Prioritizing Water Infrastructure under Conditions of Agricultural Uncertainty in the West Bank, Palestine

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Abstract

Developing countries such as Palestine are often simultaneously fiscally limited and acutely water constrained. It is vital that investments in water related infrastructure provide maximum social welfare per dollar spent. Furthermore, infrastructure must be designed to perform well under a wide range of social and environmental conditions, which increases the difficulty in making effective decisions.

The presented methodology provides robust and resilient water infrastructure investment guidance to policy makers under conditions of agricultural uncertainty. Historic social and economic variability is incorporated into estimations of demand for irrigation water in three West Bank districts, Bethlehem, Jenin, and Jericho. Uncertainty in agricultural water demand is included in a general water allocation optimization model in order to guide more robust and resilient infrastructure planning.

Results of the analysis show it is possible to identify infrastructure investments such as wastewater treatment and reuse that operate well under a wide range of conditions. Investments that improve the resilience of social welfare by protecting society against disturbances such as prolonged periods of drought are also identified.

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Introduction

It has long been recognized that systems analysis techniques are not responsive enough to adequately reflect the true concerns of water allocation decision makers (Rogers and Fiering, 1986). One of the primary reasons cited is the insufficient treatment of uncertainty in modeling (Tsur and Dinar, 1997; Harou et al, 2009). As simplifications of reality, important characteristics of a system are represented as model parameters and decision variables and the mathematical relationships among them. Parameters are typically average or calibrated values that best represent influential conditions to decision making (Cai and Wang, 2006). In truth however, model parameter values are not precisely known and small changes can lead to dramatic changes in model outputs and resulting decisions (Harou et al, 2009).

There are a number of factors that influence farm-level decision-making that are typically included in irrigation water allocation models. Examples include water and land limitations, irrigation technology, crop diversification, labor, fertilizer, pesticides, equipment, and soil type (Loucks et al, 1981). Other influences such as resistance to change, cultural practices, risk aversion, uncertainty, and variability are more difficult to model yet can also strongly influence farm-level decisions (Pannell et al, 2000). Irrigation water allocation models are increasingly capable of reflecting the true concerns of farmers when such influences are included. For example, recent work has shown that aversion to risks associated with water availability can induce farmers to reduce profits in order to minimize catastrophic loss of multi-year investments (Lavee, 2010).

Decisions about cropping patterns and irrigation strategies are also influenced by policy and infrastructure (Fisher et al, 2002; Wichelns, 2004). Policies and infrastructure have the potential to foster economic development and increase efficiency through better irrigation management (Evans and Sadler, 2008) and improved social equity (Rogers et al, 2002). Water allocation policies and infrastructure must be effective over long planning periods due to associated expenses and preparatory efforts. Robust and resilient planning helps ensure systems perform as intended under a wide range of expected social and environmental conditions. *Robust* interventions are those that perform well under a wide range of possible scenarios or outcomes (Watkins and McKinney, 1997). *Resilient* interventions are those that allow water users to withstand or recover from disturbances without fundamental loss of identity (Almeden, 2009). Incorporation of model parameter uncertainty into the analysis should increase both the robustness and the resilience of solutions because resulting plans are evaluated under a wider range of possible outcomes.

To date, the incorporation of uncertainty into agricultural water allocation models has been limited to that of water supply. For example, Willis and Whittlesey (1998) found that irrigators use more water under variable water supply conditions using linear chance constrained programming. Additionally, several researchers have found that, in addition to pricing, the availability and reliability of water supply can induce crop choices and demand management decisions that affect agricultural water use (Marques et al., 2005; Cai and Rosegrant, 2004; Carey and Zilberman, 2002).

Literature is limited on the incorporation of model parameter variability into water allocation models that focus on irrigation water demand. This important gap is addressed by including additional model parameter variability in a parsimonious irrigation water demand model and demonstrating robust and resilient infrastructure planning.

In the first chapter, steady-state demand for irrigation water in three West Bank farming districts is characterized using traditional mathematical programming techniques. In the second chapter, the demand model is reformulated to evaluate the effects of historic social and environmental variability on demand for irrigation water. In the third chapter, the effect of historic social and environmental variability on the price elasticity of irrigation water demand is evaluated. In the fourth chapter, uncertainty in agricultural water demand is incorporated into a general water allocation model in order to guide more robust and resilient infrastructure planning. In the fifth chapter, the steady-state irrigation water allocation model from Chapter 1 is used to evaluate how appropriate freshwater prices can be used to stimulate the use of treated wastewater in Jericho, followed by a summary of limitations and conclusions.

Chapter 1: Characterization of Deterministic Demand for Agricultural Water

In this chapter, the willingness of farmers to pay for irrigation water in Bethlehem, Jenin, and Jericho is evaluated using a steady-state linear optimization model. The results of the analysis are compared to Bet She'an, an Israeli farming district.

Demand for Irrigation Water

Economic modeling is a reasonable method for predicting farmer behavior such as demand for irrigation water because farming systems are primarily driven by financial and economic decisions (Loucks et al, 1981). A demand curve for irrigation water represents the relationship between water price and the quantity that farmers are willing and able to purchase. Estimating demand for irrigation water produces a tool for predicting the impact of policy and infrastructure changes on farming systems. In a recent meta-analysis, Scheierling et al. (2006) organized irrigation water demand models by method: econometric analysis, field study, and mathematical programming (MP). Medellin-Azuara et al. (2009) argue that MPs have several advantages over other methods because they add flexibility to the profit function by relaxing fixed cost assumptions, and they do not require large datasets. Hooker and Alexander (1998) argue they are more accurate than econometric studies under large price differences from historical values because they are not strictly reliant on historic data.

Increased competition, climate variability, and constrained water supplies have motivated researchers and decision makers to develop policies which improve the efficiency of agricultural water use (Johansson et al., 2002). To accomplish this, researchers have characterized demand for irrigation water to evaluate such policies in several countries, including the United States, Spain, Israel, India, Jordan, Morocco, Spain, Turkey, and Chile (Tsur and Dinar, 1997).

In the arid western United States, multi-rate volumetric pricing is commonly employed for government distributed irrigation water (Tsur and Dinar, 1997). In California, for example, prolonged periods of drought have led to innovative water market schemes which set water prices in a regulated, but competitive manner. Several MPs have been developed to evaluate various regional water pricing policies by characterizing irrigation water demand (Moore and Hedges, 1963; Shumway, 1973; Scheierling et al, 2004; Ellis et al., 1983; Gisser et al., 1979; Howitt et al., 1980).

In the European Union (EU), member countries are obliged to meet environmental requirements stipulated in the Common Agricultural Policy (CAP). This has motivated district managers to consider implementing pricing policies that motivate a more sustainable use of irrigation water. In Spain for example, areal and volumetric pricing have been implemented by several water basin authorities with various degrees of success (Varela-Ortega, 2011). Irrigation water demand has been characterized using MPs to study the effects such policies in several EU member countries including Spain (Mejias et al., 2004; Varela-Ortega, 1998; Gomez-Limon et al., 2000), Greece (Manos et al, 2006, and Italy (Bartolini et al., 2007).

