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WATER ALLOCATION FOR AGRICULTURAL USE CONSIDERING TREATED

WASTEWATER, PUBLIC HEALTH RISK, AND ECONOMIC ISSUES

by

Ahmed E. Al-Juaidi

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

Approved:

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UTAH STATE UNIVERSITY
Logan, Utah

2009

ABSTRACT

Water Allocation for Agricultural Use Considering Treated Wastewater,

Public Health Risk, and Economic Issues

by

Ahmed E. Al-Juaidi, Doctor of Philosophy

Utah State University, 2009

Major Professor: Dr. Jagath Kaluarachchi
Department: Civil and Environmental Engineering

Increasing demand on limited water resources calls for more efficient and improved approaches to maximize the benefits of water use. Typically, agricultural water use has the largest share among all water use sectors. Therefore, finding the best agricultural water management alternatives to maximize profit and reduce financial and other related risks under limited water availability is essential. Treated wastewater is an important alternative source of agricultural water which has the potential to reduce the stress on freshwater sources from urban and industrial sectors. Thus, further research on optimal agricultural water management is needed to find the best management alternatives that address profitability and reduce stress on freshwater supplies, and related risks, by considering the potential use of treated wastewater when available. The overall goal of this work is to address this research need through an integrated methodology that uses irrigation, economics, and environmental and public health principles. This dissertation consists of three parts. The analysis in the first part determines the optimal crop pattern that maximizes profit under limited water supply that can be applied at regional scale farming operations. The goal is to find different alternatives of land and crop patterns that increase profit and reduce financial risk of not achieving a given revenue target. The second part extends the work of the first part to include the use of treated wastewater to reduce the stress on freshwater sources while maximizing profitability and minimizing public health and environmental concerns. The third part evaluates the economic benefits and limitations of using treated wastewater for agriculture on the urban and industrial sectors. This part also discusses other alternatives such as desalination that increase the net economic benefits, reduce the price of water, and assesses the needs in the institutional setting to encourage the use of treated wastewater in agriculture. The Bear River Valley of Utah was used as the study area for the first part of the work. The results showed that crop rotation leads to larger risk decrease more than crop monoculture and diversification cropping systems. Thus, alfalfa–wheat rotation has significant risk advantages over monoculture production and diversification cropping because of enhanced yield and price offsetting ability. The second part of the study used data and information from the Gaza Strip, Palestine, to demonstrate the potential use of treated wastewater given the severe water shortage facing this region. The tradeoff analysis from this work showed that profitability and economic efficiency of water use can be increased significantly compared to the existing conditions through the use of treated wastewater. Groundwater extraction in Gaza can be reduced from 57 to 36 million m^3 allowing the corresponding areas of groundwater table below mean sea level to decrease from 76 km^2 to 32 km^2 as a result of using treated wastewater, indicating significant aquifer recovery. The final part of the analysis also used the Gaza Strip as the case study. The results showed that the benefits of using treated wastewater increase over time as demands increase and water becomes scarce, but the economic value of water does not fall below the seawater desalination cost of $0.60/m^3. The urban and industrial water prices reduced significantly when wastewater is used for agriculture. Net benefits from treating and using wastewater far exceed the institutional change costs borne by the corresponding institutions. The work conducted by this dissertation clearly showed that new methods of integrated analysis using the concepts of water allocation, irrigation principles, economics, environmental concerns, and public health risk can be successfully conducted to improve existing agricultural water allocation and management practices in water deficit regions. Also such analyses will provide valuable information and insight leading to better management of valuable water resources that increase profitability in agricultural production while reducing stress on freshwater supplies through the use of alternative sources of water.

(162 pages)

I cherish the inspiration of my family, teachers, and friends.

This dissertation is dedicated to all of them.

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CHAPTER I

INTRODUCTION

General Introduction

In coming decades, irrigated agriculture will be called upon to produce up to two-thirds of the increased food supply needed by an expanding world population (English, Solomon, and Hoffman, 2002). The expected increase in competing water uses and environmental effects accompanying irrigation practices (i.e. pollution) calls for re-evaluating irrigation practices.

Irrigated agriculture will need to adopt a new management standard based on an economic objective—the maximization of net benefits—rather than the objective of maximizing yields (Kirda and Kanber, 1999). Technically, irrigation to meet crop water demands is clearly defined and well established in the technical literature; however, maximizing benefits of irrigation is a more complex and challenging problem. Identifying optimal irrigation strategies requires detailed models of the relationships between applied water, crop production, and irrigation efficiency. A fundamental shift in irrigation practice is likely to evolve over the next few decades. Economic pressures on farms, increasing competition for water, and the adverse environmental impacts of irrigation justifies a new approach to evaluate irrigation plans based on economic efficiency of water use rather than crop water demand (Kirda and Kanber, 1999). This new approach, which might be described simply as "optimization" has been characterized as a new paradigm (Perry, 1999). Irrigation optimization should not be confused with practical irrigation scheduling, which involves the monitoring of soil moisture or crop water status to determine when and how much to irrigate. Typically, irrigation scheduling aims to maximize yields, hence current scheduling procedures do not explicitly account for costs and revenues (English, Solomon, and Hoffman, 2002). Therefore, optimization in irrigation is needed to represent costs and revenues explicitly.

Identifying the optimum irrigation strategies will require more detailed models of the relationships between applied water, crop production, and irrigation efficiency. Economic factors, particularly the opportunity costs of water, will need to be explicitly incorporated into the analysis. In some cases the analysis may involve multi-objective optimization (English, Solomon, and Hoffman, 2002; Kirda and Kanber, 1999). The multi-objective analysis may use other important issues for aquifer sustainability such as using treated wastewater for agriculture. The increased complexity of the analysis requires using analytical tools such as system analysis to assess how treated wastewater in agriculture impacts the other water use sectors (urban and industrial).

The present research has focused on allocation of water for the agricultural sector and between the agricultural, municipal, and industrial sectors. This study was comprised of three sections. In the first section, we developed a methodology to predict the optimal cropping patterns that will maximize profit under water deficit conditions. The second section considered treated wastewater for agriculture, its effect on aquifer recovery, and the economic efficiency of water use considering public health aspects. The last section investigated the economic impact of treated and reused wastewater for agriculture on the urban and industrial sectors, to find the best water management scenario that maximizes net benefit through inclusion of desalination to enhance water supply, and to propose an acceptable water institution arrangement that can encourage the use of treated wastewater for agriculture.

First, we developed a methodology to determine the optimal crop and land area combination for maximum profit under limited seasonal water supply that can be applied at regional scale farming operations. This task involves conducting an economic analysis to identify the significant management parameters affecting profit. Also a risk analysis was developed to identify the failure to achieve a given revenue target under a variety of cropping systems so that farmers have enough information to develop suitable cropping patterns to minimize future risk of failure. The methodology was demonstrated for Bear River Valley in northern Utah where profits are subject to significant uncertainty due to yield variability, fluctuating crop market prices, increasing production costs, and limited water availability.

A broader view of irrigation optimization tested in the first section was examined in the second section, which included treated wastewater in agriculture, associated public health risks, and economic efficiency of water use. These broader issues require multi-criteria optimization that considers treated wastewater, public health risk, and economic aspects. The Gaza Strip is selected to be the test case in the second section. The Gaza Strip is a complex hydro-political web and the current situation of water use in Gaza makes it a good example for this and the next task. Gaza is bordered by the sea from the west, and its agricultural accounts for 70% of the fresh water use. Over-extraction from the coastal aquifer to meet the water demand is causing salt water intrusion. Water demand in Gaza Strip is expected to increase in the future due to the increasing population. Without alternative sources or methods to decrease the current stress on the aquifer, the aquifer will be dewatered below replenishable levels. Aquifer dewatering will be mitigated via increased use of treated wastewater as an alternative source of irrigation water. The public health risk from the use of treated wastewater should also be taken into consideration since wastewater contains pathogens.

The last section represents an extension of the second section. The major output of the second section includes quantities of both wastewater and groundwater and is used to predict the demand function of the agricultural sector. The third section explores the economic impact of using wastewater in agriculture on the urban and domestic sectors, assess whether a reduction in groundwater pumping without the use of treated wastewater will have detrimental effects on supply and economic benefits, investigate which improved management options are available for supply enhancements to reduce future water deficits, and which are the competitive economic benefits of these improved options. This last section will also discuss changes needed in water institutions to implement procedures to use treated wastewater for agriculture.

Here, we used a system analysis methodology which examines the costs and benefits of supply and demand for urban, industrial, and agricultural sectors considering groundwater and treated wastewater. System analysis includes an objective function subject to constraints on water and treated wastewater. The objective function is to maximize the net benefit. The net benefit is estimated as the benefit from the water demanded minus the cost of water supply.

Research Motivations

Water scarcity is a serious issue especially for urban and industrial sectors due to inefficient water use by the agricultural sector. Better management of agricultural water use to meet future demands of the other water-use sectors is needed. About 70% of fresh water is used for irrigation in developed countries and over 85% is used in low income countries (Meinzen-Dick and Rosegrant, 2001). Additional or alternative sources such as reuse of treated wastewater in agriculture to reduce the gap between demand and supply and to supplement water shortages are needed. Furthermore, the use of treated wastewater in agriculture is expected to increase rapidly over the next few decades as population increases and water deficit intensifies.

Research Objectives

The overall goal of this dissertation is to develop management methodologies to address optimal agricultural water use for maximum profitability in water deficient regions with the potential use of treated wastewater where possible.

1. Develop appropriate methodology to find the best cropping and land use combination in irrigated agriculture to maximize profit under limited freshwater availability. The methods will include an economic analysis and a financial risk assessment.
2. Extend the work of Objective 1 to develop an appropriate methodology to incorporate the use of treated wastewater in irrigated agriculture while considering public health concerns, profitability, economic efficiency of water use, and the potential for aquifer recovery in water deficient regions.

3. Develop an appropriate economic analysis to investigate the economic impact of using treated wastewater in agriculture on the urban and industrial sectors. The analysis will (1) assess whether a reduction in groundwater pumping without the use of treated wastewater will have detrimental effects on supply and economic benefits; (2) investigate which improved management options are available for supply enhancements to reduce future water deficits and which are the competitive economic benefits of these improved options; and (3) propose an acceptable water institution arrangement that can encourage the use of treated wastewater.

Dissertation Organization

This work is organized to represent the framework development process, consideration, virtues and limitations, and the practical implementation for each of the three applications in water resources management. Chapter I introduce the general background about the research area and provide the objectives, the motivations, and the contributions to the existing research. Chapter II provides a review of the related literature of water management and allocation in agriculture with economic, social, and environmental orientation. Chapter III details the specific framework development and application for optimal agricultural production under water deficit conditions. Chapter IV details the specific framework development and application to treated wastewater use in water deficit regions for agriculture: Economic, environmental, and public health issues. Chapter V details the extended framework development and application to economic analysis of improvements to water management in water deficit regions for the Gaza

Strip. Chapter VI summarizes the findings of the research, describes the limitations and presents conclusions and recommendations.

CHAPTER II

LITERATURE REVIEW

Introduction

This dissertation presents a planning method for sustainable agricultural water management and water resources use in coastal regions susceptible to salt water intrusion and salinization. The methodology herein builds on the previous work of engineers, economists, political scientists, and agronomists. This chapter attempts to highlight key contributions to the presented methods.

This study develops strategies to more effectively manage agricultural water in water deficit regions, especially coastal regions where excessive groundwater withdrawals can increase salt water intrusion. In the analysis, profitability and economic efficiency of water use was highlighted and the potential use of treated wastewater to reduce stress on fresh water demand was addressed. Finally, the economic benefits of new water management policies on other water use sectors were also addressed.

Agricultural Models

Linear and non linear optimization models for the determination of optimum cropping pattern, water amount and farm income under adequate and limited water supply conditions have been developed (Mantanga and Marino, 1979a; Mantanga and Marino, 1979b; Klocke et al., 2006; Benli and Kodal, 2003; Ortega and Trajuelo, 2004; Reca et al., 2001; Kumar, Indrasenan, and Elango, 1998).

More complex models that combine economics and water quality have been developed involving agriculture, with the maximization of agricultural income as one of the objectives. For example, Chowdhury et al. (1994) combine a model of the transport of nitrates in groundwater using stochastic weather, and a risk-sensitive farm level optimization model. Bernado et al. (1993) have a similar approach, looking not only at nitrates, but also phosphorus, pesticides and sediment losses over multiple-year time horizons. Mantaga and Marino (1997a and b) give a more detailed agronomic model that looks at salinity in the root zone of plants. They use stochastic dynamic programming to maximize crop income under circumstances of increasing salinity due to leaching patterns and other irrigation decisions. Lefkoff and Gorelick (1990a and 1990b) do a similar farm-level analysis to look at water quality and quantity in a stream aquifer system, in the context of a possible water market between farmers. Crop response to depth and salinity of applied water is included in the model. McCarl et al. (1999) developed a model of agricultural water use that includes benefits to industrial and municipal users applied to the Edwards Aquifer in Texas. Recreational and habitat preservation for endangered species are also considered in the model through minimum flow requirements. Brimberg, Oron, and Merhrez (1993) developed water sources management model considers saline groundwater, treated wastewater, and rainfall harvesting in the Negev desert, Israel, based on linear programming technique. The Brimberg, Oron, and Merhrez (1993) model objective is to minimize the operational and capital costs of water supply in the whole Negev desert area. Raju and Kumar (1999) developed a multi-criteria decision-making model for irrigation planning. The authors developed three single objective functions to maximize net profit, agricultural production considering labor costs. Cluster analysis and two multi-criteria evaluation methods were used to simulate an optimal scenario. The reported method presented an interesting approach for irrigation planning on a regional scale. Prasad, Sinha, and Rai (2001) developed a multi-criteria optimization model that produces optimal crop patterns under limited water sources constraints for the Ranchi basin, India. Prasad, Sinha, and Rai, (2001) model considers maximization of net profit, cultivated area, and labor employment but using different optimization methods. Latinopoulos and Mylopoulos (2005) developed a multi-criteria model for optimal allocation of land and water resources in irrigated agriculture using goal programming methods. Five objective functions: maximize profit, minimize labor, minimize risk, minimize irrigation water input, and minimize nitrogen input. Simultaneously maximization of farmer's welfare and minimization of environmental burden were targeted. Goal programming method was implemented on the Loudias River basin in Greece to find a compromise solution in terms of area and water allocation under different cropping patterns. Ouda and Bardossy (2003) provided a model to maximize profit and minimize groundwater use recognizing dry and wet seasons. The wet and dry season's considerations produce different potential evapotranspiration (ET_o) and crop water requirements and as a result different crop yields with the season. Maximum allowable water use effectiveness, maximum allowable groundwater quantity, percentage of coverage of product demand, expected change in farmer's acceptance of reuse, and spatial equity in profit and access to groundwater and treated wastewater were set as decision variables.

Groundwater Models

Shafike, Duckstein, and Maddock (1992) employ a multi-criterion analysis with a well-defined groundwater model to optimize management of groundwater contamination, primarily minimizing risks and costs. Keshari and Datta (1996), and Taghavi, Howitt, and Marino (1994) take a slightly dissimilar approach, using a groundwater model and multi-objective programming to assess tradeoffs between water quality control and a minimum groundwater withdrawal or pumping schedule.

Salinity Models

Salinity impacts agriculture through reduced crop yields and increased farm production costs because of the need for additional leaching and/or drainage systems. Salinity also has an effect on municipal and industrial users by accelerating and deterioration of pipes and other equipment, and by necessitating the purchase of water or water treatment systems, if the salinity levels are high enough to warrant these expenditures (Lee and Howitt, 1996). Salinity can create ecosystem effects as well, for example in coastal wetlands and estuaries. A sub-class of the groundwater models discussed above model coastal aquifers and problems with saltwater intrusion. Shamir, Bear, and Gamliel (1994) minimize costs to prevent intrusion of saltwater and meet water quality constraints for a conservative contamination. Emch and Yeh (1998) connected a coastal groundwater flow model using a sharp interface approach directly with an optimization model. The objective was to minimize costs and extent of salt water intrusion, while meeting constraints of minimum demands and head drawdown.

Water as an Economic Good

Economics has undoubtedly always played a role in water resources management, in that at least costs were considered. A fundamental change in thinking was evidenced in the United States Flood Control Act of 1936, when a cost-benefits analysis was required to justify projects (Rogers, 1993a).

Several earlier studies discuss the treatment of water as an economic good (Young, 1996; Gibbons, 1986; Rogers and Fiering, 1986; Rogers, 1993b; Rogers, Bhatia, and Huber Lee, 1998; Perry, 1999; Rosegrant and Ginswanger, 1994; Seckler, 1996; Draper et al., 2003), but typically the ideas are not applied to real situations. There are, however, a growing number of examples of applications of economics to water management. Rogers (1993b) looked at the Ganges-Brahmaputra basin in the context of value of cooperation between India, Nepal, and Bangladesh, using fixed supply and a single water type. Bhatia et al. (1994) modeled the industrial sector in Jamshedpur, India, and the impacts of both water tariff and effluent charges. Huber Lee (1999) presented an inter-temporal model for sustainable management of the Gaza coastal aquifer. Huber Lee (1999) modeled the groundwater hydrology and salt transport in the aquifer, as well as the economics of water allocation and agricultural water use. Fisher (1995), Fisher et al. (2002), and Fisher et al. (2005) modeled the agricultural, industrial, and domestic sectors in Israel, Jordan, and Palestine, to determine the value of water in dispute between the countries. Harshadeep (1995) created an optimization model of the Subernarekha River Basin in India that represented the agricultural, industrial, domestic, and hydropower demands in the basin.

As seen in the previous discussion, most previous studies addressed agricultural water management purely as a water allocation problem without seriously integrating interrelated issues faced by the agricultural community such as enhancing supply through alternative sources of water, economic implications, environmental concerns or public health issues. Therefore, there is a need to address the issue of agricultural water management in water deficient regions considering alternative water sources, the implication of using such sources on profitability and economic productivity, environmental concerns, and public health impacts, and corresponding benefits and limitation on the water allocation to other sectors such as municipal and urban. A study that is capable of providing this broad outlook will give valuable information and insight to the agricultural community as well as to water resources planners on the need to better manage valuable water resources in water deficit regions especially given the future scenarios of increased population growth, climate change and climate variability. In the work reported in this dissertation, treated wastewater was an important source of alternative water that will be considered in the analysis while the corresponding benefits and limitation of this practice were evaluated.

CHAPTER III

OPTIMAL AGRICULTURAL PRODUCTION UNDER WATER-DEFICIENT CONDITIONS

Abstract

In arid to semi-arid regions such as the western US, the lack of adequate irrigation water affects agricultural productivity. There is a need to optimize allocation of scarce water resources among different crop and land combinations to maximize profitability and water use efficiency. The goal of this study was to investigate the factors affecting profitability and develop approaches to increase agricultural profitability under water deficient conditions. This study performed an economic analysis to identify the most influential parameters affecting profitability and the risk of not achieving a given target revenue under different cropping conditions. The work was extended to identify the optimal land area/crop combination for maximum profit under water deficit conditions. Since energy costs can be significant in most profit-oriented activities, the impact of using different energy options on profitability was also investigated. The methodology was demonstrated for the Bear River Valley of Utah where agriculture is prevalent and water is limited. The analysis showed that yield and price were the most influential parameters for local farmers, and production cost was the least influential parameter. Monoculture, diversified and rotation-diversified cropping patterns were evaluated for revenue and risk for not achieving a given target revenue. It was found that rotation-diversified cropping will lead to a decrease of risk more than crop monoculture and diversification cropping patterns. The results suggest that different crop/land area

combinations are available to increase profits over the existing conditions. Profits also increase with deficit irrigation while electricity is the most profitable energy option.

Introduction

Maximizing profit in agricultural activities with available resources is of great importance to land owners and farmers. However, achieving this goal is difficult owing to the many complex factors such as climatic variability, irrigation system operation, production costs, market prices, natural disasters, and subsidy policies. This paper describes a methodology for identifying the optimal production and irrigation management strategies under a limited supply of water.

Due to reduced water supplies, irrigators are facing challenges to increase profitability. To compensate for reduced water supply, irrigators have turned to more efficient irrigation application techniques and water conserving cropping practices. Both measures have improved the use of water at the farm level. Irrigation managers with limited water supplies from restricted well capacities or water allocations need to consider strategies related to crop selection, crop rotation, and water deliveries to each crop.

An economically well-managed farm is one that consistently makes more profit than similarly structured farms. External economic factors, such as crop market prices and production costs often affect the agricultural industry. Since localized natural events such as floods, droughts, or other natural disasters, often mask the differences or similarities in management, it is important to observe profit differences among farms over time. In the context of crop production management, an operator could be more profitable for a number of reasons such as the desire to produce higher crop yields compared to existing local conditions, better marketing practices or controlling production costs (Dhuyvetter and Kastens, 1999; Helms, Bailey, and Glover, 1987). An economic analysis is therefore needed to identify the influential parameters affecting profit.

Financial risk must be quantified to evaluate whether various risk management tools and strategies are effective in achieving producers' risk reduction goals. This process involves measuring variability of yield and price (i.e. market price). An example is the Bear River Valley, Utah where production costs are increasing steadily while yields and market prices of alfalfa and wheat fluctuate significantly. Therefore, farmers are unable to predict the anticipated profit reliably and accurately. In such instances, crop rotation and crop diversification can be used in reducing the risk of not achieving a given revenue target in the presence of limited water and variability of yield and price. Crop diversification risks and benefits are generally well understood, but the additional effect of rotational cropping on risk is less understood. It is also important to understand the cause when rotations reduce risk. Crop rotations can reduce risk compared to monoculture cropping (Helmers, Yamoah, and Varvel, 2001; Harwood et al., 1999).

The benefit of crop rotations to reduce risk is due to three different influences. First, conventionally practiced rotations involve diversification, an offsetting occurrence where low returns in one year of one crop are combined with comparatively high revenues from a different crop. Second, rotation cropping can reduce the yield variability compared to monoculture practices. Third, unlike monoculture cropping, rotations may result in overall higher crop yields. Rotation depends on the crops adapted to the particular soil, climate, and economic conditions of a particular area. Rotation may limit weeds, plant diseases, and pests. Risk of failure due to weeds, diseases, and pests is less with crop rotation than monoculture cropping. Cultivating the same crop from one season to another season has a negative effect on land fertility and reduces organic matter in the soil. Rotating alfalfa, legumes, and wheat in Utah is typically used to remedy this condition.

Soil nutrient replenishment is the major long-term agronomic benefit of planting wheat after alfalfa rather than alfalfa after wheat. Alfalfa roots replenish the soil with a nitrogen of range from 150 kg/ha to 190 kg/ha. When wheat is planted following alfalfa, this amount of nitrogen will be consumed by wheat at no additional cost. Certain parasites that live in the soil tend to accumulate when a crop is grown year after year. Furthermore, crop rotation is the most effective practical method for control of many weeds. Some weed species are particularly adapted to legumes, and other small grains. The continuous growth of small grains in the same land encourages weed growth (USDA, 2005). A risk analysis is therefore needed to predict the risk of failure to achieve a given revenue from different cropping systems.

The optimum use of land and water resources for maximum profit in an environmentally sustainable manner is essential. In irrigated areas, improvements in on-farm water management is the first step towards the conservation of diminishing natural resources, and it is therefore important to find production strategies capable of efficiently using the state-of-the art irrigation equipment. Even though the goal of optimal use of water and land area for maximum profit is fairly well defined, it is difficult to outline a plan of action to achieve such a goal.

When irrigation water supply is limited, an irrigation deficit exists (English, 1990; De Juan et al., 1995). In this case, two solutions are feasible: (1) reducing the area to be irrigated while providing emphasis to crops with higher profits but needing more water; followed by allotting the remaining irrigable land to dry lands, or (2) increasing the irrigated area by introducing crops with low water requirements in the crop rotation, and/or adopting restrictive irrigation programs (De Juan et al., 1995; English, Solomon, and Hoffman, 2002).

Under conditions of water scarcity, farmers must make decisions about the types of crop to be planted, crop area allocation, and when and how much these crops will be irrigated. Each of these decisions takes place within a set of physical, technical, and institutional constraints (Savenije and Zaag, 2002; Marques, Lund, and Howitt, 2005). Where irrigation water availability is limited, it may not be possible to irrigate all available land. In this scenario, an irrigator must decide between full irrigation on a reduced land area or using deficit irrigation which is defined as irrigation management with a supply of water less than the seasonal evapotranspiration requirements of the crop (Benli and Kodal, 2003; Kumar, Indrasenan, and Elango, 1998; English, 1990). In many agricultural settings, these decisions are made under conditions of uncertainty about future irrigation water availability.

Irrigators choose the crops based on the production capability, profit, crop adaptability, government programs, crop water requirement, and the preference for growing a given crop. Knowledge of crop water requirement and crop yield response to applied water is required to define economically optimal cropping patterns and irrigation scheduling (Giordano et al., 2004; Klocke et al., 2006). An economically efficient cropping pattern defines the optimal crop area and irrigation water allocation for seasonal, annual and perennial crops, subject to constraints on land and water availability (Mujumdar, 2002; Young, 1996; Botes, Bosch, and Oosthuizen, 1996). An economically optimal cropland and irrigation allocation is defined as an allocation between crop areas, and crops such that a reallocation of irrigation water between crops cannot result in a higher profit to the irrigator (Cheesman, 2005; Vedula and Nagesh, 1996). An economically optimal irrigation allocation may not necessarily result in a maximum yield due to diminishing marginal returns of product inputs (Quereshi et al., 2002). Diminishing marginal returns of production inputs implies that there is some level at which the benefit obtained from increasing irrigation allocation to a crop by one unit is less than the additional cost (Cheesman, 2005; Tobias and Wolfgang, 2006). As a result, when the demand for water exceeds the supply, optimal economic water application levels may be at levels below the maximum yield (Wardlaw and Barnes, 1999; Cheesman, 2005; Marques, Lund, and Howitt, 2005).

Uniformity and crop rotation play important roles in the optimal use of water in irrigation systems (Ortega et al., 2004). Under fully irrigated conditions; crop selection is usually straightforward in a given region. Crops that respond well to water are profitable and may also receive favorable government subsidies. Under limited water availability, however, the decision-making related to a given crop type is a challenge to farmers. Common questions are how to allocate limited water among crops, what other crops should be brought into the mix, how much water should be allocated to each crop, and how different energy sources will affect the profit. One approach to answer these questions is to develop an optimization methodology to find the management scenarios that can address profitability under water deficit conditions through an appropriate land/area combination.

The purpose of this study was to develop a methodology to determine the optimal crop and corresponding land area combination to achieve maximum profit under limited seasonal water supply that can be applied at regional scale farming operations. As a part of this methodology, an economic analysis was proposed to identify the influential management parameters affecting profit. Also, a risk analysis was developed to identify the failure to achieve a given revenue target under a variety of cropping systems so that farmers have adequate information to develop suitable cropping patterns to minimize future risk of failure.

Methodology

The methodology consisted of the following three modules: (1) an economic analysis to identify the influential management parameters that affect profit, (2) a risk analysis to predict the risk of not achieving a given revenue target under a variety of cropping patterns, and (3) an optimization methodology to predict the optimal crop/land area combination for maximum profit with a limited quantity of seasonal irrigation water. The methodology is demonstrated for the Bear River Valley in northern Utah where profits are subject to significant uncertainty due to yield variability, fluctuating crop market prices, increasing production costs, and limited water availability.

Economic analysis

As indicated earlier, the purpose of the economic analysis was to study the historical data to identify the most influential parameters affecting farm profitability.

