Balkh basin, Afghanistan (20 years average, in Million Cubic Meters/year)

<table>
<thead>
<tr>
<th>Crops</th>
<th>No Reservoir Capacity</th>
<th>Small Reservoir Capacity</th>
<th>Medium Reservoir Capacity</th>
<th>Large Reservoir Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Middle</td>
<td>Lower</td>
<td>Total</td>
</tr>
<tr>
<td>Wheat</td>
<td>53.1</td>
<td>68.1</td>
<td>32.9</td>
<td>154.1</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.7</td>
<td>0.9</td>
<td>1.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Rice</td>
<td>0.8</td>
<td>1.1</td>
<td>158.4</td>
<td>160.2</td>
</tr>
<tr>
<td>Cotton</td>
<td>2.9</td>
<td>4.8</td>
<td>6.3</td>
<td>14.0</td>
</tr>
<tr>
<td>Melons</td>
<td>96.7</td>
<td>202.1</td>
<td>118.2</td>
<td>417.0</td>
</tr>
<tr>
<td>Potatoes</td>
<td>0.2</td>
<td>0.3</td>
<td>1.6</td>
<td>2.2</td>
</tr>
<tr>
<td>Tomato</td>
<td>55.0</td>
<td>15.1</td>
<td>44.7</td>
<td>114.8</td>
</tr>
<tr>
<td>pulses</td>
<td>2.0</td>
<td>6.4</td>
<td>11.2</td>
<td>19.6</td>
</tr>
<tr>
<td>Average</td>
<td>211</td>
<td>299</td>
<td>374</td>
<td>885</td>
</tr>
</tbody>
</table>

Table 4.3. Irrigated land by crop, region, and reservoir capacity in Balkh Basin, Afghanistan (20 year average in 1000 hectares)

<table>
<thead>
<tr>
<th>Crops</th>
<th>No Reservoir Capacity</th>
<th>Small Reservoir Capacity</th>
<th>Medium Reservoir Capacity</th>
<th>Large Reservoir Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Middle</td>
<td>Lower</td>
<td>Total</td>
</tr>
<tr>
<td>Wheat</td>
<td>27.0</td>
<td>32.9</td>
<td>1.7</td>
<td>75.2</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.22</td>
<td>0.26</td>
<td>0.29</td>
<td>0.77</td>
</tr>
<tr>
<td>Rice</td>
<td>0.10</td>
<td>0.13</td>
<td>17.5</td>
<td>17.7</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.0</td>
<td>1.6</td>
<td>1.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Melons</td>
<td>38.9</td>
<td>76.0</td>
<td>41.1</td>
<td>156.0</td>
</tr>
<tr>
<td>Potatoes</td>
<td>0.10</td>
<td>0.12</td>
<td>0.56</td>
<td>0.77</td>
</tr>
<tr>
<td>Tomato</td>
<td>25.7</td>
<td>6.6</td>
<td>18.1</td>
<td>50.4</td>
</tr>
<tr>
<td>Pulses</td>
<td>0.94</td>
<td>2.8</td>
<td>4.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Average</td>
<td>95</td>
<td>121</td>
<td>98.6</td>
<td>313.7</td>
</tr>
</tbody>
</table>
These same cultivators gain more income than they lose by switching from rice to alternative crops. Development of medium reservoir storage adds more farm income for the basin. Under this reservoir scale, farmers enhance their overall net income by 16% comparing to the small-scale capacity reservoir. The added income occurs in Middle region for cultivators of wheat, melon, tomato, and pulses.

As the farmers secure required water for irrigation by medium reservoir capacity, large reservoir adds slight increase in the regional farm income. The net farm income for the basin rises by one percent in comparison to the medium scale reservoir. The only increase in the net farm income is observed in Lower Region for the rice cultivators, while the net farm income for the irrigator of pulses crops decrease slightly by 5%. Absolute increase in the net farm income generated by the reservoir capacities is shown in Table 4.5 in millions of US dollars by crop and region. Alternative additional storage capacities improve the net farm income for the Middle and Lower Regions mostly, since the Upper Regions secure their full supply even in most drought years.