Countries in the Middle-East and North Africa (MENA) region are increasingly turning to water pricing policies to address water scarcity and rapidly growing populations. In Israel, a multi-tiered pricing system was implemented in the 1970s to improve the overall efficiency of water allocations and better control agricultural allocations (Yaron, 1979). Recent policy analyses using MPs to characterize demand for irrigation water in Jordan include Salman et al. (2004), Salman et al. (2001), and Al-Assaf et al. (2007). Demand for irrigation water in Egypt and Morocco was characterized using a MP by He et al. (2006). No published evaluations of irrigation water demand are currently available for the West Bank. However, an evaluation of optimal cropping patterns for the West Bank using a MP was recently performed by Nazer et al. (2010).

In this chapter, steady-state demand for irrigation water in three West Bank farming districts, Bethlehem, Jenin, and Jericho is characterized. Results of the evaluation are compared to an Israeli farming district, Bet She'an which is approximately 10 miles northeast of the Jenin district. Due to its proximity, it is similar in climate and other environmental characteristics but because it is an Israeli farming district, the economic conditions and water constraints are different.

Model Formulation

The mathematical program used in this study to generate agricultural water demand curves is based on the Agricultural Sub-Model (AGSM) developed by Amir and Fisher (1999). AGSM is a linear program which is formulated at the district level. The program seeks to maximize net benefits by selecting the optimal mix of rain-fed and water-consuming activities which compete for available land. We solve AGSM using the General Algebraic Modeling System (GAMS).

The objective of AGSM is to maximize the net economic benefits derived from all agricultural activities in the farming district. Here, net benefits are the gross profits less the cost of water and all other farming inputs:

$$Maximize: \quad \sum_{a}\sum_{wq} X_{a,wq}\,[(Pc_a \cdot Y_a) - (Pw_{wq,} \cdot W_{a,wq}) - NWC_a] \tag{1.1}$$

where the decision variable, $X_{a,wq}$ is land area devoted to rain-fed or irrigated activity, *a,* using water of quality, wq; Pc_a is crop price per dunam, Y_a is crop yield per dunam, Pw_{wq} is water price per cubic meter, $W_{a,wq}$ is water requirement per dunam for activity *a* using water of quality wq, and NWC_a are non-water costs per dunam (including seeds, fertilizer, labor, and equipment) for activity a. Note that for this simplified representation of the farming system, crop yield is independent of the quality of water.

Crop allocations are constrained by available land and water so that:

$$\sum_{a}(X_{a,wq} \cdot W_{a,wq}) \leq TW_{wq} \qquad \textit{Water Constraint} \qquad (1.2)$$

$$\sum_{a}\sum_{wq}(X_{a,wq} \cdot CC_{a,lc}) \leq TL_{lc} \qquad \textit{Land Constraint} \qquad (1.3)$$

where TW_{wq} is total available water of each water quality, wq and TL_{lc} is total available land of each land category, lc. The land categories, lc in the model include permanent, field, irrigated, and rain-fed crops.

Crop allocations are constrained so that local and regional market conditions are not exceeded:

$$\sum_{wq} X_{a,wq} \leq P\_AG\_MAX_{a} + F\_AG\_MAX_{a} \qquad \textit{Growth Constraint} \qquad (1.4)$$

where $P\_AG\_MAX_{a}$ is the maximum allowable land allocation to currently used land for each activity, a and $F\_AG\_MAX_{a}$ is the maximum allowable land allocation to land currently unused, but in the future could be irrigable land for each activity, *a.* This is done with the assumption that farmers in the West Bank are currently making land allocation decisions in an efficient manner, *i.e.* already making good financial decisions (Wichelns, 2004).

Deviations from historical agricultural land use are limited as described as follows. The maximum change for presently used land of each activity (Eq. 1.5) is fixed at 10% or 100 du using an exponential function (Eq. 1.6); whichever is larger depending on the crop's initial land allocation:

$$P\_AG\_MAX_a = \sum_{wq}[X\_INIT_{a,wq} + 100 \cdot GC_a + \sum_{wq}(0.10 \cdot X_{INIT\,a,wq} \cdot (1 - GC_a))] \qquad (1.5)$$

$$Where\ GC_a = \sum\nolimits_{wq} \frac{0.03 \cdot (1 + (1 - \exp{(0.05 \cdot (0.10 \cdot X_{a,wq} - 100))}}{1 + \exp{(0.05 \cdot (0.10 \cdot X_{a,wq} - 100))}} \qquad (1.6)$$

where $X\_INIT_{a,wq}$ is the historic land allocation for activity, a, using water quality, wq. For example, if maize were currently allocated 90 dunams, the constraint would set maximum allowable growth to 190 dunams rather than 99 dunams. Alternately, if maize were currently allocated 3,000 dunams, the constraint would set maximum allowable growth to 300 dunams.

Because of our interest in the *maximum potential* for agricultural water use in this model, only irrigation water consuming crop allocations (and not rain-fed crop allocations) are allowed to be allocated to currently unused but irrigable land:

$$F\_AG\_MAX_a = (1.1) \cdot \frac{X\_INIT_a}{TL\_IR} \cdot TL_F \qquad (1.7)$$

where TL_IR is the total historical amount of irrigated land and TL_F is the total currently unused but available irrigable land. Increases in allocations are limited to 10% increases over than historic irrigated crop ratios.

Irrigated Agriculture in the West Bank

Agriculture in the West Bank is predominantly small-scale and employs 12% of the population (CIA, 2011). Approximately 50% of farm holdings are less than 2 hectares (ha) and only 8% are greater than 10 ha (ARIJ, 1998). ARIJ reports excessive fragmentation of irrigated lands results in poor adaptation of new, more efficient technologies and severely limits the income potential of West Bank farmers.

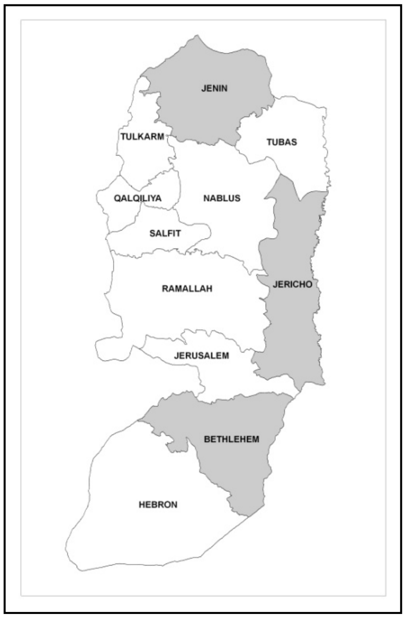

Figure 1-1, Map of the West Bank

In total, 9% of 170,000 hectares used for agriculture in the West Bank were irrigated in 2008 (PCBS, 2009). Since 1994, irrigated farming has increased 53% (PCBS, 1994; 2008). Farmers maximize the value of irrigation water by allocating 76% of irrigated land to high value vegetable crops. Though irrigated agriculture is more productive and profitable, constrained water availability and lack of investment capital has prevented more wide-spread adoption.