The Bear River Valley of northern Utah (Figure 1) is similar to other semi-arid regions of the western United States and has several variables affecting agricultural productivity. For instance, higher yields play an important role in making farms profitable (Helms, Bailey, and Glover, 1987). Furthermore, having lower production cost does not necessarily produce more profit (Quereshi et al., 2002). By taking these

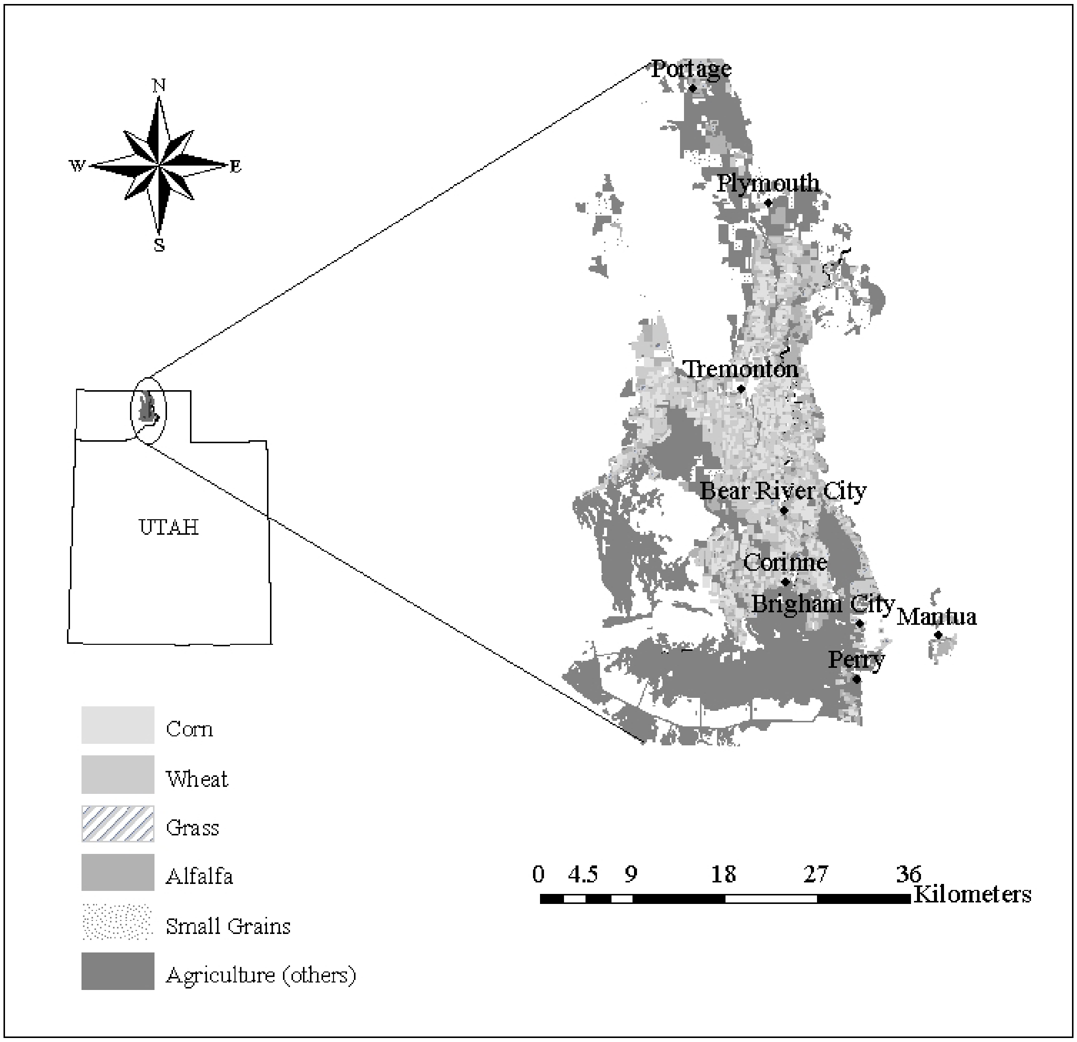

Figure 1. Layout of the Bear River Valley, Utah.

factors into consideration, the economic analysis will focus on the following management parameters: profit, yield, production cost, and price using historical data from the Bear River Valley. Field data were gathered through personal meetings with 70 farmers of Bear River Valley from 1989 to 2005. This economic analysis was applied to alfalfa, which is the major crop in the region.

Risk analysis

The purpose of the risk analysis is to determine the potential for failure to achieve a given revenue target for different cropping systems. This analysis can provide valuable information to farmers and extension services on the risk and available alternative cropping patterns to minimize the risk.

Risk is generally considered a strong behavioral force affecting decision-making. At the farm level, a higher risk may or may not accompany higher revenue alternatives. Revenue is defined as the price multiplied by yield. If higher revenue alternatives involve less or no greater risk than lower revenue alternatives, the higher revenue alternative is the obvious choice. When higher revenue alternatives involve a greater risk, a choice must be made between the two objectives.

Cropping pattern risk results from the variability of revenue over time and arises from year-to-year changes in yield and crop price. A number of risk concepts and their analytic implementations exist (Harwood et al., 1999). Often variability or a second-moment concept is used in analyzing the risk of individual activities (Freund, 1956). Another perspective of risk is how far and/or how often revenues fail to reach a below-mean target revenue level (Tauer, 1983). This approach is when the risk focus is placed on minimizing the probability of falling below a disaster target level. This approach to risk employs the Minimization of Total Absolute Deviations methodology hereafter referred to as *Target MOTAD* (Tauer, 1983; Rasyid, 1995). *Target MOTAD* is practical modeling approach with good theoretical appeal and has the ability to examine optimal combinations of cropping systems (Tauer, 1983; McCarl and Spreen, 2007; Teague, Bernardo, and Mapp, 1997; Hasanshahi, 2006; Maleka, 1993; Qiu, Prato, and Kaylen, 1998). The purpose of this task is to find the cropping pattern that gives the highest revenue and lowest risk under different management scenarios. *Target MOTAD* is capable of performing this task with good accuracy and reliability, and has been successfully used in many previous applications as indicated earlier. Details related to *Target MOTAD* are given in the next section.

The risk in this work is defined as the failure to meet an annual per-hectare revenue target due to the variability of yield and market price of two major crops, alfalfa and wheat, grown in the Bear River Valley. The production costs of these crops are steadily increasing with time, and farmers are not able to predict the yield and market prices of the crops accurately and reliably. This concern makes the profit from these two crops unpredictable and uncertain.

Monoculture crop, crop diversification, and crop rotation-diversified patterns were considered in the analysis (Helmers, Yamoah, and Varvel, 2001) using General Algebraic Modeling System (GAMS) software (Brooke, Kendrick, and Meeraus, 1996). *Target MOTAD* was used here to measure the risk as the cumulative sum of shortfalls (or negative deviations) when the annual revenues fall below a specified revenue target. The analysis was conducted using yield and price data from 70 farmers in the Bear River Valley from 1989 to 2005.

Six cropping patterns were used in the risk analysis of which four cropping patterns, monoculture alfalfa (A), monoculture wheat (W), alfalfa following wheat (A/W), and wheat following alfalfa (W/A) were based on data collected from local farmers. For alfalfa following wheat, alfalfa was grown each year but on alternating plots with wheat. This pattern is similar to the case of wheat following alfalfa. In addition, two new cropping patterns were developed and these are diversified and rotation-diversified cropping patterns. The first new cropping pattern is called diversified where different halves of the field are planted with two monoculture crops, A and W. The second cropping pattern is called rotation-diversified in which the two cropping patterns (A/W) and (W/A) are planted on two halves of the field and each crop is grown in rotation.

The series of annual revenues for a diversified cropping pattern was constructed by averaging annual monoculture alfalfa and monoculture wheat revenues from 1989 to 2005. It is termed diversified because no rotation is used, yet both crops are grown. The diversified cropping pattern could be termed 50% monoculture alfalfa and 50% monoculture wheat. Rotation-diversified cropping pattern is found by averaging the annual entries for alfalfa following wheat and wheat following alfalfa. This alternative is termed rotation-diversified because in addition to having alfalfa and wheat grown each year, each crop is grown in rotation.

Comparing the diversified risk with the rotation-diversified cropping pattern allows the identification of risks and benefits of rotation. The rotation-diversified cropping pattern involves risk/benefit from both diversification and rotation while only risk/benefit of diversification is observed from a diversification pattern. Diversification may lower risk because a year of low revenues from one crop is offset by high revenues from another crop. The risk advantage of diversification relative to a single crop cannot be evaluated using the annual physical output from each system. The reasons are (i) alfalfa and wheat have different market prices and (ii) the yields and prices of alfalfa and wheat do not move uniformly with time.

The risk analysis is expected to provide insight on combining two crops of variable risks to reduce the overall risk to an acceptable reduction of revenue. Farmers may prefer a reduced profit in exchange for lower uncertainty. The knowledge obtained from the risk assessment is used in the optimization analysis.

Target MOTAD The *Target MOTAD* is a two-attribute risk and revenue model. Revenue is measured as the sum of expected revenues of activities multiplied by their individual activity levels (Tauer, 1983). Risk is measured as the expected sum of negative deviations of the solutions from a target-revenue level. Risk is varied parametrically so that a risk-revenue frontier is traced. The *Target MOTAD* is a linear programming algorithm that has a linear objective function and linear constraints (Tauer, 1983). Mathematically, the model is stated as:

$$Max\, E(z) = \sum_{j=1}^{r} c_j X_j \qquad (1)$$

subject to

$$\sum_{j=1}^{r} a_{ij} X_j \le b_i \qquad i = 1,\ldots\ldots m \qquad (2a)$$

$$\sum_{j=1}^{r} c_{kj} X_j + y_k \ge T \qquad k = 1,\ldots\ldots s \qquad (2b)$$

$$\sum_{k=1}^{s} p_k y_k \le \lambda \qquad \lambda = \mathrm{M} \rightarrow 0 \qquad (2c)$$

$$X_j, y_k \ge 0 \qquad \text{for all j, k} \qquad (2d)$$

where *E(z)* is the expected revenue (\$); *r* is the number of activities (dimensionless); c_j is the expected revenue of activity *j* (\$/ha); *Xj* is the level of activity *j* (ha); a_{ij} is the technical requirement of activity *j* for resource or constraint *i* (in ha for land constraint and in hours for labor constraint); b_i is the limiting resource or constraint; m is the number of constraints; c_{kj} is the revenue of activity *j* for state of nature or observation *k* (\$/ha); y_k is the deviation below *T* for the state of nature or observation k (\$/ha) when *T* is the target revenue (\$/ha); *s* is the number of states of nature or observation; p_k is the probability that state of nature or observation k will occur (dimensionless); and λ is the expected shortfall defined between 0 to M ($/ha).

Equation (1) is the objective function which maximizes the expected revenue. Equation (2a) fulfills the technical constraints. Equation (2b) measures the revenue compared to the target under state k. If that revenue is less than the target T, the difference is transferred to Equation (2c) via variable y_k. Equation (2c) sums the negative deviations after weighing them by their probability of occurrence, p_r.

Land value and labor costs are represented by Equation (2a). Risk due to market price and yield ($/ha) from 17 years (from 1989 to 2005) is represented by Equation (2b). In the current analysis, two target values of $865/ha and $370/ha were used. These target values were chosen based on profits typically achieved by Bear River Valley farmers (Godfrey, Pace, and Holmegren, 2005). The expected shortfall from the target is represented by Equation (2c). The sum of negative deviations below the target T for each year is the measure of risk. The variable y_k is non-zero if the k^{th} revenue falls below T. The expected shortfall which is M in Equation (2c) is set to zero, $500/ha, and $1000/ha. Thus, the *Target MOTAD* model has two parameters relating to risk, T and λ, which must be specified. These, in turn, can be parameterized to yield different risk solutions.

Optimization analysis

As indicated earlier, the purpose of the optimization analysis is to determine the optimal crop/land area combinations for maximum profit under limited seasonal water availability. Profit is defined through production cost, yield, and market price while yield is related to water supplied. Therefore it is important to use the appropriate yield-applied water relationship in the analysis based on irrigation scheduling.

Irrigation scheduling

Irrigation scheduling is used to maintain favorable soil moisture balance in the root zone. Irrigation events can be scheduled using evapotranspiration (ET) data. ET-based irrigation scheduling is a tool that can help determine when and how much irrigation water to apply (Gary, Danny, and Briggeman, 2002). The process involves using crop water use (crop evapotranspiration), rainfall, and soil water storage to assess when an irrigation event is needed, and how much water should be applied (Allen et al., 1998).

Irrigation scheduling was used to obtain the gross applied seasonal water depth (i.e., applied water). The output from irrigation scheduling was used as input to the production function. The goal of the production function is to relate gross applied seasonal water depth and crop yield at different water distribution uniformity.

Crop production function. Irrigation water allocation becomes critical as water shortages require a refined timing of irrigation to minimize yield reductions. By allocating water at the most sensitive crop stages, the impacts on yield due to reduced water availability can be minimized (Gary, Danny, and Briggeman, 2002; English, Solomon, and Hoffman 2002; Allen et al., 1998).

Information needed to solve the problem of optimum water management consists of precise knowledge of water consumption of each crop and its response to irrigation which is called the production function. However, irrigation systems are characterized by lack of distribution uniformity when applying water. The distribution uniformity is expressed here as the coefficient of uniformity (CU) which measures how uniformly water is applied over a given area. The impact that this unequal distribution of water may have on production must be considered when determining the optimum irrigation strategies and also when selecting a crop rotation to produce the maximum economic benefits.

The term ‘production function’ describes the relationship between the response of a crop to different inputs (water, fertilizers, energy, etc.). To apply an economic maximization technique to a water production function, the knowledge of the relationship between yield and some measure of water used by the plant is required.

The relationship between yield and water use can be given (Doorenbos and Kassam, 1979),

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{z} \left(1 - k_{yi} \left(1 - \frac{ET_{ai}}{ET_{mi}} \right) \right) \qquad (3)$$

where Y_a is the crop yield (tons/ha); Y_m is the maximum crop yield under a given management scenario (tons/ha); k_{yi} is the specific yield response factor where subscript i indicates the growth and development stage (dimensionless); z is the total number of growth and development stages; ET_{ai} is the actual crop evapotranspiration for each growth and development stage i in mm; and ET_{mi} is the maximum evapotranspiration for each growth and development stage i in mm.

The production function which includes the effect of water distribution uniformity on crop yield is explained by Ortega and Trajuelo (2004), Mantovani et al. (1995), among others. When a given irrigation depth is applied to satisfy the irrigation requirement, a deficit irrigation depth is produced due to the non-uniformity of irrigation. The deficit coefficient quantifies the magnitude of this depth and the deficit coefficient is related to the evapotranspiration deficit (Reca et al., 2001; Mantovani et al., 1995). This relationship can be expressed as:

$$1-\frac{ET_{ai}}{ET_{mi}}=C_{Di}(1-\alpha_i) \tag{4}$$

where C_{Di} is the deficit coefficient for each growth and development stage i (dimensionless); and α_i is the fraction of evapotranspiration resulting from sources other than irrigation for each growth and development stage i in mm (Ortega et al., 2004). α_i is defined as:

$$\alpha_i=\left(\frac{\Delta W_i+P_{ei}}{ET_{mi}}\right) \tag{5}$$

where ΔW_i is the change in the amount of water stored in the soil for each growth and development stage i in mm; and P_{ei} is the effective rainfall for each growth and development stage i in mm.

By using Equations (3) and (4), the production function can be expressed in terms of deficit coefficient (Reca et al., 2001) as:

$$\frac{Y_a}{Y_m}=\prod_{i=1}^{z}\left[1-k_{yi}C_{Di}(1-\alpha_i)\right] \tag{6}$$

The values of k_{yi} are available for each crop from FAO 33 Publication (Doorenbos and Kassam, 1979). C_{Di} is a function of CU and the gross applied seasonal water depth and can be calculated for sprinkler irrigation systems using the procedure described by Mantovani et al. (1995) and Li (1998). Accordingly, C_{Di} is assumed constant for all irrigation events (in locations that use sprinkler irrigation) and for all growth and development stages making $k_{yi}=k_y$, $\alpha_i=\alpha$, and $C_{Di}=C_D$. Equation (6) can be used for estimating the relative yield for different gross applied seasonal water depths and C_D.

The yield-gross applied seasonal water depth relationship (or the production function) given by Equation (6) was used as an input to the optimization analysis.

Optimization methodology. The optimization analysis was conducted to maximize profit. Production costs, commodity prices, gross applied seasonal water depth and the corresponding yield, and irrigation water cost were the inputs to the optimization analysis. Crop area is the decision variable. Land area and water are considered as constraints in the analysis. The optimization analysis defined the optimal area for each crop that determines the maximum profit. The analysis was extended to include the different energy options as a part of the study objectives discussed earlier. The energy options considered here are diesel, natural gas, propane, and gasoline. Electricity is currently used by Bear River Valley farmers. The proposed optimization model can be implemented at farm- or regional-scale studies. The optimization analysis used the following objective function of maximizing profit when profit was defined as:

Profit = (commodity price) x (yield) - (irrigation cost + production cost)

$$Profit = \sum_{i=1}^{n} P_i \times Y_i \times A_i - \sum_{i=1}^{n} WC \times W_i \times A_i - \sum_{i=1}^{n} PC_i \times A_i \quad (7)$$

where i is the crop number; n is the number of crops; P_i is the price of crop i (\$/ton); Y_i is the yield of crop i as a function of gross applied seasonal water depth (tons/ha); A_i is the area of crop i (ha); WC is the cost of water (\$/m^3); W_i is the gross applied seasonal water depth to crop i per unit area (mm/ha); and PC_i is the crop production cost of crop i (\$/ha).

subject to:

Water Supply constraint:

$$\sum_{i=1}^{n} W_i \times A_i \leq TAW \quad (8a)$$

TAW is the amount of available seasonal water for irrigation, million m^3 (MCM).

Area Constraint:

$$\sum_{i=1}^{n} A_i \leq TAA \qquad (8b)$$

TAA is the total available land for cropping (ha).

Non-negativity constraint:

$$A_i > 0 \qquad i = 1, \ldots\ldots\ldots, n \qquad (8c)$$

The optimization analysis was applied to major crops of Bear River Valley which are alfalfa, corn-silage, wheat, oats, onion, and barley. The baseline water allocation of the region is based on information collected from the Utah State University Extension Program, Utah agricultural statistics, and Hill (1998). The baseline conditions assumed electricity costs for irrigation pumping to be \$0.07/kwh and a water cost of \$0.098/m^3 with electricity. Other cost information such as crop prices and production costs together with relevant references are given in Table 1. Electricity is the most prevalent energy type used in Bear River Valley. The costs of water for other energy options were obtained from University of Nebraska (2005) and these costs are identical to those available from Utah State Extension Services. The water costs when using gasoline, propane, diesel, and natural gas are \$0.145, \$0.136, \$0.113 and \$0.111 per m^3, respectively.

Study Area

Bear River Valley, shown in Figure 1, is located in northern Utah where agriculture is the primary economic activity. Alfalfa and wheat are two important crops in the Bear River Valley. The average low winter and high summer temperatures are about -10 and 32^o C, respectively while the average total precipitation is about 421 mm. There are approximately 28,935 ha of irrigated land in the Bear River Valley (USDA, 2004).

The total area of alfalfa planting is about 9618 ha. The total area of wheat planting is 9763 ha (USDA, 2004). The irrigation season usually begins early May and ends in November (Hill, Holmegren, and Reeve, 2001). Livestock and dairy operations are in abundance while dry land farming and grazing are also major agricultural activities.

The total area of agricultural land of Bear River Valley is 31,014 ha and the dry land area is approximately 2079 ha. The Bear River canal system provides 162.8 MCM of water to 26,304 ha of farmland (Hill, Holmegren, and Reeve, 2001; UDWR, 2005; Godfrey, Pace, and Holmegren, 2005). It distributes shares of water to its stockholders through a system of canals and ditches. Producers are assigned a weekly allocation which provides a predetermined stream flow over a given time period. A high peak irrigation demand usually occurs from the end of June to mid July when corn and onions need the first and second irrigation while small grains still need water. Demand tends to level off after July.

The average irrigated farm in the Bear River Valley is about 56 ha and alfalfa and wheat are the main crops followed by corn-silage, barley, oats, and onions. The range of growing season varies from 120 to 160 days. Table 1 summarizes the input information used for this study.

The information was gathered through personal communication with farmers, Utah State University Extension Specialists, and from published data of Hill (1998).

Sprinkler irrigation has been an important part of Bear River Valley's agricultural production since the 1950's (Hill, Holmegren, and Reeve, 2001; Godfrey, Pace, and Holmegren, 2005). About 65% of Bear River Valley's irrigated areas are watered with sprinklers, including hand move, wheel move, center pivot, and other types (USDA, 2005).

Table 1. Input data used in the analysis for Bear River Valley, UT for the period from 1989 to 2004 (USDA, 2005; Hill, Holmegren, and Reeve, 2001; and Godfrey, Pace, and Holmegren, 2005)

Crop	Average price (per ton)	Maximum yield (tons/ha)	Production cost range ($/ha)	Area (ha)	Approx. date of planting	Growing season length (days)
Alfalfa	$79	19	470-704	9618	April, 10	185
Corn- silage	$26.50	74	815-1112	3643	May, 10	155
Wheat	$85.12	7.1	470-642	9763	April, 8	137
Onion	$196	58.0	5137-5585	563	April, 10	135
Barley	$106.40	5.1	445-618	3534	April, 10	122
Oats	$131.60	0.4	371-519	263	April, 10	122

Results and Discussion

Economic analysis

The economic analysis is based on field data collected from 70 farms (see Table 1). Alfalfa was the crop considered in this analysis due to its dominance in the region. The influence of yield, price, and production cost on profit was investigated.

In this analysis, the average profit of each farm was calculated from 1989 to 2005 and ranked. The ranked profit was divided into three parts and is presented in Table 2. The same analysis was conducted for other management parameters (yield, price, and production cost) as well. Table 2 shows the average values of high third and low third of each management parameter. The results show a wide range for profitability and less range for other three management parameters. For example, high third and low third of profitable farms are 35.7% and 26.2% apart from the middle third. Yield and price exhibit similar ranges around 18% for the high third and around 19% for the low third. Production costs show less range (fluctuation from the middle third of around 12%).

These results show that profit variation is high among farmers of the Bear River Valley possibly due to the sensitivity of yield and price and less significant due to production cost.

Table 3 summarizes the relationship among the management parameters. It shows that high profit is related first to yield followed by price and then cost. For example, 42.2% of most profitable farms were also among the highest third of yield.

Table 2. Computed variability of management parameters from the economic analysis given as average for the group and percent change from the middle third values

Measure	High Third	Middle Third	Low Third
Profit ($/ha)	$704 (+35.7%)	$519	$383 (-26.2%)
Yield (tons/ha)	17.6 (+19%)	14.8	11.6 (-21%)
Production cost ($/ha)	$662 (+14%)	$581	$511 (-12%)
Price ($/ha)	$ 230 (+18%)	$195	$161 (-17%)

Table 3. Estimated relationship among the different management parameters

Parameter	Highest third of profit	Highest third of yield	Lowest third of cost
Yield			
Highest third	42.2%		
Lowest third	23.5%		
Production Cost			
Lowest third	30.4%	24.9%	
Highest third	18.1%	21.1%	
Price			
Highest third	36.5%	28.7%	20.3%
Lowest third	21.7%	25.4%	32.5%

This economic analysis is helpful to find practical management solutions for the parameters that affect profit. The economic analysis indicated that yield and price are important considerations to the producers. A risk analysis was conducted next to evaluate the impact of fluctuation of market price and yield on profitability.

Risk analysis

A risk analysis was conducted to estimate the revenue variability (standard deviation of revenues) for monoculture alfalfa, monoculture wheat, diversified, and rotation-diversified cropping under the market price and yield stability phenomenon. The results are given in Table 4.

In this case, diversification significantly reduces the revenue variability ($80/ha) compared to monoculture alfalfa ($131/ha) and monoculture wheat ($75/ha). This reduction is due to the offsetting phenomenon where the low revenue of one crop is compensated by the higher revenue of another crop. However, revenue variability is smaller with rotation-diversified cropping ($77/ha) than for diversified cropping.

Table 5 shows the risk calculated by totaling the dollar deficits from 1989 to 2005 (given as the summation of y_k of Equation 2b) and the corresponding expected annual revenue E(z) using *Target MOTAD*. The expected revenue E(z) is the optimum value obtained from the objective function in Equation (1).

In this simulation, two target revenues of $865/ha and $370/ha were investigated at different expected shortfalls (λ) for each cropping pattern because the choice of a target is arbitrary. The purpose of increasing the expected shortfall (λ) is to recognize its influence on the risk (the summation of yk) and expected revenue (E(z)). As shown in Table 5, the expected revenue of $770/ha is the revenue computed for monoculture alfalfa. The corresponding risk is $922/ha when the target revenue is $865/ha and the expected shortfall is zero and this value changes to $581/ha when the target revenue is $370/ha and the expected shortfall is zero.

Comparing the risk results between monoculture systems with the diversification cropping patterns demonstrates the benefits of diversification on risk. Compared to monoculture alfalfa, diversification reduces the risk from $922/ha to $663/ha using $865/ha as the risk target at zero expected shortfall. Using monoculture wheat as the comparison, diversification reduces risk from $733/ha to $663/ha using $865/ha as the revenue target. If the average risk of monoculture alfalfa and monoculture wheat ($828/ha which is the average of $922/ha from monoculture alfalfa and $733/ha from monoculture wheat) is used as a comparison point, diversification reduces risk by nearly 20%. Comparing the diversified and rotation-diversified cropping patterns indicates that risk is further decreased with the rotation-diversified cropping pattern at an additional 26.3% (from $663/ha to $488/ha) due to the enhanced yield. The overall risk from rotational cropping pattern is 40.9% of the average of monoculture alfalfa and monoculture wheat.

Table 5 shows that at zero expected shortfall and $370/ha revenue target, a dramatic reduction in risk is observed from rotation. The accumulated risks for monoculture alfalfa and monoculture wheat are $581/ha and $188/ha respectively which give an average of $385/ha. Diversification cropping results in 30.3% reduction (to $234/ha), but the rotation-diversified cropping pattern leads to a further risk reduction of 62.6% or to $144/ha. The results in Table 5 at zero expected shortfall show that the average revenue of rotation diversified cropping pattern system is $680/ha which is greater than the average revenue of diversified and monoculture cropping systems of $608 and $606/ha, respectively.

Table 4. Revenues for the period of 1989 to 2005 for four cropping patterns and the diversified and rotation-diversified patterns (A-alfalfa and W-wheat) computed from the risk analysis

	Cropping Sequences and System					
	A (Observed)	W (Observed)	A/W (Observed)	W/A (Observed)	Diversified A-W (Developed)	Rotation-diversified A-W (Developed)
	($/ha)					
1989	777	366	1176	393	571	785
1990	841	346	1087	368	594	728
1991	493	356	803	316	424	560
1992	567	449	827	473	508	650
1993	626	440	835	440	533	638
1994	830	454	969	454	642	711
1995	701	558	783	616	629	699
1996	699	544	914	565	621	740
1997	903	416	945	416	660	681
1998	837	387	837	374	612	605
1999	794	429	776	429	611	602
2000	786	439	963	482	612	722
2001	959	400	1103	359	679	731
2002	859	487	1192	561	673	877
2003	811	517	892	551	664	721
2004	817	595	1010	502	706	756
2005	996	545	1020	488	771	754
Average	782	454	949	458	618	704
Std. dev	131	75	134	84	80	77

The results in Table 5 at zero expected shortfall show that the average revenue of rotation diversified cropping pattern system is $680/ha which is greater than the average revenue of diversified and monoculture cropping systems of $608 and $606/ha, respectively. Therefore, it is obvious that the average revenue has improved when rotation-diversified cropping system is used.