4.4.6. Net farm income under different snow runoff scenarios

The average total net farm income produced by different reservoir capacities under three snow runoff water supply scenarios in additional to the estimated construction cost of those institutional capacities are demonstrated in Table 4.6.
### Table 4.4. Net farm income by crops, region, and reservoir capacity for Balkh Basin, Afghanistan (Average 20 years in Million $ US)

<table>
<thead>
<tr>
<th>Crops</th>
<th>No Reservoir Capacity</th>
<th>Small Reservoir Capacity</th>
<th>Medium Reservoir Capacity</th>
<th>Large Reservoir Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Middle</td>
<td>Lower</td>
<td>Total</td>
</tr>
<tr>
<td>Wheat</td>
<td>13.1</td>
<td>15.8</td>
<td>7.8</td>
<td>36.7</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Rice</td>
<td>0.1</td>
<td>0.1</td>
<td>9.2</td>
<td>9.3</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.3</td>
<td>0.5</td>
<td>0.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Melon</td>
<td>18.6</td>
<td>36.3</td>
<td>19.6</td>
<td>74.5</td>
</tr>
<tr>
<td>Potato</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Tomato</td>
<td>10.6</td>
<td>2.7</td>
<td>7.4</td>
<td>20.7</td>
</tr>
<tr>
<td>Pulses</td>
<td>0.2</td>
<td>0.7</td>
<td>1.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Total</td>
<td>42.9</td>
<td>55.9</td>
<td>45.6</td>
<td>144.4</td>
</tr>
</tbody>
</table>

### Table 4.5. Net farm income produced by additional storage capacity, by crop, region, and reservoir capacity for Balkh Basin, Afghanistan (20 year average, millions of $ US per year)

<table>
<thead>
<tr>
<th>Crops</th>
<th>No Reservoir Capacity</th>
<th>Small Reservoir Capacity</th>
<th>Medium Reservoir Capacity</th>
<th>Large Reservoir Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Middle</td>
<td>Lower</td>
<td>Total</td>
</tr>
<tr>
<td>Wheat</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rice</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cotton</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Melon</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Potato</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tomato</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pulses</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The data illustrates that under the historical water supply condition, the average total net farm income decreases by moving from small reservoir capacity toward large reservoir. The reason for that is the high construction cost associated with the large reservoir that has been subtracted from the total net benefits. The estimated cost for large reservoir that can hold up to 9.2 Billion Cubic Meter is 1.7 Billion USD, which considered inefficient comparing to the maximum available water for storing under the historical water supply, 2.5 Billion Cubic Meters. Under the small reduction of the snow runoff supply, 10% over 20-years period, there is no considerable change in the total net farm income. The farmers under this condition can utilize the unused water that exceeds the small storage capacity and used to be lost at the end of the basin, while they can sustain the small storage volume in wet year’s inflow.

Table 4.6. Net farm income produced by additional reservoir capacity, and reduction of snow runoff scenarios for Balkh Basin, Afghanistan (Average 20 years in Million $ US)

<table>
<thead>
<tr>
<th>Snow Runoff Scenarios</th>
<th>Reservoir Capacities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
</tr>
<tr>
<td>Base Condition</td>
<td>8,752</td>
</tr>
<tr>
<td>10 % Reduction</td>
<td>100 %</td>
</tr>
<tr>
<td>20% Reduction</td>
<td>99 %</td>
</tr>
<tr>
<td>30% Reduction</td>
<td>98 %</td>
</tr>
<tr>
<td>Estimated Construction Cost</td>
<td>0</td>
</tr>
</tbody>
</table>
In contrast, severe reduction of water supply, which presented by the 20% decreases in snow runoff, could slightly decrease the net farm income under the small reservoir. Under higher reduction of the water supply, 30%, the reduction will negatively decrease the net farm income under all reservoir capacity. However, the reduction in farm income will be the highest at the large reservoir capacities. The severe impact of snow runoff reduction under the large reservoir capacity could be explained by the high construction cost of this size of reservoir and small amount of available water for storage comparing to the medium reservoir. In general, while the small reservoir capacity is relatively more beneficial under small reduction of water supply, the medium reservoir size considers being more efficient under more severe decline in water supply for Balkh Basin.