Bethlehem

The geography of Bethlehem ranges from the semi-arid hilly west to the flat and dry Western Jordan Valley to the east (See Figure 1-1). Rainfall ranges from 65 cm per year in the west to 35 cm per year in the east. Groundwater withdrawals are highly constrained by the Oslo agreement with Israel. Springs are the only source of irrigation water available to farmers. As a result, a small percentage of total irrigable land is irrigated (Jayoussi, 2001). Farmers take advantage of

	Bethlehem	**Jenin**	**Jericho**
Primary Irrigated Crops (2008)	Cabbage, Tomato, Cauliflower, Grape	Cucumber, Eggplant, Squash, Tomato	Squash, Eggplant, Maize, Tomato
Irrigated Agriculture (2008)	2,023 du	18,269 du	42,535 du
Irrigable Land	12,000 du	119,992 du	45,607 du
Ave. Ann. Rainfall	35 - 65 cm	40 - 65 cm	15 - 20 cm
Ave. Cost of Water	\$0.26 US\$/m^3	\$0.79 US\$/m^3	\$0.26 US\$/m^3
Well Extraction (2008)	0%	99%	30%
Spring Extraction (2008)	100%	1%	70%
Total Water Use (2008)	0.6 MCM	5.1 MCM	29.0 MCM

Table 1-1, Characteristics of Irrigated Agriculture in Jenin and Jericho (1 hectare = 10 dunams)

gravity-fed conveyance systems from spring sources in order to maintain a relatively small average cost of water of \$0.27 US\$/m^3 (compared to other West Bank districts).

Jenin

Jenin is considered semi-arid with rainfall ranging from 40 to 65 cm per year. Supplemental water from groundwater is required for crops such as vegetables and citrus. Withdrawals are highly constrained as a result of politically imposed limits by Israel. Like Bethlehem, this results in large tracts of unused but irrigable land (Jayyousi, 2001). The relatively high price of water is a result of inefficient extraction methods which are typically private wells that use low capacity pumps. Tanked water priced as high as \$2.60 US\$/m^3 is often used to prevent loss of crops.

Jericho

Jericho lies in the heart of the Western Jordan Valley near the Dead Sea. Summer temperatures exceeding 40°C result in off-season harvests which bring crop price premiums. More irrigation water per dunam is required than other West Bank regions due to higher temperatures. Groundwater from springs and wells are the primary source of water because of low annual precipitation. Water extractions are not limited by political constraints so supply is much greater than that of Jenin. The average price of water is much cheaper in Jericho than in Jenin because more water is available from springs which require minimal pumping costs. As a result, a greater percentage of available irrigable land is in use (See Table 1-1).

Data Collection

Field work was carried out in The West Bank during July and August, 2010. Initial planning and data collection was performed in Ramallah in cooperation with the Palestinian Water Authority (PWA) and Ministry of Agriculture (MoA). Published and internal data kept by the Palestinian Central Bureau of Statistics (PCBS), PWA, and MoA were obtained including total annual water supply by source (PWA, 2010), potential irrigable land (Jayyousi, 2001), annual crop land allocations (PCBS, 2009), and crop yields (PCBS, 2009). The remaining data: all non-water input costs (land, labor, etc.), water use per irrigated activity, and average water prices were obtained through focus groups consisting of farmers and extension agents.

Deterministic agricultural water demand curves were generated for Bethlehem, Jenin, and Jericho (Figure 1-2) by relaxing the water constraint (Eq. 1.2) and running AGSM repeatedly over a range of water prices using nominal parameter values as described above. Though AGSM is capable of optimizing with multiple types of water, only aggregate freshwater is considered in this study. The demand curves were compared to Bet She'an, an Israeli agricultural region 10 miles to the northeast of Jenin (Amir, 2011). Agriculture in Bet She'an is more industrialized and much less constrained by water availability than Jenin and Bethlehem.

The Bethlehem, Jenin, and Jericho models were calibrated against independent data from previous studies as follows. Water requirements were verified against historic water supply estimates provided by the PWA (2010). Revenue and costs were calibrated using previous work by the Arab Research Institute of Jerusalem (ARIJ, 1998). Finally, independent net benefit estimates per unit land area were provided from a previous study (ARIJ, 1998) and the MoA (2010).

Deterministic Irrigation Water Demand

Irrigation water supply in Bethlehem and Jenin is highly constrained, as shown in Figure 1-2. The model predicts farmers in Bethlehem would be willing to use 4.69 MCM at the current average water price of \$0.26 per m^3. This is a 622% increase from 2008 irrigation water allocations of 0.6 MCM. In Jenin, the difference is even greater at its current average water price of \$0.79. Predicted use would increase from 5.1MCM to 62.81 MCM, a 1,132% increase if supply constraints were relaxed. The large increases result from the use of large tracts of unused but potentially irrigable land and would significantly increase the economic benefit from agriculture.

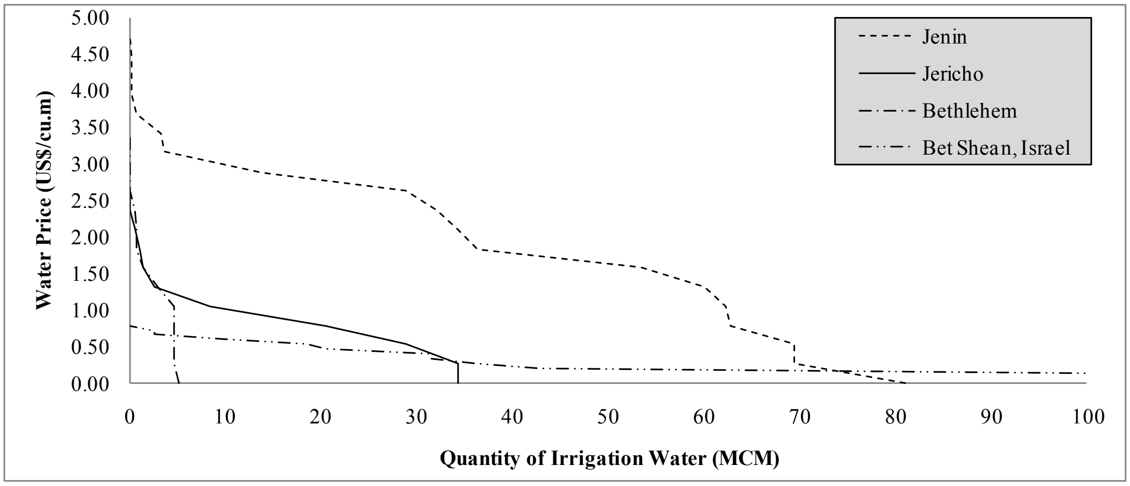

Figure 1-2, Comparison of demand curves derived using nominal (average) parameter values for Jenin, Jericho, Bethlehem, and Bet Shean.

Supply is much less constrained in Jericho and Bet She'an where historic water use nearly matches available supply. Changes in irrigation water use are much more price-sensitive, particularly compared to Jenin. This is a result of the constraint on water availability in Jenin and Bethlehem.

Figures 1-3, 1-4, 1-5, and 1-6 show the optimal mix of irrigated fruit tree, field and green house vegetable, and field crops with respect to the price of water predicted by the model. In Bethlehem and Jenin, field and green house vegetables become more dominant with increasing water prices because field crops and fruit trees have lower profit margins. In Jericho, more water is used due to its hotter and drier climate. Water intensive crops such as green house vegetables become unprofitable at relatively lower water prices than less water intensive but profitable field crops such as onions and potatoes. In Bet She'an, field crops are dominant at low water prices. Unconstrained water supplies do not hinder large allocations to less profitable field crops such as cotton and barley. As price increases and low value crops become unprofitable, vegetables increasingly dominate the mix.