When the analysis was conducted for higher expected shortfalls of $500/ha and $1000/ha, the results were similar where higher expected shortfalls produce higher revenue but at a higher risk.

Table 5. Estimated expected revenue (E(z)) and risk using *Target MOTAD* for monoculture, diversified, and rotation-diversified cropping patterns

	Expected Revenue	Computed Risk ($/ha) at different target revenues: Target $865/ha	Target $370/ha
	---------------------$/ha------------------		
	Expected shortfall of $0.0/ha		
Monoculture cropping system			
Alfalfa (A)	770	922	580
Wheat (W)	441	733	188
Diversified cropping system			
Alfalfa-wheat (A-W)	608	663	234
Rotation diversified cropping system			
Alfalfa-wheat (A-W)	680	488	144
	Expected shortfall of $500/ha		
Monoculture cropping system			
Alfalfa (A)	1305	1389	981
Wheat (W)	979	1166	408
Diversified cropping system			
Alfalfa-wheat (A-W)	1203	1159	502
Rotation diversified cropping system			
Alfalfa-wheat (A-W)	1315	1016	415
	Expected shortfall of $1000/ha		
Monoculture cropping system			
Alfalfa (A)	1861	1841	1441
Wheat (W)	1394	1535	820
Diversified cropping system			
Alfalfa-wheat (A-W)	1569	1717	1063
Rotation diversified cropping system			
Alfalfa-wheat (A-W)	1782	1488	956

Optimization analysis

Crop water production function. The simulated relationship between the gross applied seasonal water depth and yield for alfalfa and corn-silage is shown in Figure 2.

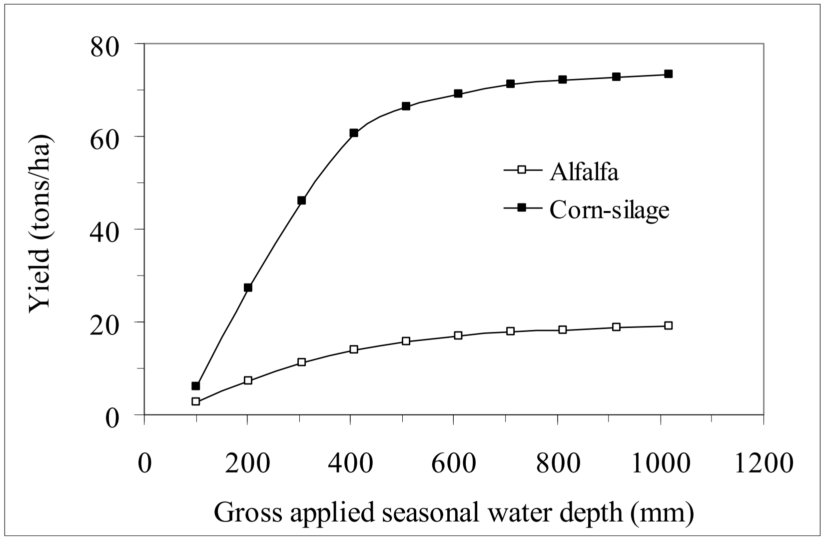

Figure 2.Computed variations between crop yield and gross applied seasonal water depth at 75 percent of CU using the crop water production function given in Equation (5).

Similar relationships for wheat, oats, barley, and onion were obtained but not presented here. The results of yield vs. gross applied seasonal water depth at 75% of CU, were used in the optimization analysis. A CU of 75% was used because the uniformity of sprinkler systems in the Bear River Valley is around 75% (Hill, Holmegren, and Reeve, 2001).

It was found that the coefficient of deficit is becoming smaller when the CU is increasing. In addition, crop yield is increasing with increasing of CU. For example, it was established that at a gross applied seasonal water depth of 609.6 mm to alfalfa, the CD is 0.267, 0.209, and 0.16 for CUs of 55, 75, and 95%, respectively. The corresponding alfalfa yields are 13.8, 15.3, and 18.0 tons/ha, respectively.

Optimal scenarios

Table 6 shows the crop water allocation for dominant crops under different energy options. As an example, when electricity is used (i.e., the baseline conditions), the profit is $12.28 million across 26,304 ha subject to the availability of 162.8 MCM of water.

Under the baseline conditions, the optimization analysis allocated a high area and a water supply for alfalfa at 20,032 ha and 135 MCM volume followed by corn-silage and wheat. The results also show that the existing area allocation for wheat is 9763 ha and optimization reduced this to around 1465 ha due to the low profit generation capacity. This reduction in area allowed the increase of alfalfa area from 9618 ha to around 19,829 ha. Table 6 also shows the crop water allocation when using different energy options.

Introduction of different energy options resulted in no significant differences in the distribution of land area per crop. Therefore it can be concluded that the optimal cropping pattern is sensitive if the cost of water is significant when compared to the crop price. The total profit at baseline conditions is $12.28 million which is the highest profit among all energy options in Table 6. With a given amount of water of 162.8 MCM, it is possible to increase the profit by extending the cropped area to 28,935 ha with deficit irrigation.

Deficit irrigation refers to increasing the irrigated area by introducing crops with low water requirements or reduced water application. For instance, the baseline conditions indicate that 162.8 MCM of water and about 26,304 ha as given in Table 6.

Table 7, however, shows an area increase to 28,935 ha is possible with deficit irrigation, resulting in 7.2% ($12.28 to 13.17 million) increase of total profit under the baseline conditions. Table 7 also shows the crop water allocation with different energy options. For example, alfalfa can use a reduced gross applied seasonal water depth of

609.6 mm instead of 660.4 mm as per Figure 2. The corresponding yield reductions for the remaining crops under deficit irrigation were computed from Equation (5).

Table 7 shows that for the baseline conditions, a total profit increase to $13.17 million can be achieved by extending the total area to 28,935 ha if 162.8 MCM of water are available. Under the baseline scenario, the optimization analysis allocated high crop area and water for alfalfa with 22,365 ha and 137.6 MCM of water followed by corn-silage and wheat. As shown in Table 7, introduction of different energy options resulted in no significant differences in the distribution of area per crop.

Figure 3 shows the total profit when using different sources of energy at a fixed water volume of 162.8 MCM for different agricultural areas. The results show that the total profit is proportional to the area to about 28,327 ha and thereafter, less sensitive to the area. For instance, a total profit is $12.2 million for 26,304 ha and 162.8 MCM under the baseline conditions. The profit increased to $13.17 million under 28,935 ha with the same water volume of 162.8 MCM. Figure 3 also showed the profit variation with different energy options.

Figure 3 indicated that the total profit for the baseline conditions is higher than the total profit with other energy options. Diesel, natural gas, and propane are the second, third, and fourth most profitable options, respectively. Gasoline is the least profitable energy option.

Table 8 shows the results of the optimization analysis for different available seasonal water corresponding to 148 and 172.6 MCM. Between the two scenarios, it is seen that the area of alfalfa remained almost the same at around 74.6% of the total area.

Table 6. Estimated optimal allocation of water and area between different dominant crops of Bear River Valley under different energy options. The available water is 162.8 MCM and the land is 26304 ha

		Crop						Profit
		Alfalfa	Wheat	Corn-silage	Barley	Oats	Onion	(million $/year)
Electric (existing situation)	Area (ha)	20032	1465	3005	830	792	180	
	Water (MCM)	135	5.6	15.1	3.2	3.0	1.02	12.28
Diesel	Area (ha)	20074	1339.5	3082	884	782.6	141.6	
	Water (MCM)	135.6	5.1	15.03	3.37	2.98	0.73	11.64
Propane	Area(ha)	20032	1464.9	3005	829	792.4	180	
	Water (MCM)	134.9	5.58	15.1	3.16	3.02	1.02	10.73
Natural gas	Area (ha)	20034	1380	3082	884	782.6	141	
	Water (MCM)	135.5	5.26	15.03	3.37	2.89	0.73	11.75
Gasoline	Area (ha)	20022	1444.7	3005	839.7	812.6	180.1	
	Water (MCM)	134.92	5.5	15.1	3.2	3.1	1.02	10.32

Table 7. Estimated optimal allocation of water and area between different dominant crops of Bear River Valley under different energy options. The available water is 162.8 MCM and the irrigated land is 28935 ha

		Crop						Profit
		Alfalfa	Wheat	Corn-silage	Barley	Oats	Onion	(million $/year)
Electric (existing situation)	Area (ha)	22365	1659	2800	1032	923	156	
	Water (MCM)	137.6	5.56	12.34	3.46	3.09	0.79	13.17
Diesel	Area (ha)	22047	1631	2982	1101	1044	130	
	Water (MCM)	136	5.47	13.14	3.7	3.5	0.66	12.65
Propane	Area(ha)	22250	1750	2902	950	923	160	
	Water (MCM)	137	5.87	12.78	3.19	3.09	0.81	11.54
Natural gas	Area (ha)	22007	1671	2983	1100	1044	129	
	Water (MCM)	136	5.6	13.14	3.69	3.5	0.66	12.72
Gasoline	Area (ha)	22209	1760	2902	963	941	160	
	Water (MCM)	136.5	5.9	12.78	3.23	3.51	0.81	11.17

The increase in profit by 23.5% was achieved by reallocation of the remaining area among other crops. For example, corn-silage area increased from 10.8 to 13.4%. When 148.0 MCM of water was available, the total profit was $11.23 million, while this profit can be $13.87 million (23.5% higher) with 172.6 MCM of water.

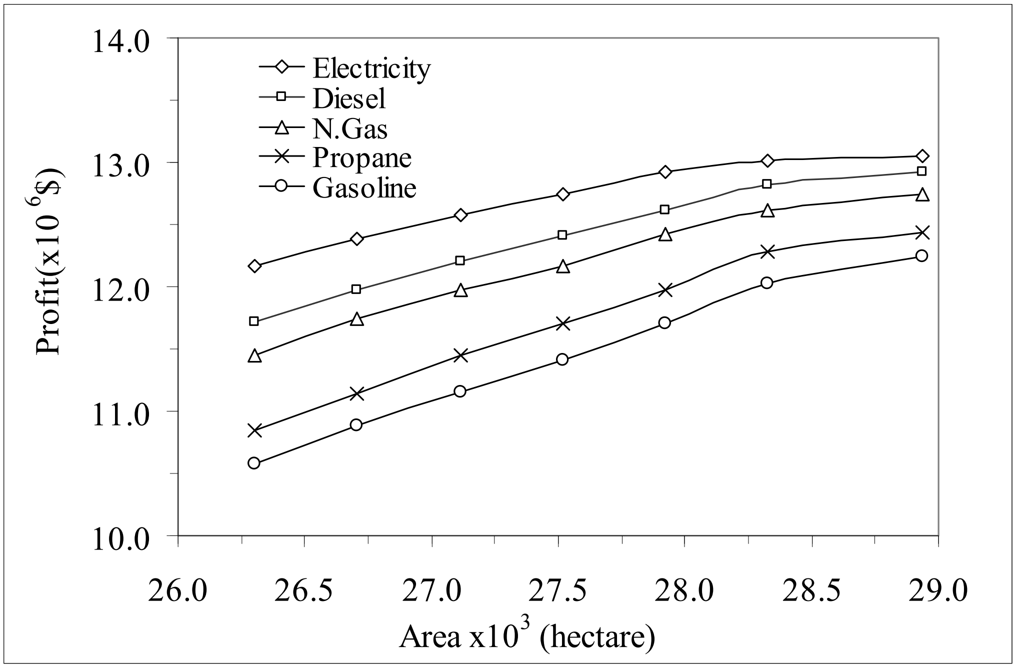

Figure 3. Variation of maximum profit with the corresponding optimal land area for different energy options with a fixed amount of available seasonal water of 162.8 MCM. Solutions obtained from the LP-based optimization.

It is established that alfalfa is the most profitable crop in the region under a variety of management scenarios. The large livestock and dairy farm industry encourages the Bear River Valley farmers to increase the alfalfa area to satisfy the local demand of the livestock industry, as well as providing exports to other regional livestock markets.

Summary and Conclusions

This work proposed a methodology to maximize profitability under water scarcity considering alternative farming practices and variability in yield and market price. The proposed methodology introduced several important concepts in decision analysis pertinent to agricultural water management and risk reduction in achieving a given revenue target. The proposed methodology estimates the maximum profit (i.e. net return) for a given water allocation, land area, crop pattern, and energy alternatives.

Table 8. Estimated optimal allocation of water and area for scenarios of 148.0 MCM and 172.6 MCM of available seasonal water and a total available area of 26304 ha

Crop	148.0 MCM				172.6 MCM			
	Area (ha)	Water volume (MCM)	% supply	% Area	Area (ha)	Water volume (MCM)	% supply	% Area
Alfalfa	19614	122.3	82.6	74.6	19485	140.1	81.2	74.1
Corn-silage	2841	12.5	8.5	10.8	3533	18.8	10.9	13.4
Wheat	1748	5.9	3.9	6.6	1449	5.7	3.3	5.5
Barley	991	3.3	2.3	3.8	830	3.5	2.0	3.2
Oats	938	3.1	2.1	3.6	799	3.3	1.9	3.0
Onion	172	0.8	0.57	0.65	208	1.1	0.66	0.79
Profit (million $/year)	11.23				13.87			

The applicability of the methodology was demonstrated for Bear River Valley, Utah where water is scarce and profit is constantly under threat due to price fluctuations and yield variations.

A statistical analysis was performed to identify the significant parameters that affect agricultural profitability of Bear River Valley. A risk analysis was performed on the two most influential parameters that have the highest impact on profit. The methodology estimates the economic loss or risk due to the variability of yield and price (i.e. market price) of major crops such as alfalfa and wheat. The optimization analysis was used for crops, land area, and water availability of Bear River Valley to demonstrate the decision-making capability of the analysis to determine the optimal irrigated cropping pattern under water scarcity.

The analysis indicated that yield and price have the highest impact on profit in the agricultural production of the Bear River Valley. The results also indicated that it is important to focus on yield and price first, followed by production cost when maximizing profit.

A risk analysis was conducted to estimate the risk of revenue loss due to the variability of yield and price of two major crops, alfalfa and wheat. Risk was defined as the cumulative revenue deficits relative to a revenue target based on data from a 17-year period. It was concluded that crop rotation of alfalfa and wheat has significant risk advantages over monoculture production. A part of reduced risk resulted from diversification inherent in rotation. *Target MOTAD* was used to examine whether alfalfa–wheat rotation reduced yield and price variability compared to a system of 50% monoculture alfalfa and 50% monoculture wheat. It was found that rotation led to a decrease of risk more than crop monoculture and diversification cropping systems. Thus, alfalfa–wheat rotation had significant risk advantages over monoculture production and diversification cropping production because of enhanced yield and price offsetting ability.

The optimization analysis estimated the economic impacts of various management options available to the farmers of the Bear River Valley. The results provide several important practical insights into the relationship between available irrigation water and agricultural production in the region. The optimization analysis developed scenarios for maximizing profit per unit of water used. The irrigation depth reported by the optimization analysis was less than the applied irrigation depth. This result produced an increase in the total irrigated area leading to a higher profit. Any increase in the total area beyond 28,935 ha with 162.8 MCM of available water will impact the applied water depth and reduce the profit. It was shown that alternative sources of energy decreased the profit. As an example, the total profit decreased 3.9% with diesel, 11.9% with propane, 3.4% with natural gas, and 11.6% with gasoline compared to the use of electricity.

The results can also help single farmers to reduce the area of planting crops which are sensitive to water shortages such as alfalfa and corn-silage and replace these with crops less sensitive to water shortages such as barley, oats, and wheat. This analysis can help farmers to irrigate more land through deficit irrigation. This study helps farmers decide which crop to plant under different water availability scenarios. The results of the proposed methodology provide insight for farmers into optimal amounts of water to be apportioned to each crop, and what proportion of land should be devoted to each crop in a water shortage scenario. This information will allow irrigation of maximum area of farmland. This study permits the selection of optimum irrigation treatments using a small amount of information typically available to the farmers. In areas where water availability is limited, this study can also aid in evaluating economic benefits for a given water availability, and fluctuations in yield and price.

The work has limitations that should be addressed in future studies. One limitation of this work is the lack of published data and information. Most information and data were gathered through personal communication with farmers and Utah State University Extension Specialists. Another drawback is the limited number of farmers that have been interviewed. A comprehensive data collection should be conducted in future research to guarantee that the collected data and information is representative of all farmers. Another limitation is the short time period of collected data. Since agricultural practices and farmer preferences can vary with time, the data and information should be collected over an extended period of time.

CHAPTER IV

TREATED WASTEWATER USE IN WATER DEFICIT REGIONS FOR AGRICULTURE: ECONOMIC, ENVIRONMENTAL, AND PUBLIC HEALTH ISSUES

Abstract

Coastal regions such as Gaza Strip of Palestine with limited freshwater supply suffer significantly due to the rapid depletion of water levels, seawater intrusion, poor water quality, and increased water demands. In such regions, use of treated wastewater is a viable option if public health issues are addressed. The goal of this chapter is to address the use of treated wastewater in agriculture while considering profitability, economic efficiency of water use, environmental goals, and public health risks. The proposed methodology considers public health risk assessment and multi-criteria decision analysis while assessing the beneficial use of treated wastewater in aquifer recovery. The methodology was demonstrated for Gaza Strip. The health risk assessment suggests that increasing the elapsed time between irrigation and consumption and switching from sprinkler and drip irrigation are practical measures to reduce public health risks. The optimization and decision analyses show that proper allocation of freshwater and treated wastewater and distribution of land area by crop type can significantly increase profitability and economic efficiency of water use. In most cases, profitability increased by 44%, groundwater use diminished by 29% while increasing the economic efficiency of water use by three fold compared to the existing conditions. The multi-criteria decision analysis with weighted goal programming can develop flexible management options that considers a given decision-maker preference. When groundwater abstraction for

agriculture reduced from 57 to 36 million m^3 as per the decision analysis, the corresponding areas of groundwater elevation below mean sea level decreased by 58% indicating significant aquifer recovery.

Introduction

Treated wastewater is a non-conventional water resource may be a potential alternative that may satisfy agricultural water demand and simultaneously save fresh water for domestic use. The need for resources such as treated wastewater is important given that more than 70% of fresh water in the world is used for irrigation in developed countries and over 90% is used in low-income developing countries (Meinzen and Rosegrant, 2001). Treated wastewater use in agriculture must be seriously considered in regions with limited fresh water resources affected by increasing demand for domestic water use and are expected to face a deficit in water supply.

Fresh water is a scarce resource in semi-arid regions and these regions typically have groundwater as the major source of water. In semi-arid coastal regions, groundwater abstraction for agriculture may produce sea water intrusion and degrade water quality. In the absence of sound policies and effective development plans, the amount of good-quality groundwater will likely decrease with time making it less available for water users. Use of treated wastewater for irrigation would reduce the degradation of groundwater quality, enhance aquifer recovery, and reduce sea water intrusion. However, use of treated wastewater in agriculture requires a comprehensive policy and an institutional framework to minimize public health concerns. Public health risk from the use of treated wastewater should be seriously considered since wastewater is known to contain viruses and potentially, other pathogens (Toze, 2006). Use of treated wastewater in agriculture may provide the benefit of aquifer recovery due to the reduced fresh water abstraction. One additional benefit may be the increased economic efficiency of water use which is defined as net benefit per unit volume of water consumed.

Most decision-making processes in agriculture attempt to satisfy economic and social criteria according to the farmers' viewpoint while ignoring other important aspects such as treated wastewater use, public health risk, and limited groundwater availability (Gomez-Limon and Berbel, 2000; Sumpsi, Amador, and Romero, 1996; Gomez-Limon, Arriaza, and Berbel, 2002). A more comprehensive approach is needed to evaluate all interrelated issues related to improved agricultural water management such as treated wastewater use, public health risk, water use efficiency, and profitability. One obvious approach to analyze these conflicting interests in agricultural water management is the use of multi-criteria decision-making approaches (Tiwari, Loof, and Paudyal, 1999).

Public health risk

Use of treated wastewater for agriculture may be an important strategy that will lead to reducing the water deficit. However, agricultural products irrigated with treated wastewater may pose an unacceptable health risk to consumers. Therefore, a health risk assessment is crucial to develop effective policy and provide important information to the decision-makers.

The purpose of health risk assessment is to quantify the risk due to the consumption of products irrigated with treated wastewater. Although risks for farmers and workers are not in the scope of this study, it is recognized that the risk to those working with irrigation water and irrigated crops may experience some risk. While the use of treated wastewater is economically efficient, transmission of pathogens increases the probability of waterborne diseases such as typhoid, bacillary dysentery, cholera, gastroenteritis, infection hepatitis, meningitis, and legionnaires' disease (Bitton, 2005; Stagnitti, 1999; Toze, 2006). Communities consuming raw agricultural products such as vegetables and fruits irrigated with treated wastewater may ingest viral bacterial and protozoan pathogens. In this study, ingestion of rotaviruses or the dose of rotaviruses is defined by the number of rotaviruses ingested due to the consumption of products irrigated with treated wastewater.

Several studies focused on health risk assessment of wastewater use in agriculture (Asano et al., 1992; Rose et al., 1996; Shuval, Lampert, and Fattal, 1997; Tanaka et al., 1998). While these studies provided a good understanding of the importance of health risk assessment, the studies provided little attention to the exposure levels and related health risk assessment for consumption of agricultural products irrigated using treated wastewater. Instead, previous studies focused on the impacts of different irrigation methods on health risk which is important in exposure estimates (Shuval, Lampert, and Fattal, 1997; Tanaka et al., 1998). Other studies estimated the health risk due to an accidental ingestion of 100 mL of irrigation water per year (Rose et al., 1996). This study is focused on the use of treated wastewater in irrigated agriculture on crops adaptable for treated wastewater, the type of irrigation method, the time between last irrigation and consumption, and treatment efficiency of wastewater for pathogen removal.

Agricultural water allocation

The purpose of this task is to find the interaction between common competing objectives in agricultural production when treated wastewater is available as a supply source. Typical competing objectives in agricultural production are profitability, water use efficiency and use of limited available water. When treated wastewater is introduced as an alternative source, public health concerns become major constraints driving agricultural water allocation policy while affecting profitability and water use efficiency. Farmers have profit as the major interest while the decision maker's main interest is the protection of the environment against short and long term effects of agricultural practices. Increased population leads to increased water demand. Increasing the use of treated wastewater for agriculture can decrease the stress on groundwater by replacing an equal quantity that would have been extracted from the aquifer otherwise. However, a policy that encourages the use of treated wastewater in agriculture should be formulated after careful consideration on the issue of public health concerns. The level of acceptance of Gaza farmers to use treated wastewater for irrigation is around 60% (Ouda and Bardossy, 2003).

Several earlier studies have guided the development of this work. For instance, Brimberg, Oron, and Merhrez (1993) developed a water resources management model that considers saline groundwater, treated wastewater, and rainfall harvesting in the Negev desert, Israel. Raju and Kumar (1999) developed a multi-criteria decision-making model for irrigation planning. Prasad, Sinha, and Rai (2001) developed a multi-criteria optimization model that produces optimal crop patterns under constraints of limited water sources for the Ranchi basin, India. Latinopoulos and Mylopoulos (2005) developed a multi-criteria model for optimal allocation of land and water resources in irrigated agriculture using goal programming methods. Ouda and Bardossy (2003) described a model aimed at maximizing profit and minimizing seasonal groundwater use.

These studies focused on the economics of irrigation planning as a major issue, but ignored the public health risk due to the use of treated wastewater, and economic efficiency of water use. Also semi-arid coastal regions typically have other groundwater issues such as deterioration of groundwater quality due to seawater intrusion (Yakirevich et al., 1998; Saleh, 2007; Issac, 2000). Such water quality issues can play a major role in agricultural water allocation and policy development that needs to be considered in research efforts.

When considering the use of treated wastewater, competing and conflicting objectives occur. These include economic objectives such as profitability and economic efficiency of water use, the environmental objective of satisfying groundwater quality, and the public health objective of minimizing public health risks due to pathogens in treated wastewater. In developing a strategy to address these competing and conflicting issues, a multi-criteria decision analysis within an optimization framework will be needed. Therefore the overall goal of this work is to develop a detailed methodology to address agricultural water allocation strategies in semi-arid regions with limited water availability under competing and conflicting economic, environmental, and public health objectives.

For the purpose of demonstrating the proposed methodology, this study will use Gaza Strip of Palestine as the study area. Gaza is a classic region experiencing multiple concerns related to the expansion of agricultural sector, population growth, limited land area, and lack of freshwater. As a result of unmanaged groundwater withdrawal from the coastal aquifer, seawater intrusion is occurring at an alarming rate while the groundwater levels are declining rapidly. Increasing population growth in the region is producing unsustainable agricultural and domestic water demands. Therefore, the use of treated wastewater to supplement freshwater supply is an attractive option that can also help reduce seawater intrusion and increase aquifer recovery.

The proposed methodology provides one of the few applications that consider treated wastewater, public health risk and economic aspects in agricultural planning. This study consists of three parts: (1) public health risk assessment due to the exposure to crops irrigated with treated wastewater, (2) single objective optimization and a multi-criteria decision-making analysis consisting of weighted goal programming to assess five common objectives in agricultural productions, and (3) the beneficial impact of aquifer recovery through reduced abstraction of groundwater with the use of treated wastewater.

Methodology

The methodology consists of three steps. The first step is the public health risk assessment due to the consumption of products irrigated with treated wastewater. If the expected health risk is acceptable, the use of treated wastewater is safe. The health risk assessment will provide the elapsed time between the last irrigation and consumption and the corresponding concentration of viruses at consumption with treatment of wastewater. This information will be used later in the optimization analysis. The second step is a detailed optimization analysis combined with multi-criteria decision analysis using weighted goal programming. The third step is to find the beneficial effect of reduced groundwater abstraction from the coastal aquifer by computing the groundwater recovery under reduced pumping.

Public health risk assessment

The purpose of the risk assessment is to quantify the health risk due to the exposure to products irrigated with treated wastewater. The analysis will find the best irrigation method, treatment level for wastewater, and the elapsed time between last irrigation and consumption of products irrigated with treated wastewater. Since some of the variables defining the exposure and dose-response models are uncertain, the Monte Carlo method was used to quantify the risk exposure to the consumers.

Exposure model. Exposure is defined as a series of occurrences in which a person or members of a community comes into contact with biological, chemical, or physical agents (Hammad and Manocha, 1995; Ginneken and Orron, 2000). Ingestion is the route of exposure of greatest concern to reclaimed wastewater for humans. Assessment of the exposure of a community to wastewater should consider the type of wastewater treatment, virus migration route from irrigation wastewater to and within the plant; virus die-off during the period between the last irrigation and consumption; and the consumption pattern of the population (WHO, 1989; US EPA, 1992). Rotaviruses are considered in this study because they can cause digestion, absorption problems; though usually present in lower numbers than other pathogens such as salmonella and enteroviruses in contaminated food (US EPA, 1992; Mara et al., 2007). Rotaviruses are also responsible for outbreaks among adult populations and are a major cause of travelers' diarrhea (Bitton, 2005). Rotaviruses are known to survive wastewater treatment. The route of exposure is typically to a human adult, who relies completely on effluent-irrigated crops for dietary intake of fruits and vegetables. This study considers no cross-contamination of crops after harvesting. In this work, rotavirus was used as the representative pathogen affecting public health from the consumption of contaminated food products. The exposure due to ingestion of contaminated food can be estimated as the product of contaminant concentration in the consumed food and the amount of food consumed per day (Hammad and Manocha, 1995). The number of rotaviruses consumed per day (λ) is calculated as:

$$\lambda = Z \times M_{body} \times c_w \times V_{prod} \times e^{(-kt)} \qquad (9)$$

where λ is the daily dose of rotaviruses (plaque forming units (PFU)/person-day); Z is the daily food consumption per person per kg of body mass (g/kg-person-day); M_{body} is the body mass (kg); c_w is the concentration of rotaviruses in irrigation water (PFU/mL); V_{prod} is the volume of irrigation water consumed by a given product (mL/g); k is the 1st order virus decay constant (day^{-1}); and t is the time between last irrigation event and consumption (days). This exposure model was coupled with the dose-response model given below to compute the annual risk of infection (Mara et al., 2007).