4.5. Conclusions

Afghanistan’s agricultural and water institutions as well as its irrigation infrastructure have suffered from decades of war and unrest. The essentially zero current water storage infrastructure capacity, places a large burden of farm income, food security, and livelihoods. These burdens are more painful in the face of ongoing climate variability that can produce high fluctuations in water supplies from year-to-year. Without additional storage developed to adapt to climate variability, current and future water supply fluctuations constrain the country’s sustainability for irrigated agriculture and its attendant capacity to secure and sustain staple food requirements. In Afghanistan, the Balkh Basin is an important source for the regional and national
grain production, essential for food security. The annual water inflow for the Balkh Basin that comes mainly from snowmelt runoff is highly variable from year-to-year. Estimated annual long run supplies are 1540 Million Cubic Meters based on data secured from the admittedly short period 1964-1978. However, given the certainty of water supply variability coming from future years of droughts and flooding, farmers are poorly positioned to take advantage of surplus water from wet years due to the current absence of significant water storage capacity. Therefore, in drought years, farmers are unable to find water for their irrigated land in the lower reach of the Basin because of unavailable releases from previous wet years’ storage.

In the Balkh Basin, weakly developed water institutions result in low capacity for growers in the lower parts of the basin to bring land into production, especially in dry years if additional developed storage capacity is not developed. In that Basin, as in most of Afghanistan, water allocation and distribution are regulated by local water managers called *mirabs*. As a default water allocation system, the highest priority is assigned for upstream users. This default institution causes major hardship to downstream users’ farm income without additional water storage capacity made available. Limited numbers of projects have been addressed the water allocation efficiency and institution policies that could be used to optimize net return of irrigation water in this country that relies so heavily on agriculture.

In summary, this work has attempted to shed light on the importance of considering the hydrologic characteristics of the basin. We evaluated three reservoir
capacities on the Balkh Basin irrigation water use, allocation, and farm income. Using available farm budget data, this research has taken a preliminary step to develop an integrated basin scale framework that encompasses hydrology, institution, cultural, and economics characteristics of the Balkh Basin. A dynamic empirical optimization model has accounted for irrigation water users in the Basin, with the intent of optimizing net agricultural benefits under the three proposed alternative reservoir capacity developments. The three reservoir scales are assigned as small reservoir that could save half of the average long term annual flow, medium reservoir that stores 150% of total average inflow, and large reservoir that store 6 times average annual inflow. With respect to upstream water right priority, a stochastic water inflow for 20 years’ time period analysis is implemented to characterize the variation in water inflow that are perceived by the Basin’s water users as the ongoing pattern of droughts and floods.

The integrated basin framework described for this study is the state-of-the art analytic method for assessing policy alternatives at the river basin scale. This framework has the advantage of explicitly including a balanced hydrology that interacts with institutions, cultural, and economic characteristics of the basin. However, investigating more policies such as water pricing, more flexible water rights systems, and irrigation technologies are beyond the scope of this research and must be left for future work. Furthermore, other benefits such as hydropower generation in addition to urban water supply and environmental impact are excluded.
from the current work. Nevertheless, a central advantage of our framework is to
provide to water policymakers, managers, mirabs, and farmers, the information
needed to formulate science-based water policy designs.

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CHAPTER V

5.0. CONCLUDING REMARKS

5.1. General Conclusion

Water is an essential need for people and ecosystems. For arid and semiarid regions, gaps between the water supply and demand are growing. Growing population, food security, economic growth, increasing living standards, and climate change pose many challenges on the limited water resources in those regions. Uneven distributions of the water resources in addition to transboundary conflicts of water use add further challenges. Great responsibilities are assigned for policy makers and water resources managers to formulate better proposals that could enhance the water economic efficiency and sustainability while respecting the requirements of equity.

The global community has recognized the need for better management for freshwater resources. The high awareness of water scarcity and current global poor management of water led for the formulation of the four water management principles in Dublin’s International Conference on Water and the Environment (ICWE) in 1992. Those four principles emphasized the finite and vulnerable nature of worldwide water resources. That conference concluded that holistic management should be applied to increase the water utilization efficiency and sustainability to meet future human needs and maintain the sustainability of ecosystems. Furthermore, the Dublin rules highlighted the need for better perception of the economic value of water in addition
to cultural dimensions of water management by increasing women’s participation in
the policy design and implementation of water programs.