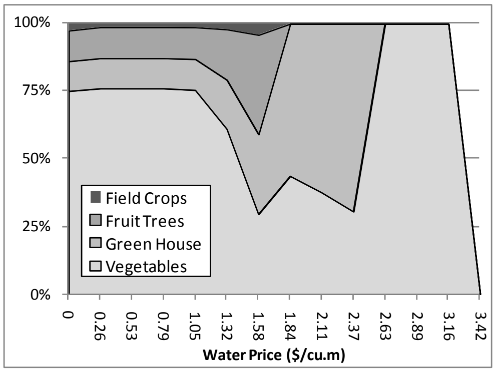

Figure 1-3, Bethlehem Crop Mix

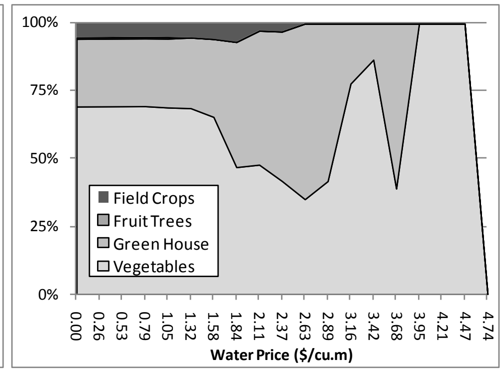

Figure 1-4, Jenin Crop Mix

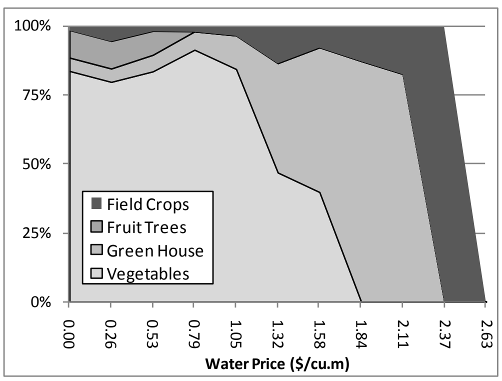

Figure 1-5, Jericho Crop Mix

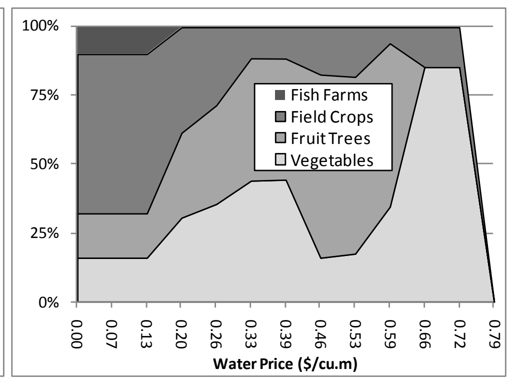

Figure 1-6, Bet She'an, Israel Crop Mix

It is revealing to compare the optimal crop mix in Jenin and Bethlehem at their current average water price to a similarly water supply constrained Bet She'an. Historic (2008) land allocations are approximately 17% and 12% of total available irrigable land in Bethlehem and Jenin respectively. In Bet She'an, land allocations are approximately reduced to this level when the average price of water reaches \$0.66. At that price, Figure 1-6 shows the crop mix is 75-80% vegetables with the remaining land split between field crops and fruit trees. This is comparable to the historic crop mixes in Bethlehem and Jenin indicating crop mixes are comparable in the three districts when similarly water supply constrained. Based on this comparison, it is clear that under severe supply constraints, Palestinian farmers are prioritizing higher value crops, just as Israeli farmers would under the same constraints.

This conclusion more fully explains the difference between the West Bank and Israeli demand curves. Recall that modeled crop mixes for Bethlehem and Jenin are fixed at their current (highly constrained) state, but allowed to expand into currently unused but irrigable land in order to assess the *total* willingness of farmers to pay for irrigation water. In Bet She'an, the crop mix does not stay constant when the water supply constraint is relaxed. Rather, the mix shifts to lower profit field crops which cause allocations to drop more quickly when the prices is increased. This shift does not occur in Bethlehem and Jenin *as modeled* so allocations are comparatively larger at higher water prices because the crop mix is dominated by higher value vegetables.

Conclusions

Demand for agricultural water was characterized using a deterministic linear optimization program. Water supplies are shown to be highly constrained in Bethlehem and Jenin. Supply is shown to be less constrained in Jericho, where nearly all irrigable land is currently being used.

Agricultural water use in all three West Bank districts is estimated to be much less price responsive than Bet She'an. One reason is that farmers in the West Bank pay significantly more for irrigation water than Israelis with hard supply constraints. As a result, they operate under conditions that are not based on elastic supply and demand behavior. Palestinian farmers are not price constrained, but quantity constrained. The reverse is true for Israeli farmers.

The development of irrigation water demand curves allows policy makers to evaluate pricing policies and the value of new infrastructure for agricultural systems. However, results of such evaluations are dependant upon decision making influences represented in the model by parameters. In the next chapter, the effects of variability of such parameters on agricultural water demand are assessed.

Chapter 2: Uncertainty in Agricultural Water Demand

In this chapter, a method for estimating historic variability in the model parameters using time-series data is presented. The effects of social and economic variability on agricultural water demand are evaluated using Monte Carlo simulation which adds uncertainty in making appropriate water allocation decisions.

Introduction

In steady-state mathematical program formulations such as AGSM, average parameter values are normally used to model demand for irrigation water under a historical condition (in this case, the year 2008). While these values are expected to reasonably represent influences to the farming system model at this fixed point in time, in reality, influences such as crop prices and yields vary from year to year. To date, few studies have evaluated the total impact of parameter variability associated with mathematical programming approaches to the determination of water demand (Harou et al, 2009).

Process-based relationships are often used to relate changes in environmental and social influences with model parameters. For example, the relationship between yield and crop water demand has been integrated into several recent agricultural water demand models (Rosegrant et al., 2000; English et al., 2002; Sethi et al., 2002). These relationships have not yet been incorporated into AGSM.

Individually, process-based relationships only partially explain variability in yield, price, water-use, and land allocations. Multiple independent and interrelated coping strategies and other complex process-based relationships contribute to historic variation in parameter values, only some of which are known and understood. Furthermore, additional elaboration of relationships requires data which are often of limited availability in developing regions and add additional uncertainties. Also, when the spatial scale of interest is regional rather than farm-level, the treatment of process-based relationships may be too fine to accurately represent the system.

An alternative to the process-based approach is to determine estimates of variability in model parameters from historical records (Lobell and Burke, 2010). By basing the analysis on historic data, the need for a complete representation of all social and environmental processes can be avoided. For example, historical data has been previously used in mathematical programming to evaluate the farmer's aversion to risk (Hazell and Norton, 1986; Varela-Ortega, 2011). Hazel and Norton (1986) quantified aversion to risk by subtracting the variance of historic incomes from the system's net benefits in the objective function. The income distribution was based upon the range of historic parameter values used to determine net benefits. The resulting analysis estimates irrigation water allocations by taking into account a pre-determined aversion to risk resulting from uncertainty in decision influences (for a recent application see Varela-Ortega et al., 2011).