Dose response model. The dose response model uses a Beta-Poisson function for rotavirus infection given as (Haas, Rose, and Gerba, 1999);

$$P_I(\lambda) = 1 - \left[1 + (\lambda / ID_{50})(2^{1/\alpha} - 1)\right]^{-\alpha} \qquad (10)$$

The annual risk of infection is given as

$$P_{I(A)}(\lambda) = 1 - \left[1 - P_I(\lambda)\right]^n \qquad (11)$$

where $P_I(\lambda)$ is the daily risk of infection by ingestion of rotaviruses; ID_{50} is the median infective dose; and α is the pathogen 'infectivity constant'; $P_{I(A)}(\lambda)$ is the annual risk of infection by ingestion of rotaviruses; and n is the total number of days in a given year. The value of $P_{I(A)}(\lambda)$ is in the range 0 to 1. If $P_{I(A)}(\lambda)=1$, infection is certain (Hass, Rose, and Gerba, 1999). The values of ID_{50} and α for rotavirus are 6.17 and 0.253, respectively (Hass, Rose, and Gerba, 1999).

A disease risk of 10^{-3} per person per year is used by WHO (2004) as the tolerable risk of waterborne disease from products irrigated with treated wastewater. This value indicates that 1 per 1,000 individuals per year may be infected from to rotavirus contaminated food. This level of disease burden is equivalent to a mild illness (e.g., diarrhea) according to Ward et al. (1989).

Wastewater treatment efficiency. Wastewater treatment consists of primary, secondary, and tertiary treatment options. In this study, rotavirus content was used as the removal efficiency measure. The virus concentration in treated wastewater c_w is calculated using the following equation:

$$E_R = (c_o - c_w) \times 100 / c_w \qquad (12)$$

where E_R is the virus removal efficiency (%); and c_o is the virus concentration in raw wastewater (PFU/L). Virus removal efficiency at the primary treatment stage is relatively low around 50% (Yates and Gerba, 1998; Feachem et al., 1983). The removal efficiency with primary and secondary stages for oxidation pond, trickling filter, and activated sludge are estimated at 80, 85, and 90%, respectively (Yates and Gerba, 1998). Typically secondary treatment, consisting of biological treatment, provides higher removal efficiency. Complete treatment, consisting of primary, secondary, and tertiary treatment phases, can improve removal efficiency to 95, 98, and 99.9% for oxidation ponds, trickling filter, and activated sludge, respectively (Yates and Gerba, 1998; Leong, 1983). Disinfection is considered to be a tertiary treatment in many parts of the world including the Gaza Strip. Tertiary treatment is conducted to reduce the number of pathogens in water. Common methods of disinfection include chlorine and ozone.

Volume of irrigation water diverted. Volume of irrigation water diverted to the crops, V_{prod} (ml/g), is given as (Gardner, Pearce, and Mitchell, 1984)

$$V_{prod} = \frac{ET_a / E_a}{Y_a} \qquad (13)$$

where ET_a is the crop evapotanspiration (m^3/ha); E_a is the irrigation efficiency (%); and Y_a is the crop yield (tons/ha). E_a is about 85, 70, and 60% for drip, sprinkler, and surface irrigation systems, respectively. V_{prod} is an input to the exposure model given by Equation (9). In the exposure model, more use of treated wastewater produce higher public health risk. In the case of surface irrigation, more treated wastewater is used due to poor efficiency and the water is used directly by the roots. In case of sprinkler irrigation, treated wastewater is used by roots and leaves and therefore, the pathogen contact is produced inside the crop product as well as the outside surface of the crop product. This exposure model does not differentiate between these two mechanisms of contact of pathogens in producing the public health risk from the consumption. In essence, the explicit risk of exposure to a given type of irrigation system is not defined. This is a major limitation of the exposure model used here.

Pathogen decay. Under adequate environmental conditions, rotavirus can survive for several months (Feachem et al., 1983) based on surrounding conditions such as moisture, temperature, and pH. The fate of pathogens in the environment is usually represented by 1st order decay kinetics given as follows:

$$c_c = c_w \times [exp(-kt)] \tag{14}$$

where c_c is the virus concentration at elapsed time t after irrigation or at consumption (PFU.L^{-1}); and t is the elapsed time between the last irrigation and consumption (days). The mean and standard deviation of decay constant of viruses are 1.07 and 0.07 d^{-1}, respectively (Hamilton et al., 2006).

The Monte Carlo method was used to study the uncertainty of annual risk of infection, rotavirus concentration at consumption, and time between irrigation and consumption under different treatment levels and irrigation methods (Thompson, Burmaster, and Crouch, 1992). The variable input parameters include rotavirus concentration of applied wastewater, human body weight, and kinetic decay coefficient. The number of random runs used was 10,000.

Agricultural water allocation

The methodology consisted of two parts. In the first part, a series of single objective optimization analyses will be conducted for common objectives sought by farmers and regulators. These objectives will address profitability, use of groundwater and treated waste water, salinity load, and economic efficiency of water use. The second part will be a multi-criteria decision analysis where the decision-maker preference is considered. The details related to each analysis will be discussed next.

Single objective optimization. These single objective functions address (1) annual profit (\$/year); (2) annual treated wastewater use (m^3/year); (3) annual groundwater use (m^3/year); (4) annual salinity load resulting from groundwater and treated wastewater (kg/year); and (5) economic efficiency of water use (\$/m^3). The next section provides the details related to each objective function followed by model constraints:

Annual profit: The objective is to find the optimal cropping pattern that generates the maximum annual profit (\$/year) while satisfying a set of constraints. The mathematical representation is given as

$$Max\ profit = \left(\sum_{i=1}^{m} P_i \times A_i \times (Y_{iavg}) - \sum_{i=1}^{m} PC_i \times A_i - \sum_{i=1}^{m} GWC \times A_i \times (CWR_{iavg}) - \sum_{i=1}^{m} WWC \times WWUI_i \times A_i \times (CWR_{iavg}) \right) \tag{15}$$

where i is the crop type; m is the total number of crops; P_i is the market price of crop i (\$/ton); A_i is the area of crop i (ha); Y_{iavg} is the average yield of crop i (tons/ha); PC_i is the production cost of crop i (\$/ha); GWC is the groundwater cost (\$/m^3); CWR_{iavg} is the average crop water requirement of crop i (m^3/ha); WWC is the treated wastewater cost (\$/m^3); and $WWUI_i$ is treated wastewater use index, which is 1 for crops capable of using treated wastewater and zero for other crops (Khalil, Al-Dadah, and Yassin, 2003; Metcalf and Eddy, 2000). The crop area (A_i) is the decision variable. It should be noted that treated wastewater cannot be tolerated by all crops. In the demonstration example, such crops will be identified and used accordingly in the analysis. The data used in the analysis were from 2000 to 2006.

<u>Economic efficiency of water use:</u> The purpose is to identify the optimal cropping pattern that provides the maximum economic efficiency of water use, $EEWU$ (\$/m^3) from irrigated agriculture (Cai, Rosegrant, and Ringler, 2003) while satisfying the model constraints. The mathematical formulation is given as:

$$Max \quad EEWU = \left(\sum_{i=1}^{m} P_i \times A_i \times (Y_{iavg}) - \sum_{i=1}^{m} PC_i \times A_i - \sum_{i=1}^{m} GWC \times A_i \times (CWR_{iavg}) - \sum_{i=1}^{m} WWC \times WWUI_i \times A_i \times (CWR_{iavg}) \right) \Big/ \left(\sum_{i=1}^{m} (CWR_{iavg}) \times A_i \right) \quad (16)$$

<u>Annual volume of treated wastewater use:</u> The purpose is to find the optimal cropping pattern that maximizes the quantity of treated wastewater use, TWU (m^3/year). The mathematical formulation can be given as:

$$Max \quad TWU = \sum_{i=1}^{m} (CWR_{iavg}) \times A_i \times WWUI_i \quad (17)$$

Annual groundwater abstraction: The purpose is to find the optimal cropping pattern that gives the allowable maximum groundwater abstraction *GWU* (m^3/year) for agriculture. The mathematical formulation can be given as:

$$Max\ GWU = \sum_{i=1}^{m}(CWR_{iavg}) \times A_i - \sum_{i=1}^{m}(CWR_{iavg}) \times A_i \times WWUI_i \tag{18}$$

Annual salinity load: The purpose is to find the optimal cropping pattern that minimizes the total annual salinity load from applied water to irrigated agriculture. The salinity load is dependent on the crop water requirement of each crop and the total dissolved solids (TDS) concentration in groundwater and treated wastewater. A crop cultivated with water of low quality and high irrigation demand will produce a high salinity load. The mathematical formulation can be given as:

$$Min\ SL = \sum_{i=1}^{m}(SL_{iavg}) \times A_i \tag{19}$$

where *SL* is the salinity load (kg/ha); and SL_{iavg} is the average salinity load of crop *i*. The salinity load is the TDS (mg/L) multiplied by the crop water requirement of each crop.

Model constraints. The model constrains for these five objective functions are the same and given as follows:

Available agricultural area: This constraint ensures the total cropping area is within the total available agricultural area, *TAA* (ha) and given as:

$$\sum_{i=1}^{m} A_i \leq TAA \tag{20a}$$

Available groundwater quantity: Groundwater used for irrigation should not exceed the available ground water quantity, *AGW* (m^3/year) and can be expressed as:

$$\sum_{i=1}^{m} CWR_{iavg} \times A_i - \sum_{i=1}^{m} WWUI_i \times CWR_{iavg} \times A_i \leq AGW \tag{20b}$$

Available treated wastewater quantity: The total treated wastewater demand should be less or equal to available treated wastewater, *ATWW* (m^3/year) and given as:

$$\sum_{i=1}^{m} CWR_{iavg} \times WWUI_i \times A_i \le ATWW \tag{20c}$$

Salinity load: To calculate the maximum salinity load (*MSL,* kg/year), a 10% reduction in yield due to salinity is allowed according to (Metcalf and Eddy, 2000; Khalil, Al-Dadah, and Yassin, 2003; Ayers and Westcot, 1994).

$$\sum_{i=1}^{m} SL_i \times A_i \le MSL \tag{20d}$$

MSL is the existing area of each crop multiplied by the salinity load at 10% reduction in crop yield (Metcalf and Eddy, 2000; Khalil, Al-Dadah, and Yassin, 2003; Ayers and Westcot, 1994).

Acceptable level of rotaviruses: The level of rotaviruses in the treated wastewater must be within the allowable maximum level *MADR* (PFU/person-year) and can be expressed as:

$$\sum_{\mathrm{i}=1}^{\mathrm{m}} Z \times M_{body} \times C_{c\,i} \times V_{prod_i} \times A_i \times WWUI_i \times 365 \le \mathrm{MADR} \tag{20e}$$

Multi-criteria decision analysis. The purpose of the analysis is to find the optimal cropping pattern based on a given decision-maker preference. First, a decision-maker preference is introduced to produce a bias between different goals. For example, economic indicators can be given higher priority than environmental conditions. Second, the optimal values of all five single objective functions computed earlier will be simultaneously considered with the decision-maker preference discussed earlier. Therefore, this tradeoff analysis provides a realistic and a flexible approach for decision-making where the decision-maker will decide on the preference given to each objective through a set of weights.

The tradeoff analysis is performed using weighted goal programming. This method optimizes several goals while minimizing the deviation of each objective from the desired target. A goal has the following general form (Romero and Rehman, 2003):

$$F_a(x) + n_a - p_a = T_a \tag{21}$$

where $F_a(x)$ is the objective function number; subscript a refers to the objective number 1 to 5; n_a (n_1 to n_5) is the negative deviational variable from the target T_a; p_a (p_1 to p_5) is the positive deviational variable from the target T_a; and T_a is the optimal value of each objective function obtained from single objective optimization.

As an example, consider the objective of profit maximization in the single objective optimization which may or may not be achieved. For each goal, negative deviational and positive deviational variables are computed. Deviational variables account for deviations from the target (T_a). For instance, if n_1 has a non-zero value, then the first goal has fallen short by n_1. The positive deviational variable does the reverse indicating the amount by which a goal's achievement has surpassed its target, T_a.

Weighted goal programming considers all goals simultaneously within a composite objective function comprising the sum of all respective deviations of the goals from their targets. The deviations are then weighted according to the relative importance of each goal given by a decision-maker preference (Romero and Rehman, 2003). In essence, all single objectives will be combined into a single composite objective function based on the decision-maker preference and the deviation from the original target. The composite objective function, z, has the following form:

$$Min\ \ z = w_1 \frac{n_1}{T_1} + w_2 \frac{n_2}{T_2} + w_3 \frac{n_3}{T_3} + w_4 \frac{p_4}{T_4} + w_5 \frac{n_5}{T_5} \tag{22}$$

subject to

1st goal: Profit $\left[\sum_{i}^{m} \Pr ofit(A_i)\right] + n_1 - p_1 = T_1$ (23a)

2nd goal: Groundwater use $\left[\sum_{i}^{m} GWU(A_i)\right] + n_2 - p_2 = T_2$ (23b)

3rd goal: Treated wastewater use $\left[\sum_{i}^{m} TWU(A_i)\right] + n_3 - p_3 = T_3$ (23c)

4th goal: Salinity load $\left[\sum_{i}^{m} SL(A_i)\right] + n_4 - p_4 = T_4$ (23d)

5th goal: Economic efficiency of water use $\left[\sum_{i}^{m} EEWU(A_i)\right] + n_5 - p_5 = T_5$ (23e)

$$A_i \geq 0 \tag{24a}$$

$$n_a, p_a \geq 0 \tag{24b}$$

Equations (22) through (24b) are subject to the same constraints given earlier by Equations (20a) through (20e). In Equations (23a) through (23e), *i* refers to the crop type from *m* crop varieties. In Equation (22), the positive deviational variable is used with the fourth objective function. This objective function refers to minimization of annual salinity load in Equation (19) where as the other single objectives functions refer to maximization.

The weight w_a (a=1,....5) describes the decision-maker preference for each objective *i* and the summation of w_a across all *a* is 100. Although decision makers' preference of an objective compared to another would give a better insight of the weight, the objectives can be judged by assigning different weights from both the decision makers' and farmers' viewpoints (Tiwari, Loof, and Paudyal, 1999). For this reason, four different policy scenarios are examined by assigning a diverse set of weights in each scenario. The scenarios used later will focus on economics, groundwater use, treated wastewater use, and a distributed scenario that addresses both environmental and economic aspects. All optimization analyses were conducted using LINGO 11.0 software (available at www.lindo.com).

Aquifer recovery

When treated wastewater is used to supplement freshwater in agriculture, the stress on freshwater supplies reduce. In coastal regions such as Gaza where groundwater depletion, seawater intrusion, and decrease in water levels are already occurring at an alarming rate, any reduction in groundwater abstraction can help recovery of the coastal aquifer.

The coastal aquifer of Gaza (Figure 4) is a part of a regional groundwater system that extends from the coastal areas of Sinai, Egypt, in the south to Haifa, Israel, in the north. The coastal aquifer is about 10 to 15 km wide, and its thickness ranges from 10 m in the east to about 200 meters in the coastline (Metcalf and Eddy, 2000). The coastal aquifer consists primarily of calcareous silty sandstones, silts, clays, unconsolidated sands, and conglomerates (Metcalf and Eddy, 2000). Near the coast, clay extends about 2 to 5 km inland, and divides the aquifer sequence into three of four sub-aquifers. Toward the east, clays pinch out and the aquifers are largely unconfined.

Historically, the groundwater elevation shows a declining trend with time. Groundwater levels below mean sea level indicate saltwater intrusion. Three zones, namely North Gaza, Deir-al-Balah, and Rafah, has average groundwater elevations of 5, 1, and 4 m below mean sea level in 2007 (Qahman, 2004; Saleh, 2007; Metcalf and Eddy, 2000). The water levels in North Gaza, Deir-al-Balah, and Rafah have fallen by nearly 4, 2, and 7 m below mean sea level from 1990 to 2007. The declining levels of groundwater are due to the increased number of unauthorized agricultural wells and corresponding over-abstraction.

In this work, it is proposed to assess the environmental and physical benefits associated with the use of treated wastewater in agriculture by conducting a groundwater modeling study to find the rate of aquifer recovery. A previously calibrated groundwater model by Saleh (2007) using MODFLOW software (Harbaugh et al., 2000) is used to assess water level recovery due to reduced pumping. The quantity of groundwater predicted by the multi-criteria analysis will be used in the calibrated groundwater flow model to assess the beneficial aspects of using treated wastewater. The groundwater model of the Gaza coastal aquifer has uniform cell sizes of 200 m by 200 m with 336 rows and 280 columns. The model domain contains one layer with a total of 94,080 cells of which 39,774 are active cells.

The model domain is larger than Gaza to ensure proper implementation of boundary conditions. The boundary along the coast has constant head cells while the remaining boundaries are stipulated as having a no-flow condition.

The sources of recharge are due to rainfall, irrigation, wastewater, and water supply network losses (Metcalf and Eddy, 2000). The value of recharge is 217 million m^3 (MCM) per year. There are approximately 3,500 wells within Gaza. The majority of these wells are privately owned and used for agricultural purposes. Only 92 wells are owned and operated by individual municipalities and are used for domestic supply (Saleh, 2007).

The total water abstraction from these wells (agricultural and municipal) was 151 MCM in 2007 based on available data from the Palestinian Water Authority. The groundwater model was calibrated under steady-state conditions using 90 observation wells. The correlation coefficient between the observed and simulated data was 85% (Saleh, 2007).

Study Area

Gaza Strip is a 40 km long and about 9 km wide area between the Negev desert, Israel, and the Mediterranean Sea (Figure 4). Gaza is located on the western-most edge of the shallow coastal aquifer that is exploited for municipal and agricultural water supply. Gaza has a semi-arid climate and there are two well-defined seasons: the wet season occurring between October and March followed by the dry season from April to September. Peak months for rainfall are December and January.

The long-term mean annual rainfall is 325 mm/year, and it decreases from north to south. The mean temperature varies from 12 to 14 ^{o}C in January to 26 to 28 ^{o}C in June. Evaporation measurements have clearly shown that the long term average open water evaporation is around 1,300 mm/year. Maximum values of 140 mm/month occur in June, July, and August while the rate reduces to 70 mm/month during winter. As discussed earlier, Gaza is an excellent demonstration study area for this work for a variety of reasons. The region faces serious issues with saltwater intrusion as well as groundwater contamination from agricultural and domestic wastes. Gaza is densely populated, faces a high growth rate and the majority of the population has relatively low income. There is widespread groundwater contamination, and over-pumping of coastal aquifers has produced sea water intrusion.

Water scarcity in Gaza is a significant problem and the concerns have been highlighted in many studies (MoA, PWA, and PHG, 2004; Metcalf and Eddy, 2000). Gaza aquifer receives an annual recharge of 134 MCM. At the same time, Gaza water demand is more than 156 MCM resulting in a deficit of approximately 22 MCM in 2002 (Metcalf and Eddy, 2000). This deficit is projected to increase further due to economic growth and the high population growth of 3.2% per year (Yakirevich et al., 1998; Palestinian MoP, 2005; PCBS, 2005; Metcalf and Eddy, 2000; Qahman, 2004). Presently the agricultural sector is the largest water consumer in Gaza with a consumption of about 70% of the total water supply (Qahman, 2004; Metcalf and Eddy, 2000). If uncontrolled groundwater pumping is allowed to continue from the aquifer, which is the primary source for the region, the freshwater supply will become unusable for municipal uses and the land will be too saline for farming. The total agricultural area is about 16,650 ha of which irrigated area is about 10,800 hectares and about 1000 hectares of greenhouses. The number of farms is estimated to be between 15,000 and 20,000 (Palestinian MoP, 2005). The average area per farm is estimated to be between 0.8 to 1.1 hectares. Presently, water is considered as a "free good" by farmers due to lack of metering or pricing. The existing agricultural water system in Gaza has a low economic efficiency of water use of about \$0.34 /m^3 in comparison to a water opportunity cost of about \$0.60/m^3 for desalination (Issac, 2000; Metcalf and Eddy, 2000; MoA, PWA, and PHG, 2004).

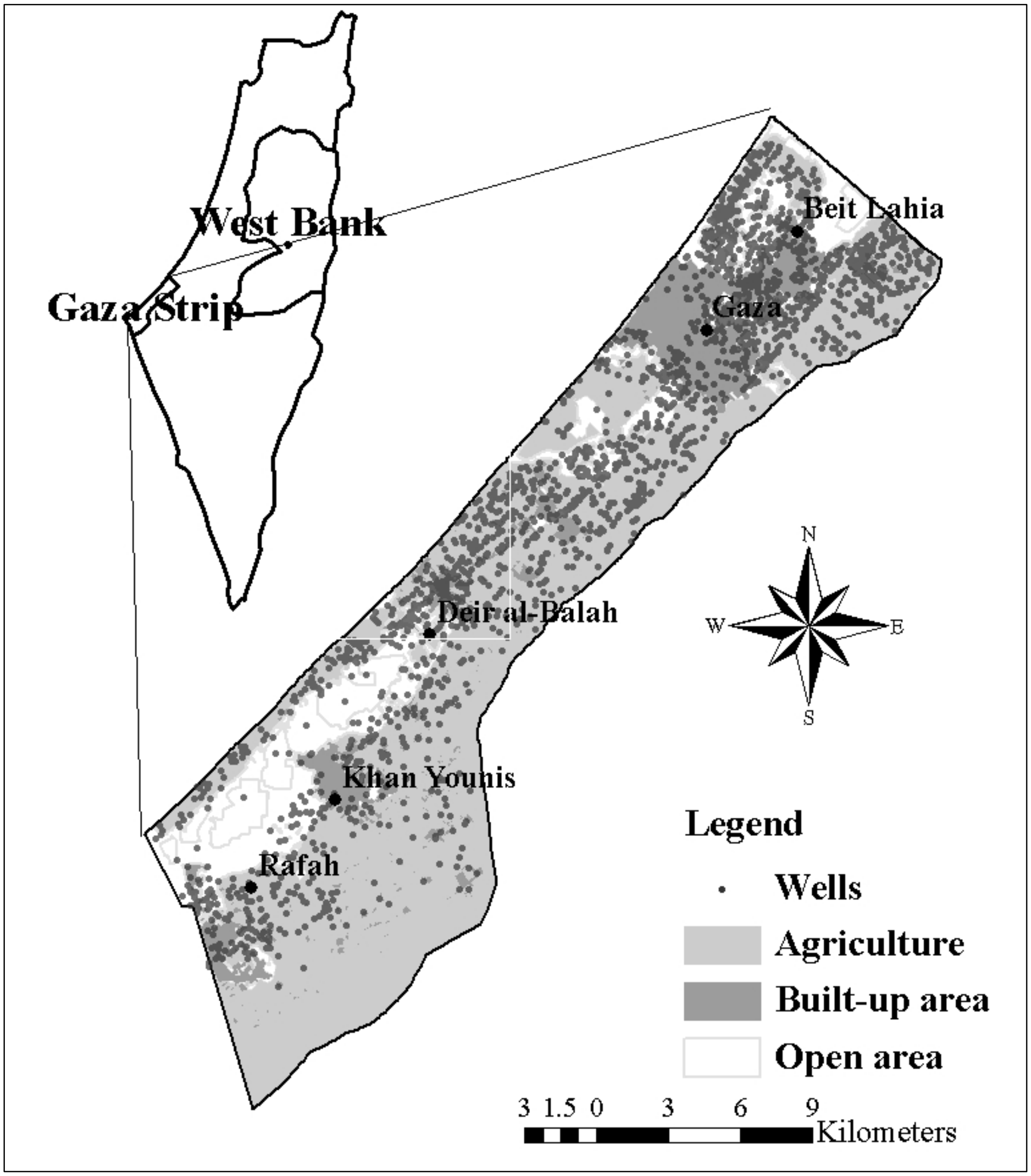

Figure 4. The overall map of Gaza Strip and the location of the agricultural areas.

The farmers determine the annual crop patterns according to their own desire rather than following an economically efficient plan. Treated wastewater is rarely used for agriculture in Gaza (Khalil, Al-Dadah, and Yassin, 2003; Afifi, 2006).

Results and Discussion

Public health risk assessment

Table 9 shows the input variables of the exposure model described by Equation (9) including the statistical representation of uncertain variables. The Monte Carlo simulations with 10,000 runs per scenario were conducted to determine the exposure and health risk across different irrigation methods, treatment efficiencies for rotavirus removal, and time between last irrigation and consumption. The volume of irrigated water consumed by products was calculated using Equation (13). The results are shown in Table 10 as the mean annual risk and the corresponding standard deviation for a 25-day period between last irrigation and consumption. It is clear that the mean annual risk of infection for scenarios with secondary and complete treatment is well below the WHO guideline of 10^{-3}. Micro irrigation with complete treatment produced the lowest risk of 10^{-12}. This risk of infection is 3 orders of magnitude less than with sprinkler irrigation and complete treatment.

The annual risk of infection is the largest with surface irrigation with primary treatment. Figure 5 shows the mean annual risk profile computed as a function of treatment efficiency and elapsed time between the last irrigation and consumption for the scenario with sprinkler irrigation. The results show that the annual risk of infection is 10^{-9} at 25 days elapsed time between last irrigation and consumption with complete treatment. Although not shown in this figure, the annual risk of infection increases to 10^{-6} if surface irrigation is used (see Table 10). These results show that the irrigation system affects the health risk when treated wastewater is used for agriculture. Micro irrigation applies less water due to higher efficiency reducing the risk of exposure to pathogens. The annual risk of infection decreases with increased elapsed time between last irrigation and consumption, and obviously with increased treatment efficiency.

Agricultural water allocation

Single objective optimization. The optimization analysis requires several types of input data. The economic data include the costs of crop production, groundwater abstraction, and treatment of wastewater. The environmental data include salinity load per crop expressed in terms of TDS. The physical data include crop water requirements and crop yield. Table 11 shows the different crops with potential for treated wastewater use. The total area of crops is 8,741 ha in 2006. The available groundwater quantity used in Equation (20b) is 57 MCM/year in 2006 (PCBS, 2005; Metcalf and Eddy, 2000; Khalil, Al-Dadah, Yassin, 2003). The available treated wastewater used in Equation (20c) is 45.6 MCM/year (Afifi, 2006). The maximum allowable salinity load used in Equation (20d) is 48.1 million kg/year (Ayers and Westcot, 1994; Khalil, Al-Dadah, and Yassin, 2003; Metcalf and Eddy, 2000). The maximum allowed annual dose of rotaviruses used in Equation (20e) is 2.19 $x10^5$ PFU/person-year or 600 PFU/person-day according to Ward et al. (1989).

Pay-off matrix. The purpose of the pay-off matrix is to find the conflicts among the different objective functions because each objective function addresses a particular issue. For example, economic efficiency of water use and profitability are focused on economics whereas the total salinity load is focused on environmental sustainability.

The pay-off matrix is a matrix comparing optimal solutions of each objective function described by Equations (15) through (19).