In the Nile Basin, Egypt is the downstream country. A dry climate and scarce
rainfall make Egypt completely dependent on the water that originates from the Nile
River. The Egyptian share of the Nile Basin, 55.5 Billion Cubic Meters per year,
contributes about 98% of the country total water supply. According to Herodotus,
Egypt is a gift of the Nile. Currently, the Nile River is still the lifeline for Egyptian
irrigation and households. Irrigated agriculture in Egypt still employs almost the third
of the country’s workforce.

With a growing population, emerging industrial sector, increased need for
food security, and threats from potential impacts of climate change, water demand
already exceeds the water supply. Water scarcity is expected to be a critical limiting
resource for the future of the country economic development. The major strategy in
the 20th century for the Ministry of Water Resources and Irrigation (MWRI) was to
meet all irrigation demand, without paying enough attention to the opportunity cost of
meeting those demands. By the early of the 21st century, debates about future water
policies receive growing attention. Egypt as of the year of 2005 attempted to
formulate national plans to increase the water supply, improve the efficient use of
existing water, reform water institutions, and protect public health and the
environment.

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While increasing Egypt’s national water supply through co-operation with other Nile Basin countries is major challenge, increasing the use of groundwater, desalination, and water harvesting programs are all expensive. Improving the management of existing water supply could be achieved by several policy alternatives. Those alternatives could include maintaining canals, limiting the planting of water intensive crops, and introducing modern irrigation technology. Regardless of the potential of those policies in conserving water, they all present challenges. New irrigation technology implementation could reduce the return flow to the river and to aquifers because of their impacts on higher crop ET as well as presenting challenge of high costs of converting from traditional surface irrigation. Another obstacle is the widespread problem of scattered land ownership that dominates the Egyptian agricultural system, which poses many technical challenges. On the other hand, options such as water pricing and input taxation are tools with some economic potential. However, those policies face great political and cultural restrictions, especially in developing countries, where the social and economic system suffers from deep chronic structural problems.

Afghanistan presents another example of an arid country that faces ongoing challenges with managing its limited water resources. In northern Afghanistan, the Balkh District and Basin has over 80% of its population in rural areas. As a result of long recent history of devastating military conflicts, the region lacks many water institutions that could produce more food security and farm income. In that basin, the
water rights are generally assigned for upstream users when drought occurs as they have the priority access to the water. Remaining water that exceeds the upstream users’ irrigation capacity is distributed among middle and lower basin farmers. During drought seasons, little water is left for the downstream users, which can lead to farm income and food security issues. By contrast, in the case of wet periods, farmers are often unable to benefit from water surpluses because they do not have adequate infrastructure to store the water for future uses.

To address those gaps in previous research, the major objective of this dissertation was to introduce an integrated basin framework approach that could address a range of water management challenges worldwide. This major objective is divided to three sub objectives. The first objective is to examine measures for improving the efficiency and sustainable use of Egypt’s Nile River. The second objective aims to investigate potential for intraregional and interregional water trading to improve the economic efficiency of water use in Egyptian agriculture. The third objective is investigating the economic returns of a range of reservoir capacity expansions on farm income and food security at the Balkh Basin, Afghanistan.

This study developed a single integrated basin management framework that applied to both Egypt’s Nile Basin, Egypt and Afghanistan Balkh Basin. The IBMF accounts for the hydrologic characteristics of the two basins with an aim of maximizing discounted net benefits from irrigation activities.
Findings for Egypt illustrate that national farm income could increase in response to implementing a limited water trading policy. While results show that intraregional water trade policy can make all irrigation water users better off, the interregional water trade will also improve the national economic welfare. Increasing water economic efficiency can move water from low valued crops to higher valued crops like vegetables and exports products. Careful application of water trading instruments could enhance the economic efficiency of water use. Moreover, it can be culturally acceptable and politically less sensitive compared to other alternatives such as water pricing and input taxes.

The water-trading alternative was found to send signals that reflect the economic value of water scarcity. Furthermore, it can protect a level of equity if the scope water trading is limited. In addition, both sellers and buyers of water rights have the opportunity to share in the benefits. The sellers of water rights obtain cash many that could be invested in water conservation programs, while the buyers of water will receive a higher economic value of water productivity than the price paid for the additional water. Results showed that implementing a limited water-trading program can contribute to food security, environmental protection, and sustainability for the storage volume of Lake Nasser. However, implementation of water trading at a national scale will require an advanced water rights system in Egypt. At a minimum, more participation of the nation’s water stakeholders is required to identify an appropriate water trading system that compatible with the nation’s culture and
socioeconomic objectives. Finally, the implementation of any scale of water trading should be preceded by widespread, open, and transparent debate on ways to address technical and institutional obstacles resulted from the scattered land holding in Egypt.