In the present study, historic parameter variability is incorporated into the steady-state irrigation water demand analyses for Bethlehem, Jenin, and Jericho. This is done by (1) estimating historic variability in parameter values, (2) running AGSM repeatedly with a range of parameter values using Monte Carlo simulation, and (3) generating bounded demand curves that include the resulting effects of social and environmental variability.

Such an approach is possible because the linear programming model can be solved with a minimum of computational effort. The Bethlehem model contains 43 decision variables and 129 constraint equations. The Jenin model contains 83 decision variables and 249 constraint equations. The Jericho model contains 40 decision variables and 120 constraint equations.

Historic Variability in Model Coefficients

All objective function model coefficients (yield, crop price, input cost, and water-use) were treated as independent normally distributed random variables with the mean equal to each coefficient's nominal value. Variability in each coefficient was represented by its coefficient of variation, C_v.

	Yield						Crop Price			Input Costs	Water Use
	Irrigated Fruit Trees	Rainfed Fruit Trees	Irrigated Veg.	Rainfed Veg.	Irrigated Field Crops	Rainfed Field Crops	Fruit Trees	Veg.	Field Crops	All Crops	All Crops
Bethlehem	* 0.21	* 0.21	* 0.18	0.39	0.09	0.40	* 0.05	* 0.08	* 0.08	0.04	0.46
Jenin	* 0.22	* 0.32	* 0.17	* 0.22	0.18	0.32	* 0.05	* 0.08	* 0.08	0.04	0.06
Jericho	0.13	-	0.08	-	0.28	-	* 0.05	* 0.08	* 0.08	0.04	0.21

Table 2-1, Coefficient of variation, C_v values for all objective function coefficients. ***Trend modeled in Time-Series***

The C_v of each coefficient summarized in Table 2-1 was estimated from the ratio of the standard deviation and the mean from time-series data. Yield variability was estimated using aggregate yield data from government agricultural reports (PCBS, 1998:2008). It was further sub-divided into 6 categories for each governorate: irrigated and rain-fed field crops, irrigated and rain-fed vegetables, irrigated and rain-fed fruit-trees. Crop price variability for the West Bank was estimated in three sub-categories from wholesale fruit tree, vegetable, and field crop price indices taken from government economic reports (PCBS, 1998:2009). Input cost variability for the West Bank was estimated using the fertilizer producer price index from the same economic reports. The fertilizer index was chosen to represent input costs. There was no time-series data available regarding crop water-use, but this was estimated from spring and well extraction data (PWA Internal Data, 2010) as a surrogate.

Linear regressions were performed on the historic time-series of each model coefficient in order to identify trends. Regression models with a significance level greater than 0.05 were rejected. If a significant trend was indicated by the regression, the standard deviation of the model residuals was used to estimate C_v. If no trend was identified, the standard deviation of the time-series was used to estimate C_v.

Demand Bound Estimation and Monte-Carlo Simulation

Monte-Carlo simulation enables us to evaluate the changes in demand that occur as a result of variability in all relevant model coefficient values, assuming their values are independent of one another. In each experiment, parameter values are drawn from a normal distribution as described above. A total of 1000 experiments were performed for each district, leading to 1000 simulated irrigation water use amounts at each water price. These were ranked from lowest to highest in value. Likely ranges associated with the demand curves were then determined using a simple non-parametric quantile estimator (Vogel and Fennessey, 1994):

$$Q_P = (1-\theta)Q_i + \theta \cdot Q_{i+1} \qquad (2.1)$$

$$\text{Where: } i = [(n+1)p]$$

$$\theta = (n+1)p - i$$

Here p is the nonexceedance probability associated with each quantile Q_p, so that for example, $Q_{0.05}$ represents the value of Q which is exceeded 95% of the time. Here, Q_i is the ith ranked water quantity and the square brackets [] denote the integer portion of the value inside the brackets. The quantile estimator in (Eq. 2.1) is used to compute the upper and lower limits of the 'likely' range associated with each demand curve. The GAMS code is attached in Appendix A.

Figure 2-1 shows the model sensitivity to the overall C_v of model coefficients. The plot was generated using fixed C_v values for each model parameter. As shown, the likely range of water demand significantly increases with increasing parameter variability. For example, when water is priced at $1.05 the 95% likely range of allocations increase from 10.24 MCM for C_v =

0.10 to 15.72 MCM for $C_v = 0.50$; a 54% increase in total demand. Secondly, the bounds become steeper as variability increases indicating increases in price elasticity with increasing variability.

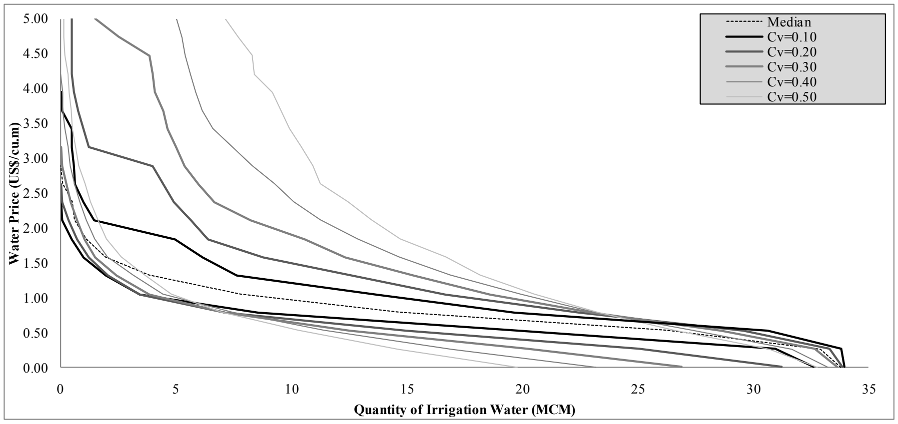

Figure 1-1, Sensitivity of Jericho irrigation water demand 95% bounds to parameter uncertainty

Historic C_v values from Table 2-1 were used to generate bounded demand curves for Bethlehem, Jenin, and Jericho. Figures 2-2 and 2-3, and 2-4 show the likely ranges associated with each application. The impact of historic variability on the range of possible water demands is shown to be significant. At $1.00 for example, simulated irrigated water use varies between 2 and 4 MCM in Bethlehem, 45 and 63 MCM in Jenin and 4 and 18 MCM in Jericho. The differences in allocations results from changing crop profitability induced by the variability in simulated parameter values. For example, a decrease in the price of maize could result in it being dropped from the optimal solution at a lower water price than its nominal price. Alternately, a decrease in water-use per dunam for lentils could result in it being dropped from the optimal solution at a higher water price than nominal water-use value.