Table 9. Summary of exposure model input data in Monte Carlo simulation for evaluating public health risk

Variables	**Mean**	**Distribution/Range/ Reference**
Rotavirus concentration of applied wastewater, PFU. L^{-1}	1250	lognormal; σ=345 (Khalil et al., 2003; MoA et al., 2004)
Daily vegetable and fruit consumption, g/kg-person-day	7.5	(Palestinian MoP, 2005)
Human body weight, kg	61.4	lognormal; σ=13.4 (Palestinian MoP, 2005; Hamilton et al., 2006)
Irrigation water volume diverted to crops		
Surface irrigation, ml/g	827.6	--
Sprinkler irrigation, ml/g	532.0	--
Micro irrigation, ml/g	438.1	--
Dose- response model		
Median infective dose	6.17	Mara et al., 2007
Pathogen infectivity constant	0.2531	Mara et al., 2007
Kinetic decay constant, per day	1.07	Normal; σ= 0.07 (Hamilton et al., 2006)
Wastewater removal efficiency	--	0-100% (Yates and Gerba, 1998)
Period between last irrigation and consumption, days	--	0-25

Table 10. Computed annual risk of infection for nine scenarios based on 10,000 computer runs at 25 days between last irrigation and consumption

Scenario		Annual Risk of Infection	
Irrigation Method	Effluent type (efficiency)	Mean	Standard deviation
Surface	Primary (50%)	10^{-4}	10^{-3}
	Secondary (90%)	10^{-6}	10^{-6}
	Complete (99.99%)	10^{-8}	10^{-8}
Sprinkler	Primary (50%)	10^{-5}	10^{-4}
	Secondary (90%)	10^{-7}	10^{-7}
	Complete (99.99%)	10^{-9}	10^{-8}
Micro irrigation	Primary (50%)	10^{-8}	10^{-8}
	Secondary (90%)	10^{-11}	10^{-10}
	Complete (99.99%)	10^{-12}	10^{-11}

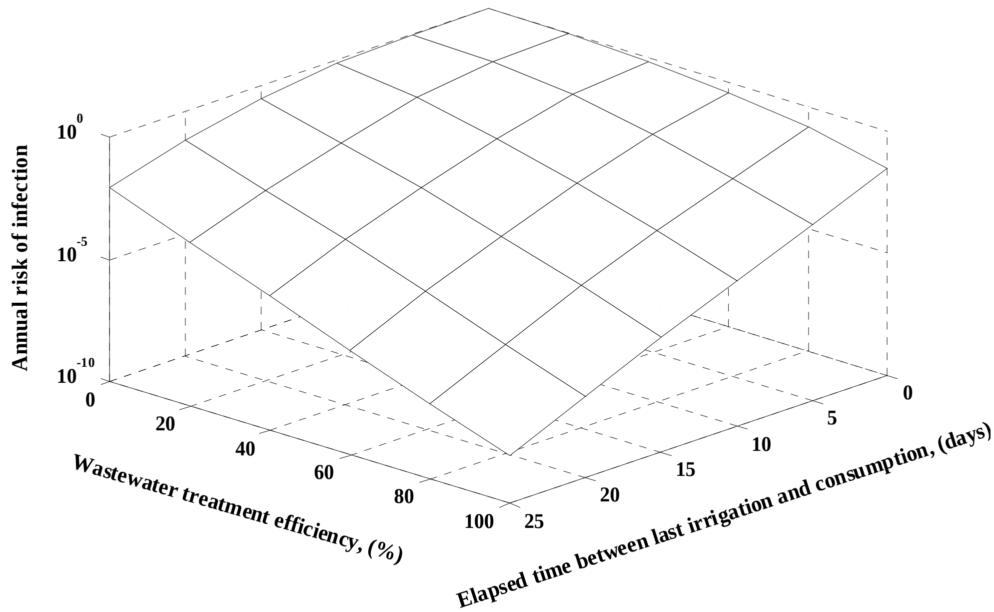

Figure 5. Computed relationship between annual risk of infection, elapsed time between last irrigation and consumption, and virus removal efficiency of wastewater for sprinkler irrigation methods using 10,000 simulations with the Monte Carlo method.

Table 11. Summary of input data used in optimization analysis (PCBS, 2005; Palestinian MoP, 2005; Ouda and Bardossy, 2003). Crops denoted in bold are capable of using treated wastewater.

Crop	Area (ha)	Crop price ($/ton) 2005	Production cost ($/ha) 2005	Average crop water requirement m^3/ha.year)	Maximum yield (ton/ha)
Cabbage	208	323	3320	2953	42
Cauliflower	115	420	3500	2289	37
Clamantina	339	339	1500	3809	27
Cucumber	290	412	3480	3718	71
Eggplant	106	309	5400	8109	40
Guava	450	377	1500	7075	43
Grapefruits	130	145	1500	7341	28
Lemon	336	473	1500	6105	5
Olive	3190	1250	1500	3109	32
Pepper	83	489	5400	7232	37
Potato	557	242	3200	3110	30
Squash	180	408	3400	3454	37
Tomato	180	367	3280	6346	42
Valencia	1930	158	1500	7655	26
Watermelon	133	160	4000	5031	22
Shamoti	510	265	1500	7655	35

The diagonal elements of the pay-off matrix are referred as the ideal values; i.e., the solution where all objectives achieve their optimum values (Romero and Rehman, 2003). The pay-off matrix computed from the single objective optimization is given in Table 12 and the results show the conflicts among the five objective functions. For instance, if the use of wastewater is maximized (column 3), the profit is $82.3 million/year, where as if the annual groundwater use is maximized (column 2), the profit decreases to $71.4 million/year. From a profit perspective, the highest profit is given when profit is maximized while almost the same result of $85.6 million/year is obtained when economic efficiency of water use is maximized. However, when the treated wastewater use is maximized, profit decreases to $82.3 million/year while increasing the salinity load. It is interesting to note that each scenario produced better profits, high economic value of water use, and less salinity load than the existing conditions. The results, however, show that there are competing conflicts between different objectives when compared at the levels of single objective optimization. Therefore, there is a need for tradeoff analysis among these objectives for effective decision-making.

Multi-criteria decision analysis. The purpose of multi-criteria decision-making is to find the optimal solution to a composite objective function (Equation 22) made of the individual objective functions described earlier (Equations 15-19) but with a given decision-maker preference.

In this analysis, four different scenarios representing: (1) economics; (2) groundwater use; (3) treated wastewater use; and (4) a distributed scenario were developed and the details are given in Table 13.

Table 12. Computed pay-off matrix for different scenarios in single objective optimization

	Max. annual Profit (1)	Max. annual groundwater use (2)	Max. annual wastewater use (3)	Min. Annual salinity load (4)	Max. Economic efficiency of water use (5)	Existing (2005)[1]
Profit (million $/year)	85.7	71.4	82.3	74.4	85.6	49.6
Groundwater (MCM/year)	35.9	39.5	33.1	38.2	35.2	57.0
Wastewater (MCM/year)	41.3	36.1	43.56	32.5	41.6	45.6
Salinity Load (million kg/year)	41.5	33.1	44.8	35.2	41.3	58.1
Economic efficiency of water use ($/m^3)	1.45	0.95	1.35	1.32	1.45	0.34

[1] The numbers given here are based on published literature. The wastewater volume of 45.6 MCM/year is the available wastewater from the treatment plants of Gaza.

As an example, the goal of the economic scenario is to maximize the profit; therefore the profit is given a higher weight than other objectives. The distributed scenario provides equal emphasis on all objectives and therefore the weights are equal at 0.2. The advantage of weighted goal programming is the inclusion of the decision-maker preference. In essence, the results then represent the combined effect of all objectives based on the preference selected. This multi-criteria decision analysis used data from 2000 to 2006.

Table 14 shows the results of these four scenarios using the weighted goal programming method.

Table 13. Goal weights allocated for different scenarios in the multi-criteria tradeoff analysis

Objective function	Economic Scenario	Groundwater Scenario	Wastewater Scenario	Distributed Scenario
Profit (w_1)	0.5	0.1	0.1	0.2
Groundwater (w_2)	0.1	0.5	0.1	0.2
Wastewater (w_3)	0.1	0.1	0.5	0.2
Salinity load (w_4)	0.1	0.2	0.2	0.2
Economic efficiency of water use (w_5)	0.2	0.1	0.1	0.2

The results clearly show that all scenarios produce a higher profit than the existing conditions while the different scenarios produce different results. The economic scenario produced a profit of $81.8 million/year which is the highest followed by the groundwater use scenario at $72.2 million/year and then the wastewater scenario at $76.6 million/year. The highest profit of the economic scenario is a result of the higher weight assigned to the profit objective function. In the groundwater scenario, the quantity of groundwater of 39.8 MCM/year is greater than the groundwater quantity in the economic and wastewater scenarios of 32.4 and 36.4 MCM /year, respectively, as a result of the higher weight given for the groundwater use scenario. In the wastewater scenario, the value of treated wastewater use of 44.2 MCM/year is higher than the wastewater quantity in the economic and groundwater scenarios of 41.8 and 40.5 MCM/year, respectively.

In Table 14, the deviational variables for each scenario are also summarized. The deviational variables indicate the deficit and the surplus of each objective with respect to the optimum value. The optimal value refers to the value obtained from the corresponding single objective optimization which is the target. For instance, the economic scenario indicates a profit of $81.8 million/year compared with the optimum profit of $85.7 million/year as shown in Table 12. The distributed scenario produced a profit of $72.5 million/year which is less than the optimum profit of $85.7 million/year obtained from single optimization. In other words, *n* is the difference between the optimum profit from the single optimization of $85.7 million/year and the profit obtained from the distributed scenario of $72.5 million/year. Table 14 illustrates the resulting cropping pattern under the four aforementioned scenarios. As seen, the economic scenario increases the areas cultivated with crops of high market price and low water consumption such as olive.

On the other hand, the wastewater scenario produced higher areas of crops that are tolerable to treated wastewater such as lemon and grapefruit. In the groundwater scenario, the areas of crops that are not suitable for treated wastewater irrigation such as cabbage, cauliflower, cucumber, pepper, and tomato, are increased.

Cost savings from fertilizers

Another advantage of using treated wastewater in agriculture is the nutrient value of treated wastewater that is otherwise supplemented by commercial fertilizers. A cost analysis was conducted to evaluate these savings by considering the amounts of nutrients present in treated wastewater and the equivalent amount of fertilizer needed to supplement the same amounts of nutrients. Gaza treated wastewater effluent contains substantial amounts of essential nutrients such as nitrogen, phosphorus, and potassium.
A literature review (Metcalf and Eddy, 2000; Khalil, Al-Dadah, and Yassin, 2003) showed that the average concentration of essential nutrients in the effluent is 5.6 mg/l (or tons/MCM) of nitrogen, 2.6 mg/l of phosphorus, and 0.5 mg/l of potassium.

Table 15 shows the estimated quantities of nutrients in treated wastewater, the equivalent amounts of commercial fertilizer, and the costs of fertilizers.

Table 14. Computed values of objective functions, deviational variables, and decision variables (crop area) for multi-criteria tradeoff analysis using weighted goal programming. Crops denoted in bold are capable of using treated wastewater

per year	Weighted goal programming				Existing (2005)[1]
	Economic Scenario	Groundwater Scenario	Wastewater Scenario	Compromising Scenario	
Profit (million $/year)	81.8	72.2	76.6	72.5	49.6
Groundwater (MCM/year)	32.4	39.8	36.4	36.5	57.0
Wastewater (MCM/year)	41.5	40.5	44.2	39.8	45.6
Salinity load (million kg/year)	41.8	40.4	44.3	40.6	58.1
Economic efficiency of water use ($/m^3)	1.38	1.24	1.28	1.10	0.34
Deviational variables					
n_1	3.9	12.5	9.1	13.2	--
n_2	7.1	0.0	3.1	3.0	--
n_3	4.36	3.06	0.0	3.8	--
p_4	0.0	0.0	1.9	0.0	--
n_5	0.07	0.21	0.17	0.35	--
Decision variables results (hectare)					
Cabbage	124	259	0.0	0.0	209
Cauliflower	72	280	0.0	154	115
Clamantina	295	375	864	497	339
Cucumber	343	390	0.0	0.0	290
Eggplant	420	369	0.0	145	106
Guava	800	614	545	815	450
Grapefruits	1029	518	730	348	130
Lemon	285	429	612	354	337
Olive	3375	2845	4825	3467	3190
Pepper	150	75	0.0	154	83
Potato	341	452	50	94	557
Squash	150	342	33	285	180
Tomato	140	242	0.0	319	181
Valencia	577	1078	652	1531	1930
Watermelon	80	122	0.0	198	134
Shamoti	560	350	430	380	510

[1] The numbers given here are based on published literature from Gaza.

For example, the economic scenario produced 41.4 MCM (Table 14) of treated wastewater use. By multiplying this quantity with 2.6 mg/l or 2.6 tons/MCM of phosphorous, the resulting amount of phosphorous generated by treated wastewater which is 107.9 tons was obtained. To convert this quantity to a cost item, each single nutrient is converted to an equivalent commercial fertilizer quantity. The single commercial fertilizers are ammonium sulfate (contains 21% N), triple super phosphate (contains 46% P_2O_5), and potassium nitrate (contains 35% K_2O). The commercial fertilizers in Gaza exist in the form of N, P_2O_5, and K_2O. For example, P_2O_5 contains 44% as phosphorous. Therefore 107.9 tons of phosphorus from the previous example is available in 245.2 tons of P_2O_5. Similar quantities of N and K_2O can be computed knowing the nitrogen and potassium contents.

Triple super phosphate used by Gaza farmers contains 46% P_2O_5. Therefore, 245.2 tons of P_2O_5 is available in 532 tons of triple super phosphate. The cost of commercial fertilizers in Gaza is around $300/ton for ammonium sulfate, $600/ton for triple super phosphate, and $1000 for potassium nitrate. This is a direct savings to the farmers of Gaza and also provides another incentive to use treated wastewater in agriculture.

Other environmental benefits of using treated wastewater in addition to cost savings, aquifer recovery and less demand on freshwater are the safe disposal of treated waste water generated from the treatment plants and the reduced usage of chemical fertilizers that contribute to various environmental hazards.

Table 15. Calculated savings from fertilizers due to the use of treated wastewater in agriculture for different scenarios of multi-criteria decision analysis

		Economic Scenario	Groundwater Scenario	Wastewater Scenario	Distributed Scenario
		(tons/year)			
Average nutrient content of Gaza treated wastewater effluent	Nitrogen (N)	232.4	226.8	247.5	222.8
	Phosphorous (P)	107.9	105.3	114.9	103.4
	Potassium (K)	20.75	20.25	22.1	19.9
Equivalent commercial fertilizer used by farmers (as a single fertilizer)	Ammonium sulfate (21% N)	1,106	1,079	1,178	1,106
	Triple super phosphate (46% P_2O_5)	532	519	567	509.9
	Potassium nitrate (35% K_2O)	72.4	70.6	76.9	69.3
		Cost of fertilizer ($/year)			
Cost of fertilizers that could be generated by using treated wastewater	Ammonium sulfate (21% N)	331,800	323,700	353400	318,300
	Triple super phosphate (46% P_2O_5)	319,200	311,400	340,200	305,940
	Potassium nitrate (35% K_2O)	86,880	84,720	92,280	69,300
				Expected savings ($/year)	
Expected saving from fertilizers		737,880	719,820	785,880	693,540

Aquifer recovery

The groundwater use considered in this study is 57 MCM/year (PCBS, 2005; Metcalf and Eddy, 2000; Khalil, Al-Dadah, and Yassin, 2003). The multi-criteria decision analysis showed the average quantity of groundwater that can be used for agriculture is reduced to 36.3 MCM/year across the economic, groundwater, wastewater, and distributed scenarios from Table 14. In essence, the multi-criteria decision analysis using weighted goal programming showed that the groundwater abstraction can be reduced by 37% compared to the existing use. The calibrated groundwater model (Saleh, 2007) was used to investigate the impact of this reduction on the groundwater levels and seawater intrusion. Figure 6 shows the relationship between the areas with water levels below mean sea level for the Gaza aquifer and the percentage of reduction in agricultural pumping.

The 37% reduction in agricultural pumping was evenly distributed across the agricultural wells. The area of groundwater levels below mean sea level decreases to 32 km^2 with 37% reduction in groundwater abstraction. Figure 6 also shows that when pumping is reduced, the areas with water levels below mean sea level (i.e. sea water intrusion) can be significantly reduced indicating that agricultural wells have a high impact on water levels.

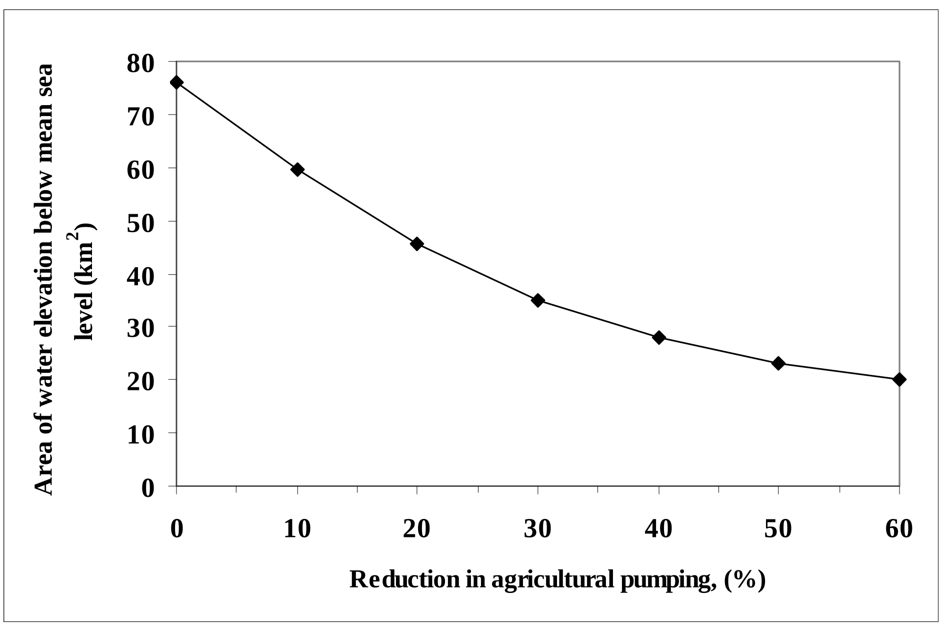

Figure 6. Computed relationship between the area falling below mean sea level and the reduction in agricultural pumping.

Summary and Conclusion

Treated wastewater is a viable source of alternative water for agricultural production in water deficit regions. Use of treated wastewater can reduce the stress on freshwater supplies and enhance recovery of affected aquifers due to reduced abstraction. In coastal regions such as Gaza, Palestine, where significant deterioration of freshwater quality due to seawater intrusion is already occurring, the use of treated wastewater in agricultural production can save freshwater resources. However, water allocation for agricultural production using treated wastewater should be conducted in a responsible manner by considering the potential impacts on public health due to pathogens in treated wastewater.

This work proposes a methodology for agricultural water allocation considering economic issues, environmental concerns, and public health risks. Economic aspects were represented through profitability and economic efficiency of water use. Environmental aspects were represented using salinity development in soils due to the use of treated wastewater. Finally public health risks due to the consumption of crops infected by pathogens present in treated wastewater were considered. Gaza Strip of Palestine was used as a demonstration example where water shortages are critical, population growth is high, and seawater intrusion due to high water abstraction for agriculture is prevalent. Presently, irrigated agriculture is the largest water consumer in Gaza consuming more than 70% of water diverted. The water levels in N. Gaza, Deir-al-Balah, and Rafah regions have fallen by nearly 4, 2, and 7 m below mean sea level over the past 17 years. However, management of agricultural water use has received little attention in Gaza. The agricultural water in Gaza has low economic efficiency of water use. Although treated wastewater is readily available in Gaza, very little work has been conducted to evaluate the potential use of treated wastewater in agriculture to reduce stress on fresh water supply and enhance aquifer recovery.

The proposed methodology was applied to Gaza Strip, Palestine, and the key findings can be summarized as follows:

1. An increase in elapsed time between irrigation and consumption reduces public health risk significantly. Other operational improvements such as increasing virus removal efficiency of wastewater treatment and switching from sprinkler to micro irrigation can reduce public health risks.
2. Optimizing individual objectives related to economic, environmental, and public health goals revealed significant conflicts. Therefore, multi-criteria decision analysis that can incorporate a decision-maker preference help significantly in determining the optimal conditions such as land area per given crop.
3. The multi-criteria decision analysis using weighted goal programming can be successfully implemented in scenarios where single objectives have competing and conflicting results. One distinct advantage of this method is the ability to include a decision-maker preference in the analysis to develop a single composite objective function.
4. The results of the analysis showed that 42 MCM of treated wastewater can be used in agriculture reducing the stress on freshwater supplies by 37% while achieving required profit levels.
5. The results also showed that all scenarios including single objective and multi-criteria decision-making produced significantly higher profitability, higher economic efficiency of water use, and less groundwater use than the current

conditions in Gaza. The distributed scenario with equal weight across economic, environmental and public health goals showed 31% higher profitability, 36% less groundwater abstraction, and 69% improved economic efficiency of water use.

6. The use of treated wastewater can also save costs to the farmers due to the nutrient value of treated wastewater. The cost analysis showed that on average, the annual savings can be $719,000 to $785,000 depending on the scenario of the multi-criteria decision analysis. In addition, the use of treated wastewater provides an avenue for safe disposal of effluent from the treatment plants while reducing the use of chemical fertilizers that are hazardous to the environment.

7. The average groundwater use predicted by the multi-criteria decision-making scenario showed that groundwater abstraction can be reduced by 37% which allowed the recovery of aquifer from an area of 76 km^2 below mean sea level to 32 km^2 as a result of using treated wastewater.

The success of a given water allocation plan depends on the existing institutional framework that is capable of encouraging the use of treated wastewater in agriculture. Wastewater treatment in Gaza may not be reliable in terms of the treatment capacity and the level of treatment. Another limitation is the inadequate infrastructure for storage, conveyance, and distribution of treated wastewater to farmers. An agricultural water policy that contains incentives for farmers using treated wastewater, attractive prices for delivered treated wastewater to the farms, and water quality monitoring will encourage the use of treated wastewater in irrigated agriculture.

CHAPTER V

ECONOMIC ANALYSIS OF IMPROVEMENTS TO WATER MANAGEMENT IN WATER DEFICIT REGIONS: A CASE STUDY FROM GAZA STRIP, PALESTINE

Abstract

Water deficit coastal regions such as Gaza Strip of Palestine have groundwater as the only natural source of fresh water. However, groundwater is severely polluted due to salt water intrusion caused by over-abstraction to satisfy the increasing demands from the agricultural sector. In regions such as Gaza, innovative methods considering desalination, use of treated wastewater, and improved water conveyance between demand centers should be considered to provide adequate water for different sectors. However, such management improvements need to be carefully studied for their economic merits given the large capital investments needed. In this work, a methodology is proposed using the Water Allocation System Model of Fisher et al. (2005) to study the economic benefits of different water supply enhancements. The improvements considered are desalination, water distribution between different Districts through improved conveyance, and the use of treated wastewater. The analysis was conducted for current and future years of 2020 and 2030 using projected demand and supply. The economic attributes considered were net benefit, shadow value of water, and the price of water. Infrastructure improvements include building of new treatment plants to increase the treated wastewater capacity and the installation of desalination units and conveyance systems while reducing groundwater pumping to minimize environmental impacts. The results showed that the cost for restructuring the institutional framework for wastewater reuse is significantly less than the benefits gained by use of treated wastewater in agriculture. We find that the shadow

value of water increases when groundwater pumping is reduced and decreases when treated wastewater is considered. The urban and agricultural water prices decreased when treated wastewater is considered. Adding a large desalination plant increases the net benefit, reduces the urban water price, and decreases the shadow value of water. Agricultural water prices decreased dramatically after considering the use of treated wastewater in agriculture.

Introduction and Background

The primary competing uses of water is typically agriculture followed by industry, domestic, recreational, and more recently environmental preservation. Proper distribution of water among these sectors requires careful planning and management. Sustainability of water resources and an equitable distribution of available water drive much of this planning (Huber Lee, 1999; McCarl et al., 1999; Orr and Colby, 2004; Loehman and Becker, 2006). Finding sustainable solutions for water stressed regions is an important focus of water resources planners and policy-makers. For sustainable water management to occur, the allocation of water must be socially fair for both current and future populations (Huber Lee, 1999; Gillig, McCarl, and Boadu, 2001; Loehman and Becker, 2006). The main goal of regional water managers is to adopt spatial and temporal policies or suggest efficient use of scarce water supplies for meeting ever increasing water demands. Integrating engineering, economic, social, and political considerations is crucial for this process (Perry, 1999; Rosenberg, 2008).

Water is not scarce in terms of quantity. Earth holds an abundance of water, most notably for those countries bordering the ocean coast lines. Coastal regions have the option of producing freshwater through desalination. For example, the approximate cost of desalination in the Mediterranean coast of Gaza, Palestine is about \$0.50 to 0.60/m^3 in 2005 (Metcalf and Eddy, 2000; Fisher et al., 2002; Al-Agha and Mortaja, 2005). Costs are even greater for land-locked countries due to the multiple actions of desalination and conveyance of water. Given the different options of producing more freshwater, two points of interest come into attention; first, water scarcity is a matter of cost and value, not merely of quantity. Second, the value of water differs from location to location. The question might be posed as to how to place a value of water as a necessity for life. Also, one might inquire as to whether water prices should be based on the direct costs of provision (extraction, treatment, conveyance) to consumers as water is a natural right. Both views controversial and may be wrong (Fisher et al., 2005). No matter how important water is or what special values are believed to be attached to water in certain uses, it is unreasonable to value water at more than the cost of providing it. Therefore, desalination represents the upper bound of the value of water.

In addition to the cost of provision, demand also plays an important role among water uses. For example, if a user is willing to pay any asking price for water, then coastal countries can produce desalinated water and export to the user irrespective of the distance or the cost of production. Land-locked countries will have to search for more expensive alternative water resources, no matter how large, to have desalination water. Clearly, this action will not happen because the costs are too high (Fisher et al., 2005).

On the other hand, the value of water does not merely consist of direct costs, such as extraction, treatment, and conveyance. Consider a scenario of a population living close to a lake where the supply of water is abundant. With increasing population growth, there will be a time at which the renewable water from the lake will not be sufficient to address the needs of the population. At such a time, the value of water becomes more than zero because the population will be willing to pay for water given the short supply (Gibbons, 1986; Giordano et al., 2004; Fisher et al., 2005).

In this paper, an upper band of water value will be its desalination cost of \$0.60/m^3 in 2005. The actual value of water will be calculated from a system analysis which considers the costs and benefits from the urban, industrial, and agricultural sectors from use of groundwater and treated wastewater. The shadow value of water is the price that a buyer who values additional water the most would be willing to pay to obtain that additional water given the optimal water flows.

Developing an approach for the assessment of efficient use of water is the underlying goal of this paper. Water resources planning and management in regions with limited supply should consider long-term goals and consequences due to unwise actions that have detrimental impacts on future users and sustainability of resources. Gaza Strip of Palestine is a good example where unmanaged groundwater withdrawal from the coastal aquifers have caused seawater intrusion, poor water quality, deterioration of valuable land due to high salinity, and large areas falling below mean sea level. To minimize these serious impacts to the society, science based water resources planning and management should occur in these water deficit regions. An important part of this analysis is to consider the economics of water development and use in the overall planning framework.

Several earlier studies discussed the treatment of water as an economic commodity (Gibbons, 1986; Rogers and Fiering, 1986; Rosegrant and Ginswanger, 1994; Sekler, 1996; Young, 1996; Rogers, Bhatia, and Huber Lee, 1998; Perry, 1999; Draper et al., 2003), but typically this approach has not been applied in real-life scenarios. There are, however, a growing number of examples of applications of economics to water management. Rogers (1993b) studied the Ganges-Brahmaputra basin in the context of value of cooperation between India, Nepal, and Bangladesh, using fixed supply and single water type. Bhatia et al. (1994) modeled the industrial sector in Jamshedpur, India, and the impacts of both water tariff and effluent disposal charges. Huber Lee (1999) presented an inter-temporal model for sustainable management of the Gaza coastal aquifer. Huber Lee (1999) modeled groundwater hydrology and salt transport, as well as the economics of water allocation and agricultural water use. Fisher (1995), Fisher et al. (2002), and Fisher et al. (2005) modeled the agricultural, industrial, and domestic sectors of Israel, Jordan, and Palestine, to determine the value of water in these disputed countries.