For Afghanistan’s Balkh Basin, results showed growing economic returns from additional irrigation activities associated with developing added reservoir capacity. Results showed that raising storage capacity for the Balkh basin increases the farmer’s ability to hold, store, and allocate the water for use in future drought periods. Moreover, expanding the reservoir capacity positively affects farm income stability over space and over time. While the current water rights system in Afghanistan favors upstream users, the largest share of economic benefits from reservoir capacity expansion will occur in downstream regions. Even though no environmental and hydropower benefits are analyzed in this limited analysis of Afghanistan, the country has a better chance to limit the negative impacts of drought and also secure improved food security by adding more reservoir storage capacity.

5.2. Limitations

This dissertation has several limits that point to future improvements needed. Economic gains from water allocated to other uses rather than the irrigation activities are not directly addressed in this work. These uses include hydropower, urban and domestic use, recreation, groundwater recharge, transportation, fishery, and environmental uses. This dissertation also performed no analysis of the technical, financial, or institutional requirements needed to establish or sustain water trading.
Compared to the base year water institution of no water trading, only two policy alternatives for managing Egypt’s Nile Basin waters in agriculture are analyzed among the many being debated. In addition, this analysis was only able to secure detailed data on land in production by crop and region for a single base year, 2006. A longer time series would make for a much better analysis with stronger policy implications. The lack of data from stakeholders associated with water trading in Egypt is a major limitation of this work that needs to be addressed in future work. Egyptian water stakeholders will need to be consulted with great sensitivity to their needs before water trading can be initiated on a large scale.

For the Afghanistan application, the framework described in this work has the advantage of explicitly including a balanced hydrology that interacts with institutions, cultural, and economic characteristics of a river basin. However, investigating more policies such as water pricing, water trading options, more flexible water rights systems, and programs to introduce irrigation technologies must be left to future work. Furthermore, economic benefits such as hydropower generation in addition to urban water supply and environmental values are excluded from the current work. Nevertheless, a central advantage of the framework developed is to provide to water policymakers, managers, mirabs, and farmers, the information needed to formulate science-based water programs.

5.3. Future Research Plans
Despite the findings of this integrated basin framework, much future work can be done to improve it. Incorporating groundwater hydrology and use in addition to existing surface water use will add more dimensions to the existing integrated basin framework. Furthermore, adding more details about hydropower generation, fishery, tourism, and recreation activities and how they are affected by different water policies and programs could be helpful for decision-makers. Assessment of water conservation programs could play an important role in the future improvement of the water use efficiency. Investigating the economic cost and return of promoting adaptation of modern irrigation technologies to reduce the gaps between regional and national water supply and demand would help in more efficient water management design and implementations.

In recent years, in response to increasing needs for food security, Egypt took the first steps toward mega agricultural projects such as Toshka, East Uwaynat, Al-Salam canal, and Darb Al-Araba’in projects. How those projects could affect the water budget in Egypt is still unknown. Is there enough water to sustain those projects in the future? An important question centers on the opportunity cost of using water in those projects and how they could influence the existing irrigation system in the old valley. All are questions that need to be answered. This proposed integrated framework has enough flexibility to address those questions in the future. Meanwhile, the threat of global warming and climate change receives increasing attention.
worldwide. The potential impact of increasing atmospheric temperature on the agricultural activities and water resources needs to be carefully addressed.

One of the major strengths of the integrated basin scale framework designed in this work is its up-scalability. Given the fact of huge water supplies in the Nile Basin, most of the Nile Basin countries do not currently realize the benefit of better integrated management for this basin with the river’s potential to improve the economic future for all riparian countries if efficiently utilized. Important future work needs to focus on integrating the entire basin. Such integration could help inform the debate over ways for efficient and sustainable water resources management. In addition, it could contribute to the basin’s economic development and as tool for poverty reduction.