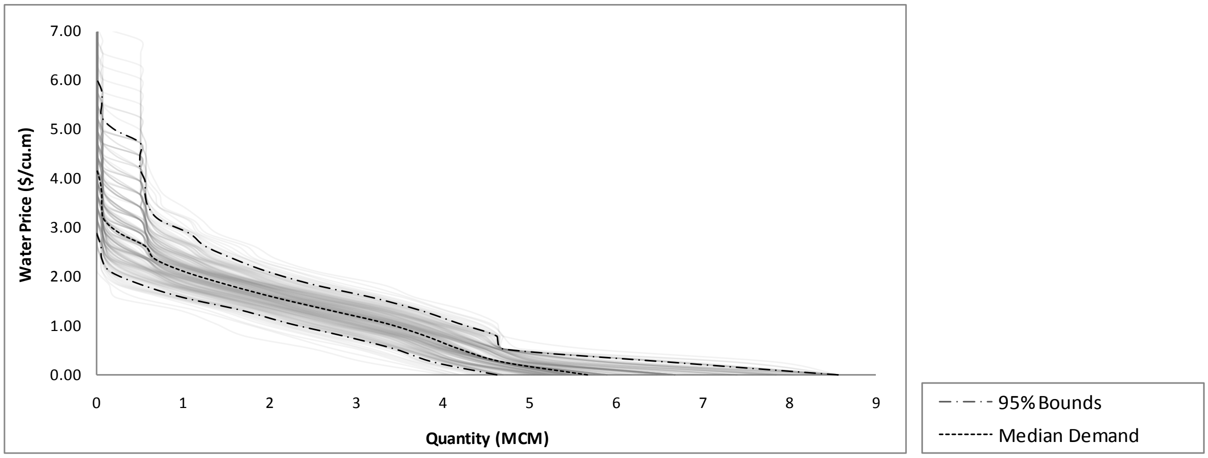

Figure 2-2, Likely Range of Irrigation Water Demand in Bethlehem, 95% CI

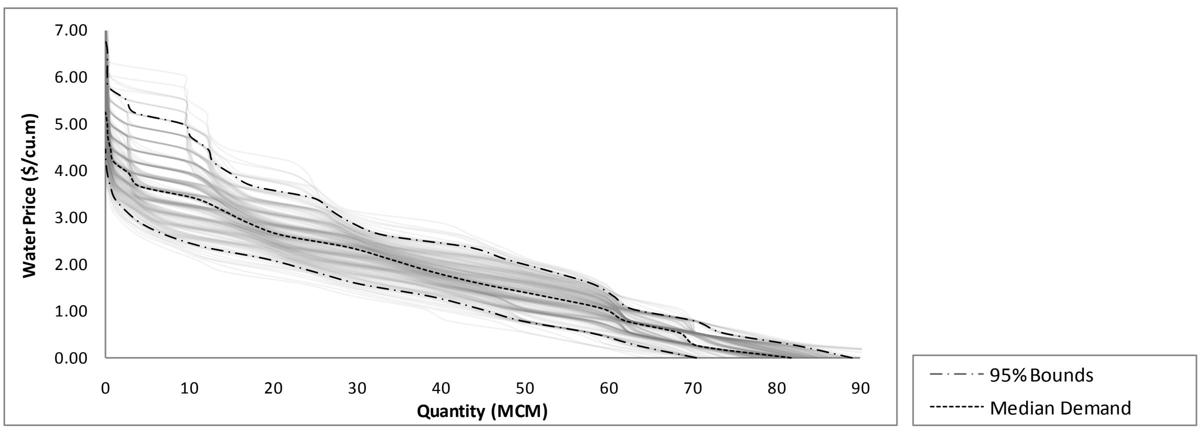

Figure 2-3, Likely Range of Irrigation Water Demand in Jenin, 95% CI

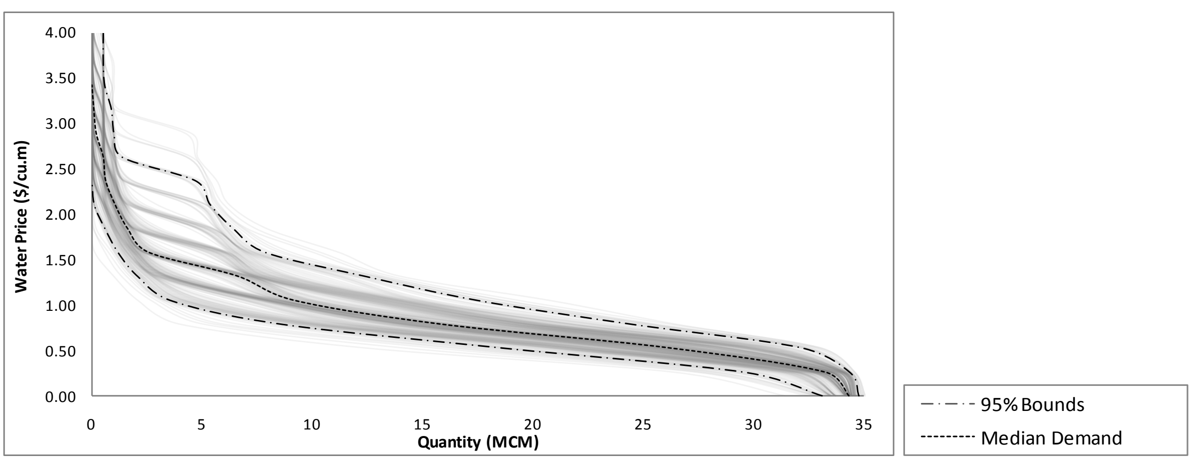

Figure 2-4, Likely Range of Irrigation Water Demand in Jericho, 95% CI

Conclusions

The presented methodology can be used to predict the likely range of agricultural water demand as a function of price resulting from parameter variability in a deterministic water allocation model. The model is shown to be responsive to variability in parameter values. The technique was demonstrated on the deterministic water demand models developed in Chapter 1.

Historical social and environmental variability is shown to induce significant changes in agricultural water use. This information is critical to the decision-support process because plans must be able to account for the range of conditions that are likely to be encountered in the future.

Chapter 3, Uncertainty in the Price Elasticity of Agricultural Water Demand

In this chapter, the price elasticity of irrigation water demand is estimated as a function of average water price. This chapter also considers the uncertainty in estimates of price elasticity as a result of social and environmental variability.

Introduction

The price elasticity of demand is the percent change of the quantity of a good or service in response to a percent change in price. The price elasticity of irrigation water demand indicates the degree to which agricultural water use changes with price. Because an increase in average water price results in a reduction in water use, price elasticity values are typically negative.

Price elasticity of demand is mathematically defined as:

$$\epsilon_P = \frac{P}{Q}\frac{dQ}{dP} \qquad (3.1)$$

where $\frac{dQ}{dP}$ is the derivative of the demand function *Q(P)* evaluated at a price, *P* and associated water use, *Q*. In practice, price elasticity indicates the potential for price policies to effect change in water use. For example, a price increase in a system with elasticity of -1.2 would have a greater effect on water use than if elasticity were -0.8. When price elasticity values are low, price changes induce large losses in farmer income rather than significant water savings (Hooker and Alexander, 1998). However, this assumption has been recently challenged by Scheierling et al., who demonstrated low price elasticity can also be associated with significant water savings (Scheierling et al., 2003).