The purpose of this work is to study the economic value of water in water deficit regions and to assess the economic potential of new management approaches to overcome existing and future deficits. Many studies have discussed the public health implications related to the use of treated wastewater in agriculture while treated wastewater can help reduce the stress on freshwater supplies. In sustainable water resources planning in water deficit regions, the potential use of treated wastewater in agriculture should be investigated and the corresponding impacts on other water use sectors such as domestic and industry should also be addressed. As discussed earlier, water comes with a given economic value based on supply and demand. Therefore, no effective water resources planning effort can be successful until economic valuation of water needs are properly addressed.

As indicated before, the goal of this work is to assess the economic viability of improved water management options suitable for water deficit regions that has the potential to use treated wastewater in agriculture. The proposed methodology will be applied to Gaza Strip, Palestine. The specific research questions addressed by this work will be (1) How are the urban and industrial sectors affected when wastewater is used for agriculture; (2) Will a reduction in groundwater pumping without the use of treated wastewater have detrimental effects on supply and economic benefits? (3) What improved management options available for supply enhancements to reduce future water deficits and what are the competitive economic benefits of these improved options?

Methodology

This work will use the water allocation model proposed by Fisher et al. (2005) and the details related to this model are given in the next section. A water allocation model maximizes the net benefits by allocating water to the different sectors in a given location based on the demand. Associated with these allocations is a system of shadow values of water in different locations. There are two fundamental concepts in a water allocation model. First, water scarcity provides a value for water. As water scarcity become higher, consumers are willing to pay relatively higher prices for small amounts of water. Water becomes less valuable where water is abundant. Second, a social value of water gives governments the incentive to subsidize water. In countries where agriculture is not profitable but socially and politically desirable, the government may decide to subsidize water for agriculture. This action will allow delivering water to farmers at a lower price (Fisher et al., 2005). The water allocation model explicitly allows for such social values to be taken into account.

Water allocation model description Several economic and engineering principles will be discussed and applied to identify opportunities for regional water resource planning and management: Water is a scarce resource and has value. This value reflects the benefit from use, costs to procure, treat, and convey water to the point of use. Costs of seawater desalination plus conveyance to the point of use produce the upper bound of value of water as this is the most expensive option in water deficit regions such as Gaza, Palestine. The water allocation system model utilized herein (Fisher et al., 2005) is a steady-state, deterministic optimization model for a single year. The model maximizes net benefits from water use subject to physical, economical constraints on water availability, use, reuse, and conveyance. The net benefit is the area between the demand and cost curves (Figure 7). The optimal allocation is the quantity, q* in Figure 7. Constraints are specified for the different districts and water-use sectors. For example, the quantity demanded must balance with the water extracted from local sources, imported from and exported to other districts and wastewater treated for reuse that cannot otherwise be put to economical use.

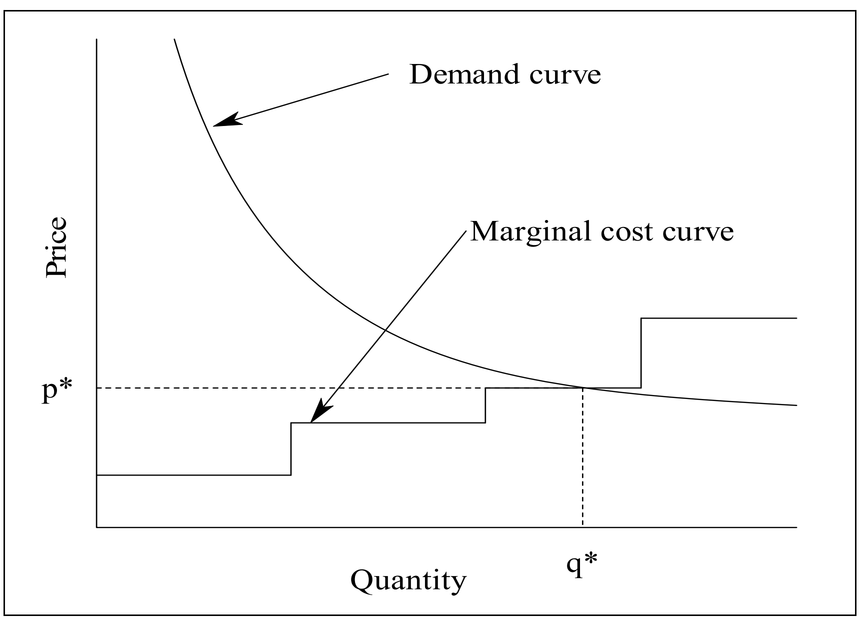

Figure 7. Demand curve and net benefit from water (Fisher et al., 2005).

The mathematical formulation of the water allocation system model is described in the Appendix.

Mathematical formulation The mathematical model studies the costs and benefits associated with water supply and demand across multiple water use sectors in each demand district. The analysis assumes the entire region, in this case Gaza Strip, as a single integrated system consisting of a number of demand districts and each district contains different water use sectors. The water use sectors considered in the analysis are agriculture, domestic and industrial.

Net benefit (Z) is estimated as the benefit of water demanded (from water related services) minus the cost of water used. The demand or willingness to pay curves using constant elasticity can be represented as:

$$P_i = \beta_i \times Q_i^{\alpha_i} \tag{25}$$

where P_i is the price; Q_i is the quantity demanded; β_i indicates the position of the demand curve and allows the exploration of the effects of greater or lesser demands for district *i;* and α_i is the price elasticity of demand and measures the response of demand to price of district *i.* Price elasticity of demand is defined as the percentage change in quantity induced by a 1% change in price. Price elasticity of demand is a measure of the sensitivity of quantity demanded to changes in price.

The literature on price elasticity of demand for urban and industrial water use is extensive (Espey, Espey, and Shaw, 1997; Gibbons, 1986; Fisher et al., 2005). Typically the value of price elasticity of demand is in the range of -0.2 for urban use, -0.3 industrial, and -0.5 agricultural uses. Specification of demand here does not merely mean specifying the quantity that will be used. Rather, the focus is how benefits change with different quantities of use.

The objective function used in the water allocation system model is presented in Equation (A1) in the Appendix. The proposed objective function maximizes net benefits from water use subject to physical, environmental, and political constraints on water availability. The first term of the objective function is the integral of the inverse demand function. The rest of the objective function represents the costs of water local supply, wastewater treatment, convey of water and treated wastewater to other districts, and desalination.

Water demand function were estimated for Gaza Strip for 2010, 2020, and 2030 using data collected from a variety of sources (Huber Lee, 1999; Metcalf and Eddy, 2000; PWA and SUSMAG 2003; Fisher et al., 2005; Palestinian MoP, 2005; PCBS, 2005). These estimates for each water district and different sectors are given in Table 16.

<u>Demand and supply</u> The water balance for freshwater is given in equation (A2) in the Appendix. The amount of fresh water consumed in any location must equal to the sum of water extracted from the location, desalinated quantity, and water brought from other locations minus the amount conveyed to other locations.

Similar to freshwater, treated wastewater balance is given by Equation (A3) in the Appendix. In this case, the amount consumed in any location must equal the amount produced there plus the amount brought in from other locations minus the amount conveyed to other locations. The water available for treatment is assumed to be available from domestic and industrial sources only. In other words, agricultural consumption is assumed not be available for treatment or recycling.

Table 16. Projected urban, industrial, and agricultural water demands

District	Demand (MCM/year)		
	2010	2020	2030
Urban Sector			
Gaza North	11.3	15.91	20.22
Gaza	26.84	37.81	46.87
Deir al-Balah	11.22	15.8	22.81
Khan-Younis	15.48	21.81	27.53
Rafah	8.24	11.61	16.72
Total	73.08	102.94	134.15
Industrial Sector			
Gaza North	1.1	1.5	2.43
Gaza	2.7	3.5	5.62
Deir al-Balah	1.1	1.5	2.74
Khan-Younis	1.6	2	3.3
Rafah	0.8	1.1	2.01
Total	7.3	9.6	16.1
Agricultural Sector			
Gaza North	22	20	19
Gaza	28	26	25
Deir al-Balah	15	14	14
Khan-Younis	14	12	11
Rafah	9	8	8
Total	88	80	77

Additionally, the quantity of treated wastewater from urban and industrial sectors is a percentage of the quantity demanded by the urban and industrial sectors and only up to 2/3 of water consumed by urban and industrial sectors is available for use in the agricultural sector (Metcalf and Eddy, 2000; Fisher et al., 2005).

Area of Study

Gaza Strip is 40 km long and approximately 9 km wide and located between the Negev desert, Israel and the Mediterranean Sea. Gaza depends on water from the coastal aquifer that runs from the border of Egypt to Haifa in Israel. The aquifer drains from east to west, with negligible north-south flows. Gaza coastal aquifer is presently being overexploited by agricultural abstraction, with total pumping exceeding total recharge. Gaza Strip has a semi-arid climate. There are two well-defined seasons: the wet season is from October to March and the dry season is from April to September. Peak months for rainfall are December and January. The long term mean annual rainfall is 325 mm/year, and it decreases from north to south. The mean temperature varies from 12 to14 ^{o}C in January to 26 to 28 ^{o}C in June. Evaporation measurements have clearly shown that the long term average open water evaporation is approximately 1,300 mm/year. Maximum rates of 140 mm/month in June, July, August, and the minimum is around 70 mm/month during winter.

Gaza is an interesting case study for a variety of reasons. Gaza faces serious issues with saltwater intrusion, as well as aquifer contamination from agricultural and domestic wastes (Afifi, 2006; Agha, 2006). Gaza Strip is densely populated with a growth rate of 3.2%. A majority of the population has relatively low income while the region has a highly uncertain political situation. Political uncertainty has produced the absence of effective political institutions, particularly in the management of natural resources such as water. Given the small area of Gaza in combination with serious political and social issues, it is not surprising that the environmental quality is rapidly deteriorating. There is widespread groundwater contamination, and over-pumping of aquifers has led to seawater intrusion (Yakirevich et al., 1998; Metcalf and Eddy, 2000; Melloul and Collin, 2000; Qahman, 2004; Weinthal et al., 2005; Agha, 2006).

The urban sector is expected to consume about 74 and 134 million m^3 (MCM) of water in 2010 and 2030, respectively. The industrial sector expected to consume 7.5 and

16 MCM at 2010 and 2030, respectively. The agricultural sector is expected to consume 88 and 77 MCM at 2010 and 2030, respectively (Metcalf and Eddy, 2000; Qahman, 2004). The agricultural sector consumes 70% of the total water demand (Issac, 2000; Khalil, Al-Dadah, and Yassin, 2003; Afifi, 2006). The total agricultural area is about 16,650 ha. Presently, water is considered as a "free good" for farmers, without subject to metering or pricing. The farmers pay only the water abstraction cost (pumping), which is less than $0.05/m^3.

Gaza is divided to five districts and are known as Gaza, North Gaza, Deir Al-Balah, Khan Younis, and Rafah (Figure 8). The population of Gaza in 2010 is expected to be 1,557,000 and 1,993,100 in 2010 and 2020, respectively. The population distribution is about 15.4% in North Gaza, 36.7% in Gaza, 15.3% in Deir Al-Balah, 21.1% in Khan-Younis, and 11.2% in Rafah. The urban sector will likely require 73.08 and 102.94 MCM of water in 2010 and 2020, respectively. The industrial water sector is expected to consume water about 7.3 and 9.6 MCM in 2010 and 2020, respectively. The agricultural sector expected to consume water of 88 and 80 MCM in 2010 and 2020, respectively. The projected water demand for 2010, 2020, and 2030 are given in Table 17 (Huber Lee, 1999; Metcalf and Eddy, 2000; PWA and SUSMAG, 2003). Water demand of each district is the summation of urban, industrial, and agricultural water demands. The water allocation system model will be used to investigate the different demands for 2010, 2020, and 2030.

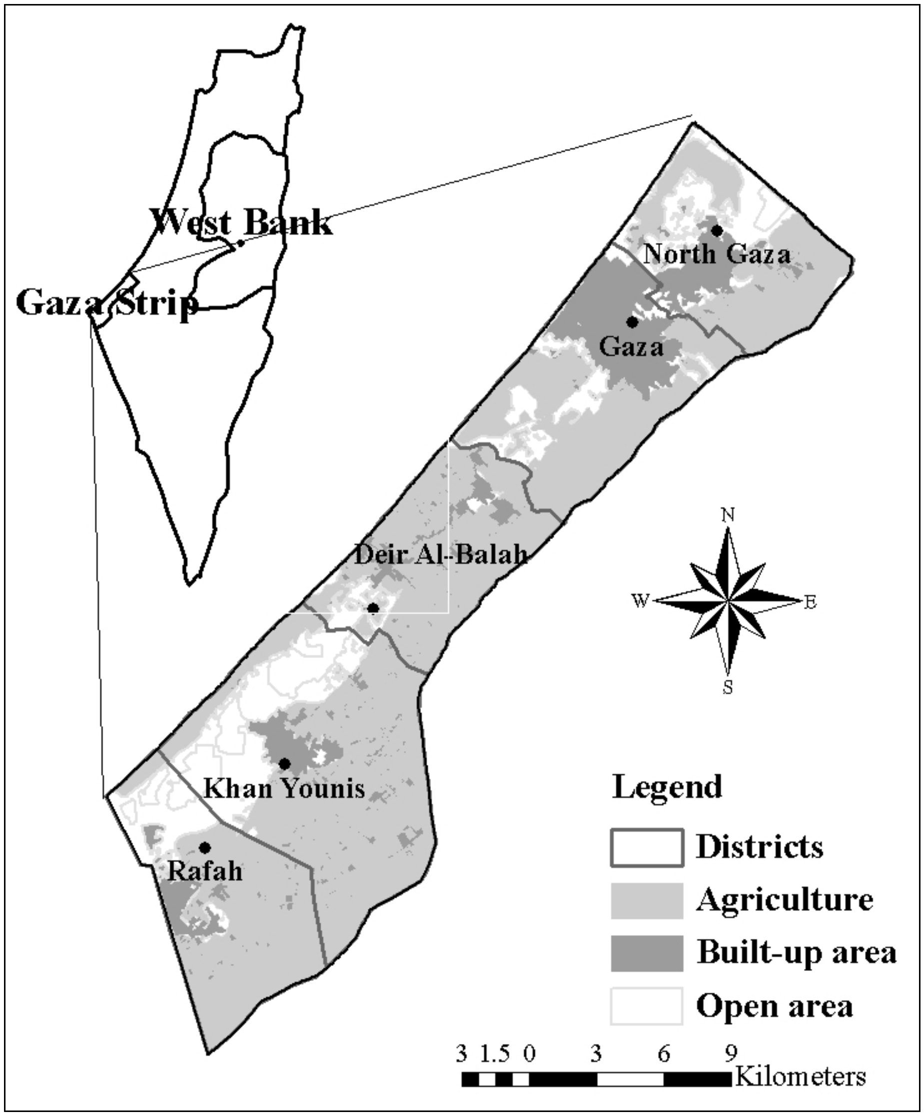

Figure 8. Gaza districts.

Water supply. The Palestinian Water Authority (PWA) stipulates the maximum allowable groundwater extraction in each district based on the water budget, sustainability, and seawater intrusion (Metcalf and Eddy, 2000).

The available water supply to Gaza is 138 MCM/year in 2010. This 138 MCM of water is the maximum groundwater withdrawal from the Gaza coastal aquifer.

Table 17. Projected water demand function characteristics for the urban, industrial, and agricultural sectors in Gaza Strip for 2010, 2020, and 2030

	2010		2020		2030	
	β	α	β	α	β	α
Urban Sector						
North Gaza	0.81	-0.42	0.89	-0.39	1.12	-0.46
Gaza	1.02	-0.38	1.18	-0.38	1.32	-0.39
Deir Al-Balah	0.81	-0.41	0.86	-0.39	1.03	-0.41
Khan Younis	0.91	-0.41	0.92	-0.38	1.18	-0.42
Rafah	0.71	-0.41	0.79	-0.37	1.19	-0.49
Industrial Sector						
North Gaza	0.32	-0.54	0.36	-0.47	0.47	-0.56
Gaza	0.53	-0.54	0.56	-0.52	0.61	-0.42
Deir Al-Balah	0.31	-0.60	0.36	-0.47	0.49	-0.51
Khan Younis	0.36	-0.48	0.39	-0.49	0.54	-0.54
Rafah	0.25	-0.42	0.30	-0.49	0.42	-0.52
Agricultural Sector						
North Gaza	1.00	-0.56	0.98	-0.57	0.89	-0.55
Gaza	0.99	-0.57	0.91	-0.55	0.84	-0.53
Deir Al-Balah	1.12	-0.55	1.09	-0.55	0.88	-0.47
Khan Younis	0.69	-0.66	0.64	-0.66	0.54	-0.62
Rafah	0.68	-0.61	0.66	-0.62	0.54	-0.52

Note: The demand function is $P = \beta \times Q^{\alpha}$.

The supply of 138 MCM is distributed as 45 MCM rainfall recharge, 30 MCM from lateral inflow from Israel, 5 MCM from lateral inflow from Egypt, 15 MCM from water system leaks, 10 MCM from wastewater return flows, 25 MCM from irrigation return flows, and 8 MCM from other recharge sources.

The use of treated wastewater in agriculture is low in Gaza due to the poor social acceptance. Water supply is expected to remain the same for the years of 2020 and 2030 (Metcalf and Eddy, 2000).

The supply is distributed as follows: 30.6, 45.1, 32.2, 24.5, 14.6 MCM for North Gaza, Gaza, Deir al-Balah, Khan-Younis, and Rafah, respectively. The price of water is

$0.33/m^3 for the urban and industrial sector in 2010. The price of water for the agricultural sector is $0.16/m^3 in 2010 (Melloul and Collin, 2000; Fisher et al., 2005; Weinthal et al., 2005).

The costs of water pumping are 0.033, 0.014, 0.018, 0.031, and 0.032 \$/m^3 for North Gaza, Gaza, Deir al-Balah, Khan-Younis, and Rafah, respectively in 2010 (Fisher et al., 2005; Melloul and Collin, 2000; Weinthal et al., 2005).

Management Options for Water Deficit

The following management options have been discussed by PWA for improving the existing and future water deficits.

Desalination PWA proposes to build two desalination plants each capable of producing 1.83 MCM/year of freshwater at North Gaza and Deir al-Balah districts. Also PWA proposes to construct a large desalination plant of capacity 54.8 MCM/year in the Gaza district. Two other studies recommended one additional desalination plant in each of the five districts (PWA and SUSMAG 2003; PWA and CDM, 2003) with individual capacity of 15 MCM/year. These studies anticipate a growing population and consequently high demand on freshwater in the Khan-Younis and Rafah districts.

Wastewater treatment PWA plans to reconstruct and rehabilitate the three existing wastewater treatment plants located in North Gaza, Gaza, and Khan-Younis districts with a proposed maximum capacity 21.5, 65.7, and 29.2 MCM/year, respectively. Also PWA plans to construct two additional wastewater treatment plants for Deir al-Balah and Rafah districts with a maximum capacity of 5.3 MCM/year each (PWA, 2003; Metcalf and Eddy, 2000).

Water purchases PWA plans to purchase additional 5 MCM/year to be delivered to Khan-Younis district in the future. At present, 5 MCM/year of potable water is purchased from Israeli National Water Supply Company for the Gaza district.

The options discussed earlier have been proposed through various studies conducted in Gaza. However, none of these infrastructure improvements have been undertaken due to the financial situation and more importantly the existing unrest and political crisis. This study will use some of the proposed options in developing scenarios to improve water management in Gaza.

Results and Discussion

In the first part of this study, the focus is to evaluate if the use of treated wastewater in agriculture is sustainable and economically attractive while considering some restriction on groundwater abstraction to reduce sea water intrusion. Based on the results obtained from this part of the analysis, the second part will consider the need to improve the infrastructure for supply enhancement through desalination, conveyance, and new wastewater treatment plants.

Use of treated wastewater in agriculture and reduced groundwater abstraction

The proposed scenarios are (1) the existing conditions, i.e., no reduction in groundwater abstraction and no use of treated wastewater; (2) existing conditions with the use of treated wastewater for agriculture; (3) existing conditions with 50% reduction in groundwater pumping only; (4) existing conditions with 50% reduction groundwater pumping and the use of treated wastewater in agriculture.

All four scenarios were simulated for 2020 demand conditions. Treated wastewater used in these scenarios will be available from existing wastewater treatment plants. When treated wastewater is not used, only freshwater is available for agriculture. In other words, $QREC_{id}$ in Equation (A1) in the Appendix is zero. The agricultural water demand in the objective function (QD_{id}) uses fresh water only. When reduced pumping is considered, a percent reduction on groundwater pumping is imposed on the allowable maximum abstraction value in the right hand side of Equation (A7) in the Appendix.

Maintenance of existing groundwater abstraction

Table 18 provides detailed results of Scenarios 1 and 2 where groundwater pumping is maintained at current levels but includes with and without the use of treated wastewater in agriculture. The net benefit increased when treated wastewater is used for agriculture due to the availability of more water for each district. As an example, the shadow values for Rafah district with and without treatment plants are 0.35 and 1.68 $\$/m^3$, respectively. The water prices of urban and industrial sectors decrease when the sector's wastewater is treated and reused in agriculture. The agricultural sector received all treated wastewater which was greater than the quantity of fresh water originally allocated to agriculture. Agricultural water prices also decrease as a result of the increased water allocation to the agricultural sector. Overall, the total net benefits increase by $172 million/year (the difference between 616.43 and 444.8 millions $) when treated wastewater urban and industrial wastewater is treated and reused in agriculture. Due to the low chemical hazard and low quantities generated from the industry in Gaza, there is no special treatment for industrial water. Industrial wastewater is treated with domestic wastewater in the same treatment plants.

As shown in Table 18, the shadow value of water decreased in all districts after considering treated wastewater in agriculture. As an example, the shadow value of Rafah district without and with the use of treated wastewater in agriculture were 1.68 and 0.35 $\$/m^3$, respectively. This reduction in shadow value of water refers to the increase of water availability.

Reduction of groundwater abstraction by 50%

Table 19 shows the detailed results of Scenarios 3 and 4 where groundwater pumping is reduced by 50% from the existing conditions but with and without the use of treated wastewater. Table 19 shows that the net benefit increases by $70.1 million/year (the difference between $172.94 and 242.95 millions (when wastewater is treated and used in agriculture).

The urban and industrial water prices decrease because of increased allocation of water to the urban and industrial sectors. This increase in allocation of water results from the use of treated wastewater in agriculture.In this case too, agricultural sectors received all treated wastewater which is greater than the amount of fresh water originally allocated to the agricultural sector. As an example, the urban and agricultural prices decrease by $\$0.07/m^3$ (which is the difference between $\$0.48/m^3$ with and $\$0.41/m^3$ without the use of treated wastewater) and $\$0.97/m^3$ (which is the difference between $\$1.22/m^3$ with and $\$0.25/m^3$ without the use of treated wastewater) in Rafah district. The reason is that the quantity of wastewater allocated for agriculture increased from 0.21 MCM of freshwater to 4.81 MCM of treated wastewater as shown in Table 19. The results of Tables 18 and 19 clearly indicate that for a given groundwater withdrawal, the use of treated wastewater already available from the different treatment plants can be used in agriculture providing significant economic benefit.

Table 18. Selected model results for the demand year of 2020 without reduced pumping

Item	Scenario 1 - Without use of treated wastewater					Total
	North Gaza	Gaza	Deir al-Balah	Khan Younis	Rafah	
Net benefit (millions $)	127.10	185.00	85.96	31.00	15.74	444.8
Fresh water demanded in urban sector (Q_{du}), MCM	0.098	44.63	0.099	23.33	13.05	81.21
Fresh water demanded in industrial sector (Q_{di}), MCM	0.82	0.39	0.85	0.85	1.33	4.24
Fresh water demanded in agricultural sector(Q_{da}),MCM	29.67	0.67	22.24	0.31	0.22	53.11
Fresh water supplied (QS_n),MCM	30.66	45.10	23.20	24.50	14.60	138.06
Urban water price ($\$/m^3$)	2.20	0.28	0.75	0.28	0.31	--
Industrial water price ($\$/m^3$)	0.39	0.91	0.39	0.42	0.26	--
Agricultural water price ($\$/m^3$)	0.14	1.13	0.20	1.38	1.69	--
Shadow value of water ($\$/m^3$)	3.22	4.57	2.96	2.64	1.68	--
Item	**Scenario 2 - With use of treated wastewater**					**Total**
	North Gaza	Gaza	Deir al-Balah	Khan Younis	Rafah	
Net benefit (millions $)	136.20	268.15	91.13	87.40	33.55	616.43
Fresh water demanded in urban sector (Q_{du}), MCM	29.77	44.70	22.30	23.60	13.26	133.63
Fresh water demanded in industrial sector (Q_{di}), MCM	0.82	0.39	0.85	0.85	1.33	4.24
Fresh water demanded in agricultural sector(Q_{da}),MCM	0.00	0.00	0.00	0.00	0.00	0.00
Recycled water supplied ($QREC_{na}$),MCM	20.19	29.70	15.31	16.17	9.63	91.00
Fresh water supplied (QS_n)	30.66	45.10	23.20	24.50	14.60	138.06
Recycled water from the urban sector (QRY_u),MCM	19.60	29.50	14.70	15.60	8.75	88.15
Recycled water from the industrial sector(QRY_i),MCM	0.545	0.26	0.56	0.56	0.87	2.795
Urban water price ($\$/m^3$)	0.24	0.28	0.26	0.28	0.30	--
Industrial water price ($\$/m^3$)	0.39	0.91	0.39	0.42	0.26	--
Agricultural water price ($\$/m^3$)	0.18	0.14	0.24	0.10	0.16	--
Shadow value of water ($\$/m^3$)	2.75	2.91	2.59	0.54	0.35	--

The shadow value of water increased when the pumping was constrained due to the higher scarcity of water. The prices of water in each sector decrease especially in the agricultural sector while increasing the net benefits. Districts such as Gaza and Rafah showed significant increase in net benefit.

<u>Impacts of reduced groundwater pumping</u>

The results of Table 18 and 19 need to be compared to assess the overall impact of reduced groundwater pumping. The results clearly show that when groundwater pumping is reduced which in this case 50%, the net benefits reduced across all districts and sectors. With the use of treated wastewater, the net benefit in North Gaza decreased from $136.2 to $47.28 million, which is a reduction of 65%. Also prices of water in all sectors in all districts increased significantly too. For example, North Gaza will experience an increase of urban water prices from 0.24 to 0.31 $/m^3 and the agricultural water prices from 0.18 and 0.26 $/m^3.

Similar results are obtained for the case of not using treated wastewater in agriculture. For example, the net benefits of North Gaza reduced from 127.1 to 41.33 million $/year. The urban water price reduced from $2.20 to 0.33/m^3. However, this reduction appears as an increase in agricultural water price where the price increased from $0.14 to $3.35/m^3 for North Gaza. In essence, these results suggest negative economic benefits with reduced groundwater pumping due to the lack of adequate supply when groundwater pumping is reduced.

Figure 9 shows the shadow value of water for 2010. Figure 10 shows the shadow value of water for 2030. The shadow values are highest in Gaza followed by North Gaza and others. The highest shadow value is observed without the use of treated wastewater and 50% reduction in groundwater.

Table 19. Selected model results for the demand year of 2020 with 50% reduction in pumping

Item	Scenario 3 - Without use of treated wastewater					
	North Gaza	Gaza	Deir al-Balah	Khan Younis	Rafah	Total
Net benefit (millions $)	41.33	70.62	21.50	26.88	12.61	172.94
Fresh water demanded in urban sector (Q_{du}), MCM	14.64	22.21	10.98	11.64	6.38	65.67
Fresh water demanded in industrial sector (Q_{di}), MCM	0.57	0.27	0.52	0.45	0.70	2.51
Fresh water demanded in agricultural sector (Q_{da}),MCM	0.09	0.07	0.10	0.15	0.21	0.937
Fresh water supplied (QSn), MCM	15.30	22.50	11.60	12.25	7.30	68.95
Urban water price ($/m^3)	0.33	0.39	0.38	0.42	0.48	--
Industrial water price ($/m^3)	0.64	1.06	0.69	0.83	0.51	--
Agricultural water price ($/m^3)	3.35	3.55	2.60	1.72	1.22	--
Shadow value of water ($/m^3)	6.12	6.61	4.14	3.48	2.66	--
Item	**Scenario 4 - With use of treated wastewater**					
	North Gaza	Gaza	Deir al-Balah	Khan Younis	Rafah	Total
Net benefit (millions $)	47.28	96.67	31.57	29.58	10.86	242.95
Fresh water demanded in urban sector (Q_{du}), MCM	14.47	22.15	10.74	11.39	5.96	64.71
Fresh water demanded in industrial sector (Q_{di}),MCM	0.82	0.39	0.85	0.85	1.33	4.24
Fresh water demanded in agricultural sector (Q_{da}), MCM	0.00	0.00	0.00	0.00	0.00	0.00
Recycled water supplied ($QREC_{na}$), MCM	10.09	14.88	7.65	8.09	4.81	45.52
Fresh water supplied (QS_n), MCM	15.30	22.55	11.60	12.25	7.30	69.0
Recycled water from the urban sector (QRY_u), MCM	9.55	14.62	7.09	7.56	3.94	42.76
Recycled water from the industrial sector (QRY_i), MCM	0.55	0.26	0.56	0.56	0.88	2.81
Urban water price ($/m^3)	0.31	0.36	0.34	0.37	0.41	--
Industrial water price ($/m^3)	0.39	0.91	0.39	0.42	0.26	--
Agricultural water price ($/m^3)	0.26	0.21	0.36	0.16	0.25	--
Shadow value of water ($/m^3)	4.74	3.83	4.0	0.81	0.62	--

The minimum values are observed with the use of treated wastewater and no reduction in groundwater pumping for all years. Introducing treatment and the use of treated wastewater has a positive economic impact on Gaza. Even with wastewater treatment and use, shadow values of water in most Gaza districts are above \$ 0.60/m^3 (Figure 9 and Figure 10).

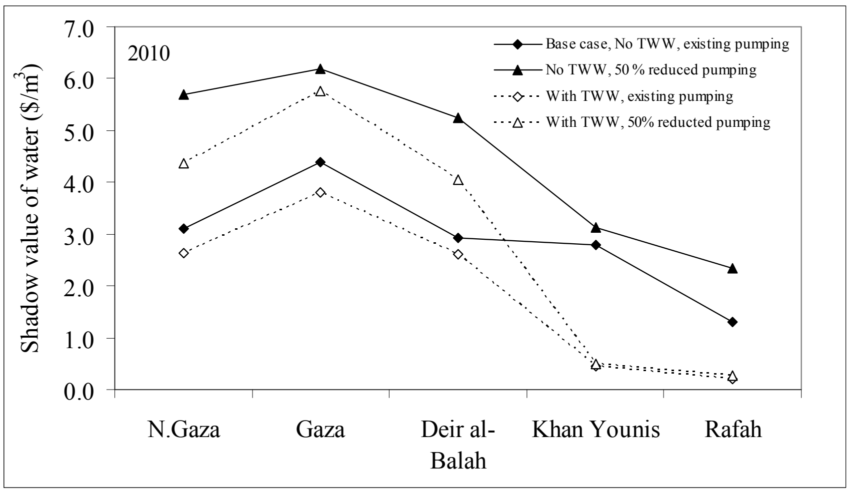

Figure 9. Computed shadow value of water for Scenarios 1 through 4 for 2010. TWW refers to treated wastewater.

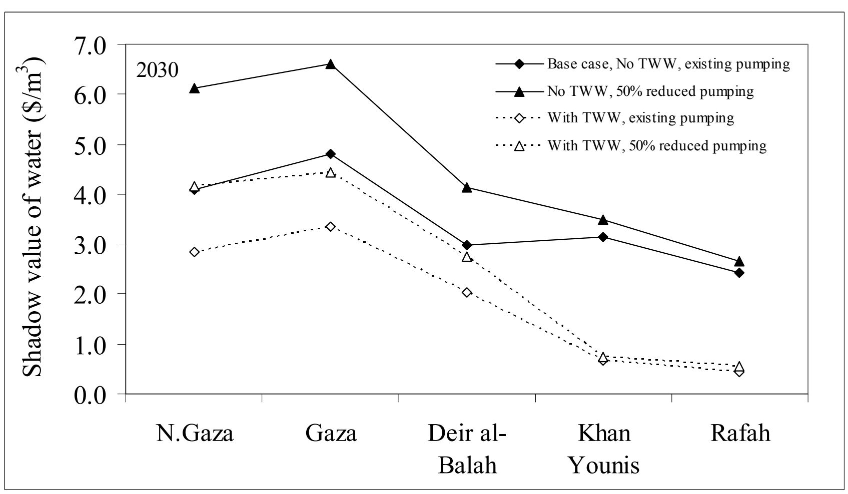

Figure 10. Computed shadow value of water for Scenarios 1 through 4 for 2030. TWW refers to treated wastewater.

This result motivates a search for new and additional water sources that will be addressed in the next section.

Options for Water Supply Enhancements

As discussed earlier, treated wastewater reuse for agriculture did not reduce the shadow value of water below $0.60/m^3. Moreover, the shadow value of water increases in 2020 and 2030. These two factors necessitate the search for new and additional water resources. In this work, the approaches considered to enhance supply are (a) the use of desalinization to increase freshwater output; (b) increase the number of wastewater treatment plants to increase wastewater output; (c) a water conveyance system between districts to distribute water on a demand basis. This work will consider different combinations of these approaches to enhance supply and the applicability of a given option will be evaluated using net benefit and shadow value of water.

Previous work clearly showed that the shadow value of water is highest in 2030 followed by 2020. The reason is that the demand increases with time due to the increased population while the supply remains the same. Therefore this work will develop several management options to increase supply based on the three approaches discussed earlier. The proposed management options are as follows: (1) base case scenario where there is no constraints on pumping and no use of treated wastewater; (2) Addition of five wastewater treatment plants for all Gaza districts; (3) Option 2 with 50% reduced pumping; (4) Option 3 including conveyance pipeline from distribute water from districts with low shadow value to districts with high shadow value of water. The conveyance line is proposed from Khan-Younis district to North Gaza district and from Rafah district to

Gaza district. The maximum volume of water to be transported is 5 MCM; (5) Option 4 including a desalination plant to each district with a maximum capacity of 15 MCM; (6) Option 3 with the addition of three desalination plants of capacity of 1.825 MCM for North Gaza and Deir Al-Balah, and 54.75 MCM for Gaza. (7) Option 6 including a conveyance pipline from Gaza district to Rafah and Khan-Younis districts. The maximum volume of water to be transported from Gaza district is 10 MCM.

Shadow value of water

Figure 11 shows the shadow values of water in different sectors under the different proposed options. The shadow values for the year of 2010 decreased from $4.40/m^3 to $3.81/m^3 (or a 13%) as a result of five new wastewater treatment plants in the Gaza district. Similarly, shadow prices decreased from $4.57/m^3 to $2.91/m^3 (36%) and $4.81/m^3 to $3.35/m^3 (30%) for 2020 and 2030, respectively. It is obvious that the addition of wastewater treatment plants is more beneficial after 2020. However, the treated wastewater in agriculture did not reduce the shadow value of water to a desirable level from $0.6/m^3. Therefore, other options such as the use of desalination and water conveyance should be considered.

Figure 11 shows the shadow value of water for the year 2030 for options 1, 2, 3, 4, 5, and 6. The shadow value is highest in the absence of wastewater treatment plants which is Option1. Adding five wastewater treatment plants as per Option 2 and reusing treated wastewater in agriculture reduced the shadow value. Option 3 shows that reduced pumping from the Gaza aquifer by 50%, increased the shadow value of water in all districts. This increase reflects additional scarcity of water in all districts. When a conveyance system from Rafah to Gaza and from Khan-Younis to N. Gaza is simulated and added to Option 3 which is Option 4, the shadow value of water decreased for N.Gaza and Gaza but increased in Khan-Younis and Rafah districts as expected. By adding desalination plants for each district with a total capacity of 15 MCM as in Option 5, the shadow value of water decreased to the lowest value in all districts. These reductions in the shadow values reflect the increase in supply.

Option 6 is Option 3 with three desalination plants are added to North Gaza, Deir al-Balah, and Gaza district. In Option 6, the shadow value of water decreased dramatically for Gaza district to $0.52/m^3 due to increased freshwater supply. The shadow value of water increased in Option 6 in Khan-Younis and Rafah districts to 1.37 and 0.79 $/m^3, respectively. This is because desalination was not introduced in these districts. When Option 6 was modified with a conveyance system from Gaza to Rafah and from Gaza to Khan-Younis to generate Option 7, the shadow value of water decreased in Khan-Younis and Rafah districts to $0.76/m^3 and $0.57/m^3, respectively. This increase reflects the new available water of 10 MCM delivered to each district. The shadow value of water increased in Gaza district to $0.82/m^3 due to the export of 20 MCM from Gaza district to Khan-Younis and Rafah districts.

Net benefits

Figure 12 shows the calculated net benefit for Options 1, 2, 3, 4, 5, and 6 for the demand year of 2030. The base case produced a total net benefit for all districts of $477.8 million $/year. The addition of five wastewater treatment plants in Option 2 increased the total net benefit to $694.2 million. When pumping was reduced by 50% to Option 2, the total net benefit decreased to $245 million.

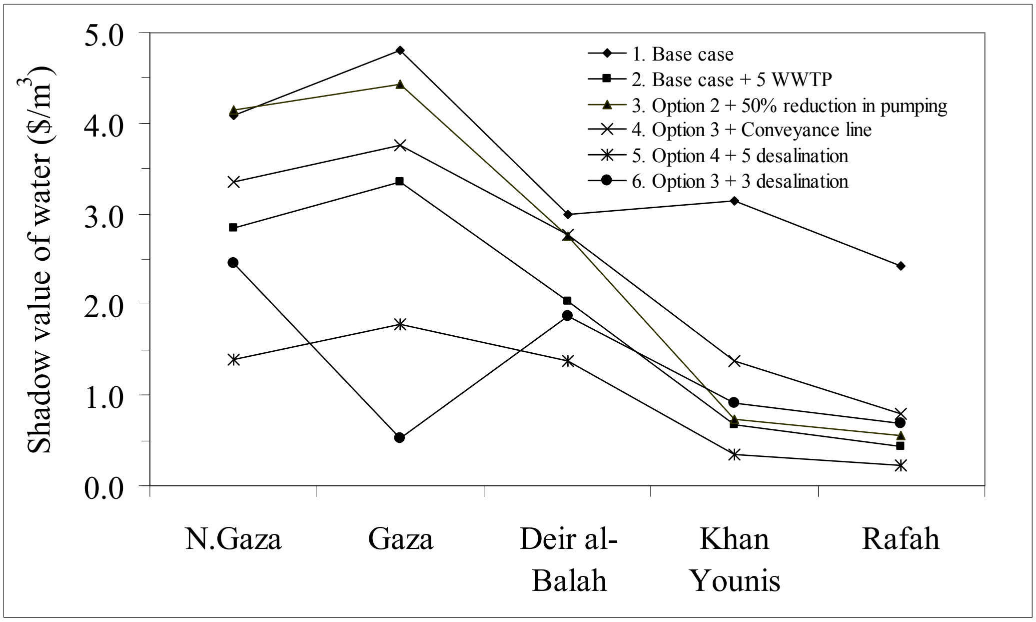

Figure 11. Computed Shadow value of water for 2030.

This reduction in benefit is due to the reduction of water availability. When a conveyance system was introduced from Rafah to Gaza and from Khan-Younis to North Gaza, the total benefit increased to \$279 million. The addition of desalination plants to each district with a total capacity of 15 MCM, the total net benefits increased to \$691 million. The net benefit increased in Option 6 after considering three desalination plants with five wastewater treatment plants. In Option 7 where Option 6 was amended to include a conveyance system from Gaza district to Rafah and Khan-Younis, the total benefit increased to \$746.6 million.

<u>Water prices</u>

Figure 13 shows the urban water prices for different sectors. Urban water prices decrease when treated wastewater is used for agriculture since more availability of groundwater for the urban sector. However, the urban prices increased after reducing pumping by 50%.

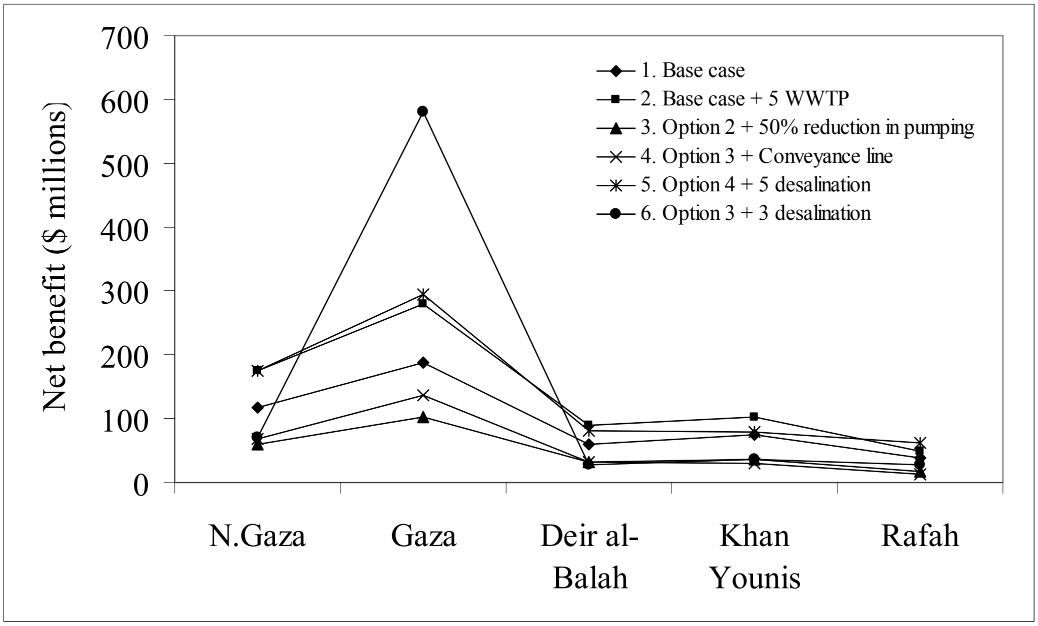

Figure 12. Computed Net benefit for 2030.

The urban water prices were also affected when transferring water from district to district. The urban water prices were increased in Khan-Younis and Rafah districts and reduced from Gaza and North Gaza.

These reductions in urban water prices in Gaza and North Gaza are due to the increased water availability due to the imported water from Rafah and Khan-Younis districts. The urban water prices were lowest with desalination plants of 15 MCM capacity in each district. In addition, the urban water prices were the lowest with a large desalination plant of 54.75 MCM in Gaza district.

The agricultural water prices decreased dramatically when treated wastewater was used in agriculture due to the availability of more water. In other words, other water management options have low impact on agricultural water prices. Figure 14 shows that the agricultural water prices decreased when treated wastewater is used for agriculture.

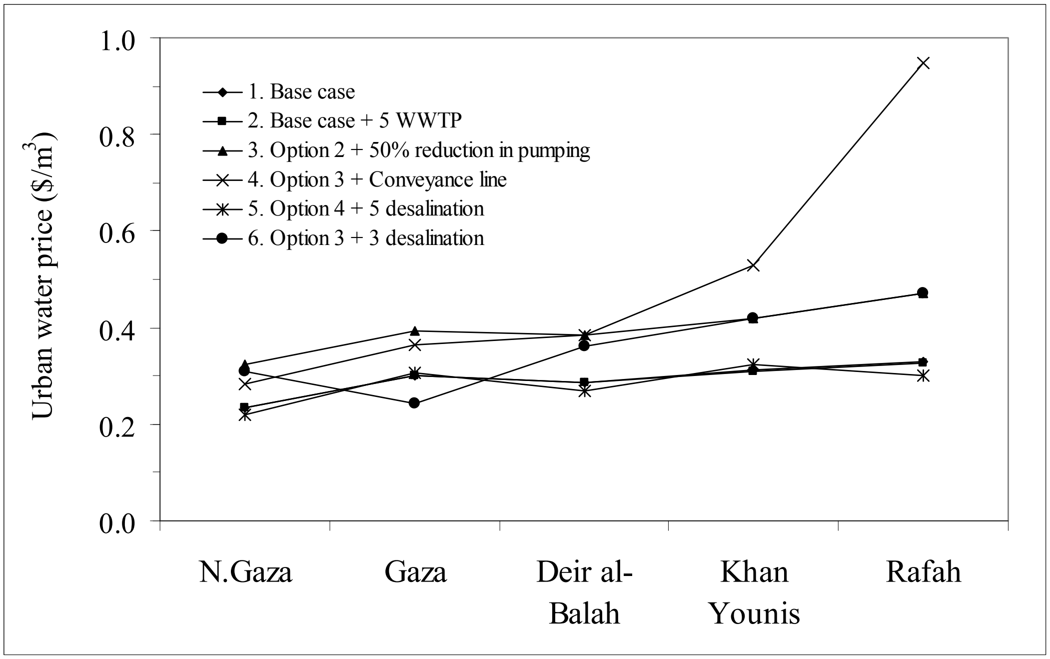

Figure 13. Computed urban water price for 2030.

The base case Scenario produced agricultural water prices of 3.34, 3.54, 2.59, 1.72, 1.21 $\$/m^3$ for N.Gaza, Gaza, Deir al-Balah, Khan-Younis, and Rafah districts, respectively. These agricultural water prices decreased to 0.17, 0.139, and 0.09 $\$/m^3$ for N.Gaza, Gaza, Khan-Younis districts, respectively, with the introduction of wastewater treatment plant in each district (Option 2). These reductions in agricultural water prices are due to the complete allocation of all treated wastewater to agriculture. The other water management scenarios have low impacts on agricultural water prices.

Benefits of Combinations of Options

Table 20 shows the net benefits for different combinations of desalination plants combined with and without the use of treated wastewater and groundwater withdrawal.

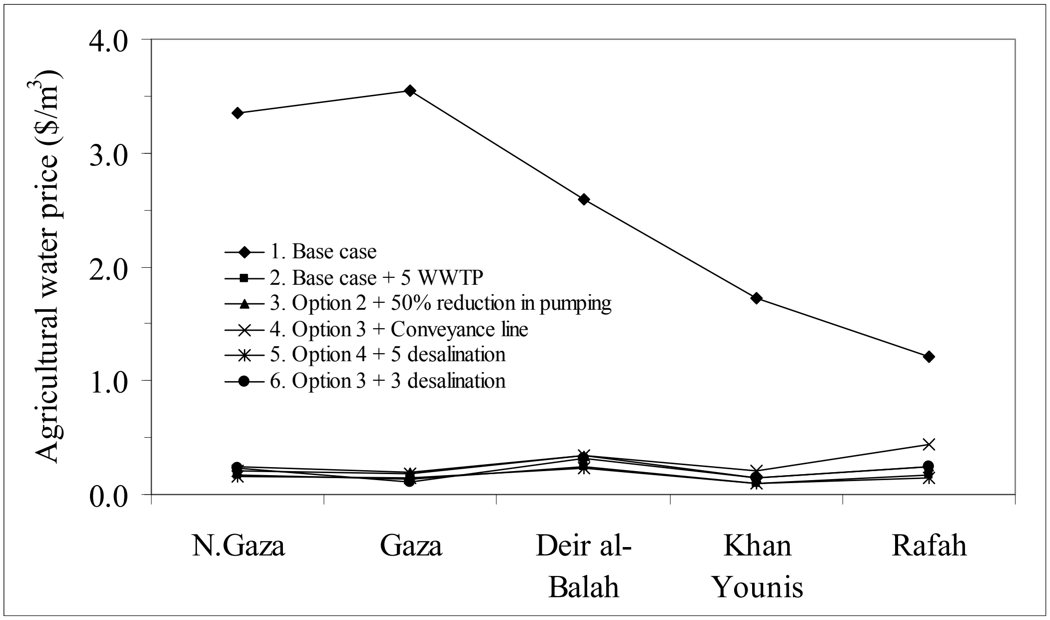

Figure 14. Computed agricultural water prices for 2030.

The results shows that lowest net benefit for a given year is obtained with no use of treated wastewater and 50% reduction in groundwater pumping. This reduction corresponds to more than 60% reduction from the base case. As treated wastewater is added to any given option, the benefits increase by about 50%. As desalination is included, these benefits can increase by 50% or so with three desalination units. For example, the net benefits increased from $616.4 to $1189.9 in 2030 with use of treated wastewater. However, increasing the number of desalination units to five will provide insignificant increase in benefit; for example from $1189.9 to $1190 million/year. Similar results are seen with year 2030. In general, the results indicate that the best management options are use of treated wastewater through increase wastewater treatment plants followed by three desalination units without a reduction in groundwater pumping. However, given the situation of seawater intrusion and poor groundwater quality, some reduction in groundwater pumping is beneficial even at a cost of reduced net benefit.

Optimal Infrastructure Developments and Associated Net Benefits

The analyses and results discussed so far from this work addressed some of the options discussed by Metcalf and Eddy (2000), and PWA and CDM (2003).

However, it is also important to find the best combination from the different approaches of desalination, wastewater treatment and reuse and reduced groundwater withdrawal from the Gaza aquifer while addressing benefits. A simulation was conducted with a high upper bound of 200 MCM/year set for each desalination plant in each district to find the optimal desalinization capacity required in each district.

Table 21 shows the optimal infrastructure developments and associated net benefits at different percent reductions of pumping. The estimated capital costs of 1 MCM/year desalination is $2.72 million (Metcalf and Eddy, 2000; PWA and CDM 2003).

The capital cost of building and rehabilitation wastewater treatment plants are $82, $82, $100, $100, and $82 million for N. Gaza, Gaza, Deir al-Balah, Khan-Younis, and Rafah, respectively (Metcalf and Eddy 2000; PWA and CDM, 2003).

The net benefits listed in Table 21 are the differences in the objective function value of the Water Allocation System Model between 200 MCM/year upper bound desalination scenario and the base case. For example, the net benefit of $809.0 million at no reduction in pumping is the difference between $1287 million (with 80.5 MCM/year capacity of desalination) and $477.88 million (without desalination). By applying a discount rate of 3%, the present value of benefits is about $12.02 billion with no reduction in pumping. The profit is the difference between the present value of annual benefits and the capital cost of infrastructure.

Table 20. Computed net benefit with different management options for supply enhancement

Option			Net Benefit (millions $/year)	
Year	Desalination Plants[1]	Reduction in pumping (%)	Without wastewater treatment plants	With wastewater treatment plants
2020	No	0	444.8	616.4
		50	153.8	215.9
	3	0	759.8	1189.9
		50	416.1	689.1
	5	0	786.2	1090.7
		50	409.5	574.2
2030	No	0	477.8	694.2
		50	172.9	245.9
	3	0	841.4	1294.5
		50	478.1	740.6
	5	0	837.3	1241.0
		50	480.8	709.7

[1] Five desalination plants consider a desalination plant in each district with a capacity of 15 MCM/year. Three desalination plants consider two reverse osmosis desalination plants for North Gaza and Deir al-Balah with individual capacity of 1.825 MCM/year and one large desalination plant for Gaza district with a capacity of 54.75 MCM/year.

Table 21. Optimal infrastructure developments and associated net benefits for 2030. The results show the changes in benefits between the base case and with the simulation with an upper bound for desalination of 200 MCM/year

Item	Reduction in Pumping (%)			
	0	15	25	50
Net benefit (million $/year)	809	813.9	818.2	849.1
Total desalination capacity (MCM/year)	80.5	92.5	100.6	120.7
Total wastewater treatment capacity (MCM/year)	141	135	131	124
Capital costs of treatment plant and desalination (million $)	300	333	373.6	428.4
Present value of net benefit (billion $)	12.02	12.1	12.16	12.62
Profit (billion $)	11.73	11.76	11.79	12.19

The profit is lowest with no reduction in pumping and at the lowest desalinated water volume as shown in Table 21. The profit is the highest at 50% reduction in pumping or with highest quantity of desalinated water. The lowest value of profit at 0% reduction pumping ($29.6 million) is due to the low value of net benefit of 809 million $/year. To increase the profit, to the volume of desalinated water and wastewater treatment for reuse should increase to 120.7 MCM and 124 MCM, respectively.

One limitation of this analysis is the uncertainty of some of the key input parameters. These include the treatment efficiency of wastewater treatment plants, and cost and reliability of reverse osmosis plants for desalination. Other uncertainties include the reliable network for diversion of raw wastewater to treatment from different sources and lack of adequate monitoring and quality control measures.

Institutional Framework

Existing water institutions

This section overviews the existing water institutions in Gaza and will recommend changes needed to encourage wastewater treatment and reuse in agriculture. Costs of changes are compared with increased net benefits predicted by earlier results.

Ministry of Planning and International Cooperation (MoPIC) MoPIC is responsible for policy development, and planning for the overall development of Palestinian areas, including both the water resources and agriculture sectors.

Ministry of Agriculture (MoA) The main goal MoA is to improve and develop the agricultural sector in Palestine by transferring new technologies to the farmers and formulating long term and short term agricultural policy to achieve food security.

Palestinian Standards Institute (PSI) The PSI is the official institute of accreditation to standard measures and specification for wastewater qualities and reuse.

Environmental Quality Authority (EQA) The EQA seeks to promote sustainable environmental development of the Palestinian society. The main goal of EQA is to protect all elements of the environment and prevent health risks.

Local Authorities (Municipalities and Village Councils) Local authorities are the representative of the government at a local level and are stakeholders of all infrastructure projects.

Ministry of Local Government (MoLG) MoLG is responsible for the physical planning for the expansion of built-up areas. The MoLG is the government body responsible for providing the municipalities and village council (local authorities) with financial and administrative assistance.

Ministry of Health (MoH) MoH is responsible for public health and is therefore involved in the control and monitoring of potable water quality, food quality, wastewater related disease.

Palestinian Central Bureau of Statistics (PCBS) PCBS is the main source of information and data about the Palestinian Territories. PCBS collects and estimates population data, and agricultural statistics.

Palestinian Agricultural Relief Committees (PARC) PARC is an important agricultural organization in Palestine working on agricultural development. PARC works in rural Palestinian areas specifically in public awareness to guide the farmers to improve farming practices.

Recommended changes for water institutions

Figure 15 shows the proposed plan for roles and functions of water related institutions involved in Gaza to promote treatment and use of wastewater in agriculture.

Local authorities will manage the wastewater transport network to supply the wastewater storage ponds. Also local authorities will oversee the conveyance of raw wastewater to these ponds but MoLG will supervise on the local authorities. EQA will verify compliance of local government overseen sewage ponds to the PSI standards such as residence time and organic matter concentration. Local authorities supervised by MoLG will convey storage pond effluents to the wastewater treatment plants. The EQA will examine the quality of the effluent treated wastewater based on the treatment standards set by PSI. Thereafter the MoH verifies the quality of treated wastewater based on crop requirements. The MoPIC and MoA will use the database and research, conducted by the PCBS and other academic institutions, to develop and manage future plans for the agricultural sector. The MoPIC and MoA will also provide the PWA with the management plans. PARC institute provides farmers with agriculture equipments, seeds, fertilizers, and instructions. This task makes the role of PARC vital as they have the most interaction with farmers and farmer needs. PARC will supply PWA with information that illustrates farmer's requirements and needs. The PWA will allocate the water among the different sectors based on the demand. The PWA will evaluate the results and studies provided by MoPIC and MoA with the existing conditions for future planning. The PWA will give the feedback to the MoPIC and MoA.