A primary influence to price elasticity is the functional form of the demand curve, which is the relationship between the quantity of a good or service and the price that consumers are willing to pay for it (See Chapter 1). The most popular forms include linear, double-log, logit, and log-linear (Oum, 1989; Parks, 1969; Espey et al., 1997). In a meta-analysis of residential demand for water, Espey et al, (1997) report linear and double-log forms are the most popular due to their ease of use. Importantly, price elasticity increases with price at a constant rate for linear models and is derived as follows:

$$Q = a - b \cdot P \qquad (3.2)$$

$$\frac{dQ}{dP} = -b \qquad (3.3)$$

Combing Eq. 3.2 and Eq. 3.3 into Eq. 3.1 yields:

$$\epsilon_{P,linear} = -b \cdot \frac{P}{a-b\cdot P} \qquad (3.4)$$

In this case, price elasticity values must be reported at a specific point, Q_n, P_n using Eq. 3.1. This is typically done at the mean price and quantity. The double-log form is popular because price elasticity is explicitly constant at any point on the demand curve and is derived as follows:

$$Q = a \cdot P^b \qquad (3.5)$$

$$\frac{dQ}{dP} = a \cdot b \cdot P^{b-1} \qquad (3.6)$$

Combing Eq. 3.5 and Eq. 3.6 into Eq. 3.1 yields:

$$\epsilon_{P,power} = b \qquad (3.7)$$

Espey et al. (1997) reports that this is thought to be more realistic because of the implication that consumer behavior is insensitive to price. A third possibility is to model demand using a polynomial form. For example price elasticity of a 3-parameter polynomial model is derived as follows:

$$Q = a + b \cdot P + c \cdot P^2 + d \cdot P^3 \qquad (3.8)$$

$$\frac{dQ}{dP} = b + 2c \cdot P + 3d \cdot P^2 \qquad (3.9)$$

Combing Eq. 3.8 and Eq. 3.9 into Eq. 3.1 yields:

$$\epsilon_{P,polynomial} = (b + 2c \cdot P + 3d \cdot P^2) \cdot \frac{P}{a+b \cdot P+c \cdot P^2+d \cdot P^3} \qquad (3.10)$$

When demand is modeled using an econometric approach, the form of the curve is predetermined and implicit in the analysis. Alternately, discontinuous or irregularly stepped curves are generated when demand is empirically derived or estimated using a mathematical program (MP) (Moore et al., 1974; Shumway, 1973; Varela-Ortega et al., 1998). In this case, price elasticity must be numerically estimated between two points using the *arc elasticity* method:

$$\epsilon_{P,arc} = \frac{P_1+P_2}{Q_1+Q_2} \cdot \frac{Q_2-Q_1}{P_2-P_1} \qquad (3.11)$$

In a recent meta-analysis of the price elasticity of irrigation water demand, Scheierling et al. derived or reported arc elasticity values from 24 US based studies (Scheierling et al, 2006). Values from each study were determined between the current average water price and a 25% price increase. Price elasticity values were found to range between -0.001 and -1.97 with a mean of -0.48 and a median of -0.16.

Price policies do not need to be implemented near the current average water price where elasticity is often reported. It may be advantageous to consider price policies at other sections of the demand curve. Elasticity is one indicator that can be used to identify prices where policies can be implemented to meet desired goals. Iglesias et al. (1998) present a method of segmenting derived demand curves and evaluating the elasticity of each segment to determine price ranges that may stimulate a desired change in water use or agricultural benefits. Elasticity can be determined at a point using a numerical estimation technique:

$$\epsilon_{P\,n} = \frac{P_n}{Q_n} \frac{Q_{n+1}-Q_{n-1}}{(P_{n+1}-P_{n-1})} \qquad (3.12)$$

where the slope, $\frac{dQ}{dP}$ in Eq. 1 is estimated numerically to determine the price elasticity (Chapra and Canale, 2005).

The implementation of the arc elasticity method (Eq. 3.11) or numerical method (Eq. 3.12) can be inconsistent between studies because the price intervals, $(P_1 + P_2)\ or\ (P_{n+1} + P_{n-1})$ often differ in value. One solution is to fit the stepped curve to a commonly used functional form (listed above). The price elasticity can then be analytically evaluated using Eq. 3.1. For example, Tsur (2005) has fit a linear demand model to the relation between historical Israeli agricultural water use and price. The primary disadvantage of this method is the heavy dependence of the price elasticity estimate on the assumed choice of model form. Therefore, the choice of model form is of great importance in order to minimize error in resulting elasticity estimates.

There are few examples in the literature in which estimated irrigation water demand has been fit to various functions. Shumway (1973) used the power law model and Amir and Fisher (1999), Amir and Fisher (2000), and Salman et al. (2001) used the linear form.

Methodology:

The price elasticity of irrigation water demand in Jenin and Jericho is evaluated by fitting curves (Eq. 3.1) and numerical estimation (Eq. 3.12). In chapter 2, median demand curves were estimated using Monte Carlo simulation for Jenin and Jericho. They represent the typical demand for irrigation water considering social and environmental variability. The data collection methodology is described in Chapter 1. The goals of this study are (1) to develop a price elasticity model for each district without a need for discrete price intervals and (2) to evaluate the impact of social and environmental variability on elasticity estimates.

Linear (Eq. 3.2), double-log (Eq. 3.5), and 3-parameter polynomial (Eq. 3.8) models are fit to median demand curves (See Chapter 2, Figures 2-3 and 2-4). The linear and double-log forms are chosen because of their overall goodness of fit, popularity, and simplicity. The 3-parameter polynomial form is chosen because of its accuracy. Price elasticity as a function of price is estimated from each demand model for Jenin and Jericho (Eq. 3.4, 3.7, and 3.10). The results are compared to numerically estimated price elasticity values (Eq. 3.12).

Finally, the effect of social and environmental variability on price elasticity in Jenin and Jericho is evaluated using the Monte Carlo simulation performed in Chapter 2. Numerically estimated price elasticity values for each water price (Eq. 3.12) are estimated for each of the 1000 Monte Carlo experiments. The 1000 resulting price elastic values for each price are ranked and the 95% bounds and median rank are estimated using Eq. 2.1 in Chapter 2.

Estimation of Price Elasticity of Irrigation Water for Jenin and Jericho

Price elasticity as a function of irrigation water price was evaluated for each of the three models using Eq. 3.1 for Jenin and Jericho. The results are compared to numerical price elasticity estimates as a function of price using Eq. 3.12 and shown in Figure 3-3 and 3-4. The median demand curve is also provided. Price elasticity of -1 (where a 1% change in price produces a 1% change in irrigation water use) is shown for reference.

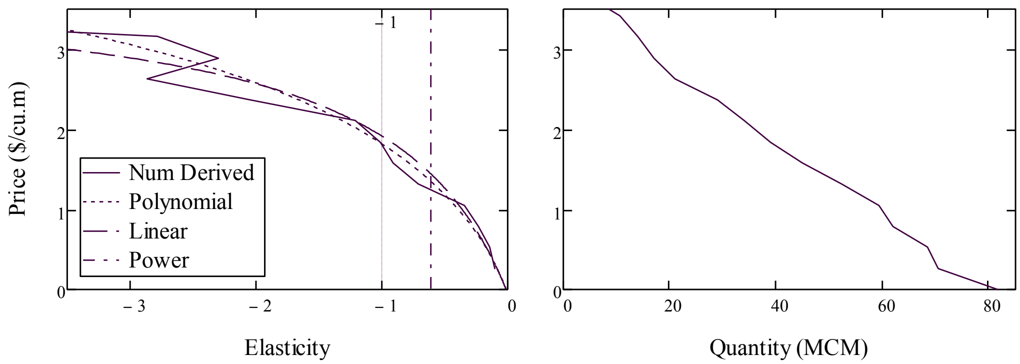

Figure 3-3, Comparison of Price Elasticity of Irrigation Water Demand as a Function of Price in Jenin