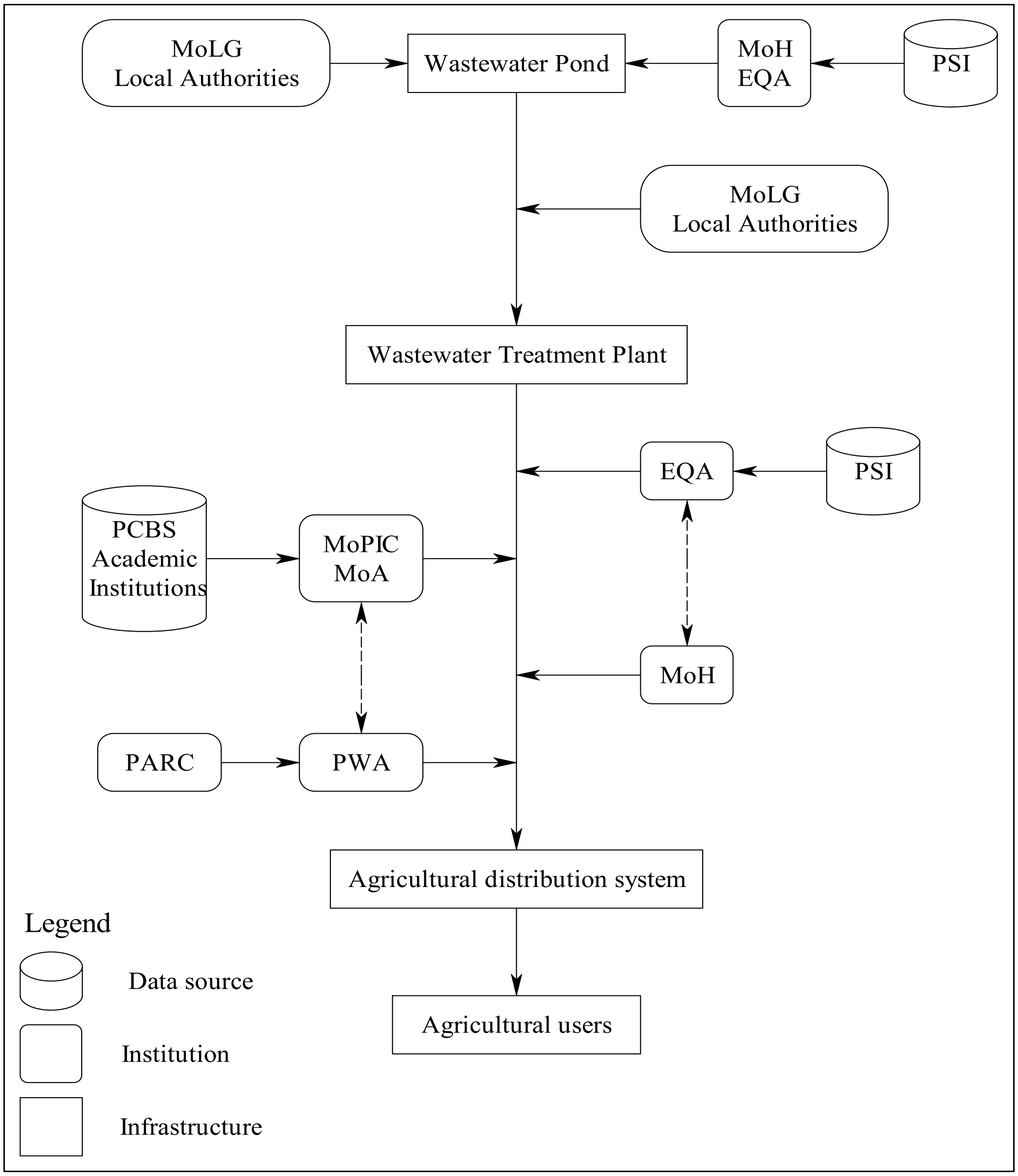

Figure 15. Flowchart of the institutional interaction to encourage reuse treated wastewater in agriculture.

Economic evaluation of recommended institutional changes

Since the net benefit of using three treatment plants is economically more beneficial than using five wastewater treatment plants, we will compare the net benefits obtained from using the three wastewater treatment plants with the institution budget.

The net benefit obtained from the water allocation model with five wastewater treatment plants in 2010 is \$611 million/year. Metcalf and Eddy (2000) estimated the total operating budget of \$ 4.7 million/year for the Palestinian institutions involved in implementing and regulating wastewater treatment and reuse for 2010. This budget is small compared to the estimated \$611 million/year increase in net benefits predicted by the water allocation system model when five wastewater treatment plants are built and operated in Gaza. This increase should motivate and potentially fund both the institutional improvements and wastewater treatment and reuse infrastructure and facilities. This profit of \$606.3 million encourages the use of treated wastewater in agriculture.

Conclusions

Most water deficit regions in the world are suffering from lack of adequate water due to increasing demands from population growth. Therefore, water cannot be treated as a "free" good and instead, the actual costs associated with the development and management of water to each user should be considered. In managing water, planner and policy developers need to be innovative in developing alternative water sources when the supply is limited but demands are increasing. Gaza Strip, Palestine is a classical example experiencing these issues together with groundwater quality deterioration due to excessive pumping from the coastal aquifer. In addition, the population growth in the region is well above the regional and global average and also experiences significant political unrest. In such regions, water planners should be innovative in developing alternative sources of water while ensuring water from these sources is delivered in an economically efficient manner. The use of sophisticated economic and optimization tools can be readily used in these situations to assess the applicability of different management options. In this work, the Water Allocation System Model of Fisher et al. (2005) is used here to find the applicability of using treated wastewater in agriculture to reduce the stress on freshwater supply. The work was extend to include new sources of water through desalination and the introduction of water conveyance system between different water districts to assess best management options to satisfy the demands in 2020 and 2030. The applicability of different management options were evaluated using the net benefit and shadow value of water in each sector. The key findings from this work can be summarized as follows:

1. The shadow value of water and water availability are inversely proportional. The introduction of treated wastewater has a large impact on the overall availability of water in Gaza Strip because it effectively frees up freshwater for use by urban and industrial sectors and allows for a second use of effluent by agriculture.
2. The benefits of using treated wastewater increase over time as demands increase and water becomes scarce. However, the shadow value of water will not fall below $0.60/m^3 with the use of treated wastewater only.
3. The urban and industrial sectors benefit significantly when their wastewater is treated and used in agriculture. This approach reduces the prices of urban and industrial water.
4. Use of treated wastewater in agriculture has a high impact on reducing the agricultural water prices. The urban water prices also decreased when use of treated wastewater is considered.

5. Adding a large desalination plant in Gaza with a capacity of 54.75 MCM/year increases net benefits, reduces the urban water prices, and decreases the shadow value of water for the Gaza district.
6. Adding a large desalination including the existing wastewater treatment plants and conveying water from the district had effectively reduced the shadow value of water in the district that received the desalinated water. Transfer desalinated water is more economical than constructing a desalination plant in every district.
7. Transferring water among districts reduces in the shadow value of water in the districts receiving water more than the increasing in the shadow value of water in districts providing water.
8. The suggested institutional framework to encourage wastewater treatment and reuse in agriculture is economically beneficial to implement. Net benefits from treating and reusing wastewater far exceed the costs borne by the institutions that will carry out the implementation.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The overall goal of the work reported in this dissertation is to analyze and develop appropriate methodologies for optimal agricultural water management in water deficit regions using treated wastewater, where available, while addressing economic efficiency and productivity, and environmental and public health concerns. The dissertation is divided into three parts. In part 1, optimal agricultural water allocation using freshwater supplies only was investigated. The proposed methodology addressed management parameters affecting profitability, risk of not achieving a given target revenue, and finally the optimal land are/crop combination to maximize profit with a given allocation of seasonal water under different energy options. The methodology was demonstrated for Bear River Valley of Utah where agriculture is prevalent, water is in short supply, and agricultural productivity is uncertain due to water shortages and rising production costs. Part 2 of this dissertation extended the earlier work to include the use of treated wastewater. The proposed methodology addressed the optimal water allocation between freshwater and treated wastewater to maximize profitability while minimizing public health risks and salinity loads. The work used Gaza Strip of Palestine as a demonstration example where groundwater is severely limited, demand is increasing due to the high population growth, and the continuous occurrence of seawater intrusion. In the final part, the work conducted at Gaza Strip with the use of treated wastewater was extended to include an economic benefit analysis to understand the implication of using treated wastewater on urban and municipal sectors.

Summary and Conclusions

In this research, the framework developed in Chapters III, IV, and V are used to develop and apply practical framework for common applications in agricultural water management. The conclusions obtained are presented for each application.

Optimal agricultural production under water deficit conditions

The objective of this chapter was to develop a methodology to determine the optimal crop and corresponding land area combination to obtain maximum profit under limited seasonal water sources that can be applied at regional and small-scale farming operations. As a part of this methodology, an economic analysis was proposed to identify the significant or persistent management parameters influencing profit. Also a risk analysis was developed to identify the failure to achieve a given revenue target under a diversity of cropping systems so that farmers have sufficient information to develop suitable cropping patterns to minimize future risk of failure.

A risk analysis was carried out to estimate the risk of economic loss because of yield and price variability of two major crops, alfalfa and wheat. Risk was defined as the cumulative revenue deficits compared to a revenue target based on data from a 17-year period. It was surmised that crop rotation of alfalfa and wheat has significant risk advantages over monoculture production. A part of reduced risk stemmed from diversification inherent in rotation. *Target MOTAD* was implemented to assess whether alfalfa–wheat rotation decreased yield and price variability relative to a system of 50% monoculture alfalfa and 50% monoculture wheat. It was discovered that rotation led to a decrease of risk more than crop monoculture and diversification cropping systems. Thus, the alfalfa–wheat rotation had significant risk advantages over monoculture production and diversification cropping production due to enhanced yield and price offsetting ability. The optimization methodology estimated the economic impacts of several management options available to Bear River Valley farmers. The results provide important practical insights into the relationship between available irrigation water and agricultural production in the region. The optimization analysis outlined scenarios for maximizing profit per unit of water used. The irrigation depth shown by the optimization model was less than the applied irrigation depth. This result produced an increase in the total irrigated area resulting in a higher profit. Any increase in the total area beyond 28,935 ha with 162.8 MCM of available water will affect the applied water depth and decrease the profit. It was demonstrated that alternative sources of energy decreased the profit. As an example, the total profit decreased 3.9% with diesel, 11.9% with propane, 3.4% with natural gas, and 11.6% with gasoline compared to electricity use.

The major limitation of this work is the deficit of published data and information. Most information and data were collected through personal communication with farmers and Utah State University Extension Specialists. Another drawback is the limited number of farmers that have been interviewed. In the future, comprehensive data collection should be conducted to guarantee that the collected data and information is representative of all farmers. Another limitation is the short time period of collected data. Agricultural practices and farmer preferences can vary with time, and therefore the data and information should be collected over an extended period of time.

Treated wastewater use in water deficit regions for agriculture: Economic, environmental, and public health issues

This application has the principal purpose of considering the use of treated wastewater in agricultural production, its effect on aquifer recovery, and the economic efficiency of water use and profitability while considering the public health risks due to the presence of pathogens in treated wastewater. The tasks for this objective are to create a framework to quantify public health risks due to ingestion of crops irrigated with treated wastewater, develop a tradeoff analysis among the various competing objectives (groundwater use, profit, salinity load, wastewater use, and economic efficiency of water use), and assess the beneficial use of treated wastewater in aquifer recovery.

With increased time between irrigation and consumption comes a significant reduction in public health risk. Other operational improvements are on the rise of virus removal efficiency of the wastewater treatment, bettering wastewater treatment and switching from surface to micro irrigation. These improvements increase the virus removal efficiency and decrease risk in the public health sector. The results of the analysis showed that 42 MCM of treated wastewater can be used in agriculture reducing the stress on freshwater supplies by 37% while achieving required profit levels. The use of treated wastewater can also save costs to the farmers due to the nutrient value of treated wastewater. The cost analysis showed that on average, the annual savings can be $719,000 to $785,000 depending on the scenario of the multi-criteria decision analysis. In addition, the use of treated wastewater provides an avenue for safe disposal of effluent from the treatment plants while reducing the use of chemical fertilizers that are hazardous to the environment. he average groundwater use predicted by the multi-criteria decision-making scenario showed that groundwater abstraction can be reduced by 37% which allowed the recovery of aquifer from an area of 76 km^2 below mean sea level to 32 km^2 as a result of using treated wastewater.

The success of the proposed methodology depends on efficient institutional bodies capable of encouraging utilization of treated wastewater in irrigation. The methodology produces optimal management scenarios that necessitate a capacity to enforce and monitor many farmers at the regional level. The wastewater treatment in Gaza Strip may not be reliable in terms of the possible and available level of treatment. Another limitation for the study area is the inadequate infrastructure for storage, conveyance, and dispersal of the treated wastewater to farmers. A water policy for agricultural water use that contains incentives such as compatible price for treated wastewater, subsidized the products irrigated by treated wastewater.

Economic analysis of improvements to
water management in water deficit regions:
A case study from Gaza Strip, Palestine

The purpose of this work was to investigate the impact on urban and industrial sectors when treated wastewater is used in agriculture. The work also addressed the best water management scenarios that maximize net benefit (i.e. profit) and institutional changes need to motivate the use of treated wastewater in agriculture. The best management scenarios discussed include the addition of new treatment plants, construction of freshwater pipelines among districts, and/or new desalination plants.

The shadow value of water and water availability are inversely proportional. The introduction of the treated wastewater has a large impact on the overall availability of water in Gaza Strip because it effectively frees up freshwater for use by urban and industrial sectors and allows for a second use of these sector's effluent by agriculture. The benefits of using treated wastewater increase over time as demands increase and water becomes scarce. However, the shadow value of water will not fall below $0.60/m^3 with the use of treated wastewater only. The urban and industrial sectors benefit significantly when their wastewater is treated and used in agriculture. This approach reduces the prices of urban and industrial water. Use of treated wastewater in agriculture has a high impact on reducing the agricultural water prices. The urban water prices also decreased when use of treated wastewater is considered. Transferring water among districts reduces the shadow value of water in the districts receiving water more than the increasing in the shadow value of water in districts providing water. The suggested institutional framework to encourage wastewater treatment and reuse in agriculture is economically beneficial to implement. Net benefits from treating and reusing wastewater far exceed the costs borne by the institutions that will carry out the implementation.

The major limitation of this analysis is the uncertainty of some of the key input parameters. These include the treatment efficiency of wastewater treatment plants, and cost and reliability of reverse osmosis plants for desalination. Other uncertainties include the reliable network for diversion of raw wastewater to treatment from different sources and lack of adequate monitoring and quality control measures.

Research Contributions

The work reported in this dissertation proposed a number of methodologies to develop optimal agricultural water management strategies applicable to water deficit regions. The work focused on situations where only freshwater is available as well as locations where both freshwater and treated wastewater is available. The focus of the work is to increase profitability and economic efficiency of water use with and without the use of treated wastewater while addressing environmental and public health concerns where applicable. The work also developed a framework to assess economic benefits achieved through the use of treated wastewater on urban and municipal sectors and seek to find new sources of alternative water for water deficit regions in an economically competitive manner.

Specific research contributions made through this dissertation can be summarized as follows:

1. Part 1 of this work integrated important concepts in irrigation science and economic principles to develop an optimization framework to identify the best land area/crop combination to produce the maximum profit for a given water allocation. This analysis can be conducted with readily available field data from the extension services and with the help of the local Extension Agent. Knowing this information, a farming community can better prepare for a given season knowing the available water allocation. This work also introduced several important concepts in decision analysis pertinent to agricultural water management and water use efficiency. These include quantification of the risk associated with crop rotation system and the ability to identify and compare risks between different cropping systems. The risk analysis allows the prediction of risk of not achieving a given target revenue under a variety of cropping patterns such as rotation and diversifications that give farmers valuable information to develop suitable cropping patterns ahead of a given farming season. This type of information reduces the concerns of a farming community and improves farming practices especially in the presence of uncertain and varying yearly revenues.

2. Although treated wastewater is now becoming a popular alternative source of water in water deficit regions, no single study exists that captures the important concepts of profitability, economic efficiency of water use, and public health concerns. The work conducted in part 2 introduced a single methodology that is capable of addressing these important issues. While treated wastewater can enhance the supply of water, the benefits and limitations of using treated wastewater from an economic, public health and environmental view point are not well understood. The proposed methodology is capable of providing valuable information to the farming community to identify the best combination of crop and water allocation for maximum profitability. The work also provide information to the water resources planner on methods of overcoming existing and future water deficits through the use of treated wastewater without producing public health and environmental concerns, while enhancing aquifer recovery where applicable and savings on commercial fertilizer costs. The work also motivates the use of treated wastewater in agriculture and provides insight to improve the infrastructure to accommodate delivery and transfer of treated wastewater to needed farming communities. Most importantly, the applicability of the work was demonstrated to one of the most water deficit regions, Gaza Strip, Palestine.

3. Most water resources management programs address the need in one sector over another. Since agriculture typically uses more than 75% of available water, planners pay significant interest in reducing this demand while searching for other options for water sources. While treated wastewater is a viable option, the economic implications of using treated wastewater in urban and municipal sectors

are not well understood. The work conducted in part 3 of this dissertation provided a methodology to assess these implications using the concept of shadow value of water in the different sectors, and how this value can be reduced to be competitive in developing other sources of water. The work also addressed many practical management options such as desalination, interregional water transfer through new pipelines, and building of new treatment plants to increase treated wastewater capacity. This study provided the framework to assess the economic benefits and the selection criteria for these different management options such that water resources are economically sustainable in the future. The work also demonstrated not only the economic framework but also the proposed changes needed in the institutional framework and how these changes can be implemented through the savings generated from alternative water resources.

4. Although sophisticated mathematical analyses of optimization, economics, and health risk are available in the literature, most applications have been focused on a single objective such as enhancing water supply, assessment of health risk, or determining economic benefits. This study clearly demonstrated that these individual analyses can be formulated in an integrated manner to develop practical measures and assess the applicability of these measures through simultaneous screening for environmental, health risks, and economic criteria to address water related issues. Such approaches are gaining wide support in many engineering disciplines given the limitations of financial and other resources while the needs to satisfy societal problems are becoming ever more urgent. Therefore, the approach of using sound science with an integrated framework addressing multiple issues is a definite contribution from this dissertation.

Recommendations

This work develops new approaches for aquifer recovery by reuse of treated wastewater in agriculture and expanding fresh water supply via considering desalination. Based on the concepts developed and the results demonstrated in this dissertation, the following recommendations are worthy of consideration for future research.

1. It is recommended to apply the proposed methodology of Part 1 to more than two crops with different cropping systems (diversification and rotation) to determine the risk of not achieving target revenue.
2. This work addressed the issue of salinity in a coastal aquifer. Other issues of water quality could be examined as well, and these may have more serious implications. For the case of Gaza Strip, nitrate levels are high, and may have more important short term consequences.
3. It is recommended to incorporate an appropriate groundwater model with the application in chapter V to better representing of the coastal aquifer system. In other words, in coastal aquifer such as Gaza strip, the cost of pumping can be linked to the aquifer table elevations. This can be done throughout presenting the cost of pumping as a function of head generated from the groundwater model.
4. It is recommended to include the water conservation practices that can reduce the water demand in chapter V. Water conservation programs include short-term and long-term actions. In the short term, a water user may buy-expensive privately vended water or temporarily reduces the length or frequency of water use such as with showers, dishwashing, landscaping irrigation and other water uses. Over the long-term, users may continue behavioral changes or purchase and install more

water efficient appliances. Urban users may purchase and install rain-and grey-water collection systems, low flow showerheads, low flush toilet mechanisms, drip irrigation systems, low water-use landscapes, and other water-saving devices.

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APPENDIX

Water allocation model

The water allocation system model is an optimization analysis. The mathematical representation of this model is given below:

Objective function:

$$\max Z = \sum_i \sum_d \left[\frac{B_{id} \times (QD_{id} + QREC_{id})^{\alpha_{id}+1}}{\alpha_{id}+1} \right] - \sum_i \sum_s (QS_{pumped\,is} \times CS_{pumped\,is})$$
$$- \sum_i \sum_j QTR_{ij} \times CTR_{ij} - \sum_i \sum_d QRY_{id} \times CR_{id} - \sum_i \sum_j QTREC_{ij} \times CTREC_{ij} \quad \text{(A1)}$$
$$- \sum_i \sum_d QREC_{id} \times CRY_{id} - \sum_i QDES_i \times CDES_i$$

Subject to:

$$\sum_d QD_{id} = (\sum_s QS_{pumped\,is} + \sum_i QDES_i + \sum_j QTR_{ji} - \sum_j QTR_{ij}) \times (1 - \mathrm{LR_i}) \;, \quad \forall i \quad \text{(A2)}$$

$$\sum_d QREC_{id} = \sum_i QRY_{id} + \sum_j QTREC_{ji} - \sum_j QTREC_{ij} \,, \quad \forall i \quad \text{(A3)}$$

$$QRY_{id} = PR_{id} \times QD_{id} \;, \quad \forall i, d \quad \text{(A4)}$$

With the following bounds:

$$(QD_{id} + QREC_{id}) \geq \left[\frac{P_{\max}}{B_{id}} \right]^{1/\alpha_{id}} \,, \quad \forall i, d \quad \text{(A5)}$$

$$QS_{pumped\,is} \leq QS_{pumped\ \max\ is} \;, \quad \forall i, s \quad \text{(A6)}$$

$$PR_{id} \leq PR_{\max\ id} \;, \quad \forall i, d \quad \text{(A7)}$$

Indices

i is represents the district

d is the demand type (urban, industrial, or agricultural)

s is the supply source or steps

Parameters

B_{id} - coefficient of inverse demand curve for demand d in district i (dimensionless)

α_{id} - exponent of inverse demand function for demand d in district i (dimensionless)

$CS_{pumped\,is}$ - cost of water supplied from groundwater supply step s in district i ($/m^3),

CTR_{ij} is the cost of transport fresh water from district i to district j (\$/m^3)

$CTREC_{ij}$ - cost of transport treated wastewater from district i to district j (\$/m^3)

CR_{id} - cost of treated wastewater from sector d in district i in (\$/m^3)

CRY_{id} - cost of treated wastewater from sector d in district i in (\$/m^3)

$CDES_i$ - cost of desalination water in district i in (\$/m^3)

LR_i - loss rate in district i (dimensionless)

$P_{\max}$ - maximum price in the demand curve from sector d in district i in (\$/m^3)

Decision Variables

Z - net benefit in million dollars

QD_{id} - quantity demanded by sector d in district i in MCM

$QS_{pumped\ is}$ - quantity supplied by source s in district i in MCM

QTR_{ij} - quantity of freshwater transported from district i to district j in MCM

QRY_{id} - quantity of treated wastewater from sector d (M&I) in district i in MCM,

$QTREC_{ij}$ is the quantity of treated wastewater transported from district i to district j in MCM

$QTREC_{ji}$ - quantity of treated wastewater transported from district j to district i in MCM

$QREC_{id}$ - quantity of treated wastewater supplied to use d (agriculture) in district i in MCM

$QDES_i$ - quantity of desalinated water supplied to all sectors d in district i in MCM

PR_{id} - percent of treated wastewater from sector d (used in agriculture) in district i in MCM

P_{id} - shadow value of water for demand sector d in district i (computed) (\$/m^3)

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- M.S., Water Engineering, (September 1999–October 2002), Birzeit University, West Bank. The program was in cooperation between Birzeit University and the IHE- UNESCO institute in the Netherlands.
  Thesis: Enhanced Pretreatment of Black Wastewater from Birzeit University Using UASB Technology.

- B.S., Civil Engineering, (August 1993–August 1998), Islamic University of Gaza.
  Thesis: Management and Re-Design of Treatment Plant Using Activated Sludge System for Northern part of the Gaza strip, 1998.

PUBLICATIONS AND CONFERENCES

- Aljuaidi, A. and J. Kaluarachchi, 2009. Profit and Risk Analyses of Optimal Agricultural Management Practices under Water Deficit Conditions. *Submitted to the Journal of Irrigation Science.*

- Aljuaidi, A., J. Kaluarachchi, and U. Kim, 2009. Economic, Environmental, and Public Health Issues Related to Treated Wastewater Use in Agriculture in Water Deficit Regions. *Submitted to the Journal of American Water Resources Association.*

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- Al-Juaidy, A., Z. Mimi, and R. Al-Sa'ed, 2003. Palestinian Experience with Enhanced Pre-treatment of Black Wastewater from Birzeit University Using a UASB Septic Tank System. Proceedings of the 2nd International Symposium on Ecological Sanitation, Luebeck, Germany, 5-8 April.

- Al-Juaidy, A., and J. kaluarachchi, 2007. Optimal Agricultural Water Management under Irrigation Deficit Conditions. Poster presented, Runoff conference, Utah State University, 5-6 April.

- Al-Juaidy, A., and W. Hashlamoun, 2008. Development of Cost Effective On-Site Wastewater Treatment Using Up-flow Anaerobic Sludge Blanket (UASB) Technology under Semi-Arid Conditions. Poster presented, Utah On- Site Wastewater Association (UOWA), Eighth Annual Conference, E-Center, Salt Lake City, 12-13 February.

RESEARCH EXPERIENCE

Researcher, Engineering Dean Office, Birzeit University, CORETECH project. The project was held between Wageningen University in the Netherlands and Birzeit University in the West Bank (September 2001- August 2003).

- Monitoring and operating two Up-flow Anaerobic Sludge Blanket (UASB) reactors, one for domestic water and the other for black wastewater.
- Conducted wastewater sampling collection, and wastewater quality lab analysis.
- Performed risk and socio-economic studies on rural areas in the Ramallah district, West Bank, to explore the possibilities of applying the on-site sanitation and using the treated effluent for irrigation.

Research Assistant, Stuttgart University-Germany (September 2003 - January 2005).

- Groundwater Mapping Using Additional Information for Baden Wuerrtemberg Region using Geostatistics, and GIS.
- Comparison between homogeneous and heterogeneous variograms for ground water chemical pollutants for Baden Wurttemberg geology using Arc-object library in GIS.
- Attended several courses related to GIS, surface hydrology, groundwater modeling, and stochastic methods in groundwater.

PROFESSIONAL EXPERIENCE

Office Aid and Site Engineer in Palestinian Ministry of National Economy, Ramallah and Hebron, (February, 2000 - August, 2001). This position involved issuing licenses to the Palestinian factories which fulfilled the Ministry's requirements of the engineering safety, product quality, and proper waste disposal, and others.

COMPUTER SKILLS

Microsoft project 2000, AutoCAD 2000, MODFLOW-2000, FORTRAN 77, MatLab, R (Statistical computing), GAMS, Arc GIS 9.3, LINDO, Visual Basic 6.0.

Hydrological Modeling

- Surface Hydrology Modeling: HEC-RAS, HEC-HMS, SWMM, DAM-BREAK.
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Machine learning (data-driven models):

- Used Support Vector Machines (SVMs), Artificial Neural Networks (ANN), and Relevance Vector Machine (RVM) in various applications including soil moisture forecasting, and stream flow modeling.

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- Member of Golden Key International Honor Society, Atlanta, USA.
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