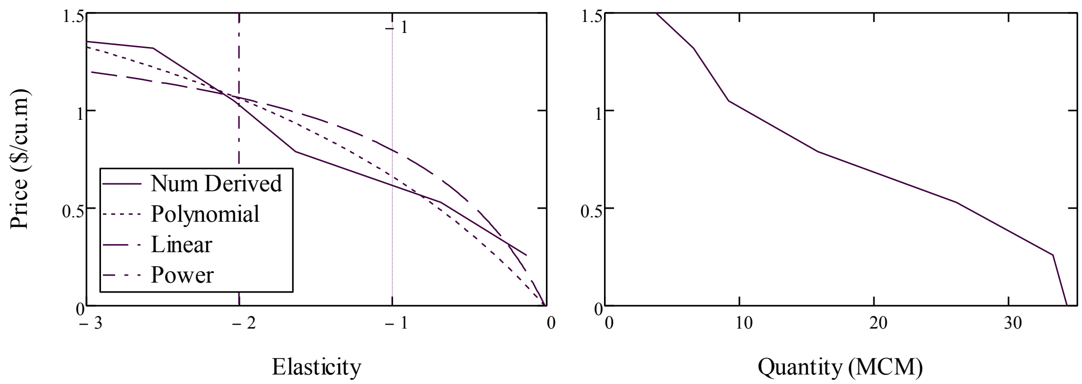

Figure 3-4, Comparison of Price Elasticity of Irrigation Water Demand as a Function of Price in Jericho

In Jenin, the polynomial and linear price elasticity models compare favorably to the numerical elasticity estimates. The correlation coefficients between the polynomial and numerical models and the linear and numerical models are 0.94 and 0.96 respectively over the range of $0 to $3.50. All models match numerically estimated elasticity poorly above $3.50. In Jericho, the correlation coefficients between the numerical model and the polynomial and linear model respectively are 0.96 and 0.86 over the price range $0 to $1.50. All models match numerically estimated elasticity poorly above $1.50. As shown, the double-log model compares poorly with the numerical elasticity estimates in both districts.

Model price elasticity values for Jenin and Jericho compare favorably to results from the meta-analysis performed by Scheierling et al. (2006) at respective average water prices (shown in Table 3-1). The estimated values from the models and numerical estimates are close to the median value of the meta-analysis. The Jenin models report slightly higher price elasticity than the meta-analysis but the estimates are well within the range of results (see Table 3-3).

The irrigation water allocation model for Jericho predicts a much larger reduction in water use at the current water price compared to Jenin (shown in Table 3-1) even though the price elasticity is smaller. This is caused by a difference in the quantity of water used in each district at its current water price. The quantity used in Jenin is much less than the quantity used in Jericho. Thus, a larger elasticity value is associated with a smaller reduction in water use which support Scheierling's claim.

		Price Elasticity of Irrigation Water Demand						***Reduction in Water Use***	
	Avg. Water Price	**Meta-Analysis (Median)**	**Meta-Analysis (Mean)**	**Linear Model**	**Polynomial Model**	**Double-Log Model**	**Numerical Estimation**	**Quantity (MCM)**	**% Change**
Jenin	$0.79	-0.16	-0.48	-0.26	-0.27	-0.60	-0.22	2.7	4%
Jericho	$0.27	-0.16	-0.48	-0.19	-0.33	-2.00	-0.12	7.2	22%

Table 3-1, The price elasticity of irrigation water demand for Jenin and Jericho is reported at the average water price. The change in water use is given over an interval of $0.27.

Uncertainty Analysis of Price Elasticity of Irrigation Water for Jenin and Jericho

The effect of social and environmental variability on price elasticity in Jenin and Jericho is shown in Figures 3-5 and 3-6. The figures show the likely range of price elasticity as a function of price compared to the linear elasticity model (described in the previous section). When price is below $2.50, the linear model matches the median rank well. The linear model performs less well in Jericho compared to the median. However, both linear price elasticity models are well within the likely range of elasticity values.

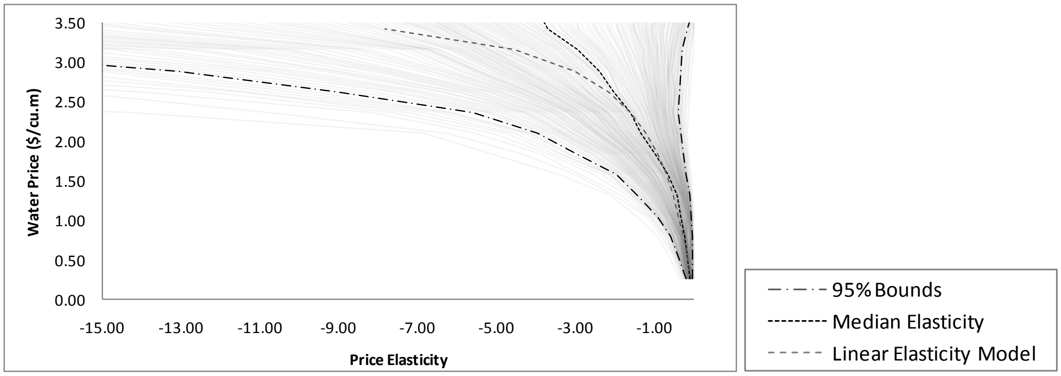

Figure 3-5, Uncertainty of Price Elasticity for Irrigation Water in Jenin

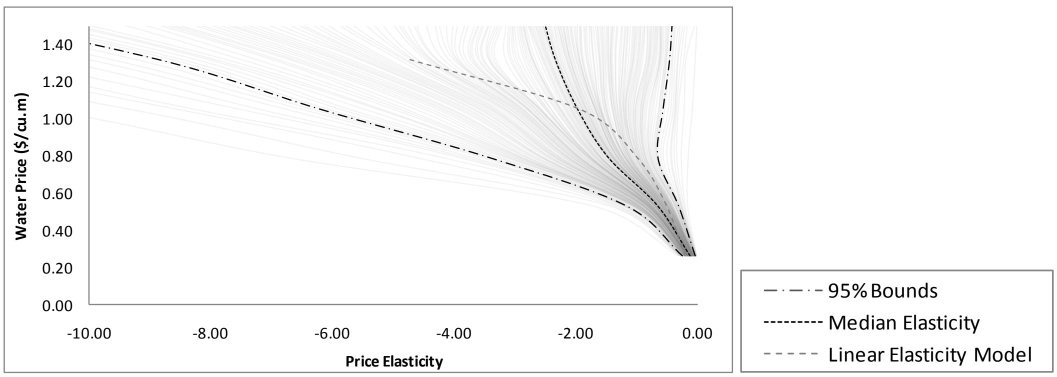

Figure 3-6, Uncertainty of Price Elasticity for Irrigation Water in Jericho

When historic parameter variability is taken into account, the range of elasticity estimates were shown to increase with price. In Chapter 2, Figures 2-2, 2-3, and 2-4 show the likely range of demand resulting from parameter uncertainty. The range of demand is shown to consistent across the range of water prices. Here, the difference in elasticity between bounds is shown to increase significantly with price. Price elasticity values are affected by the magnitude of the quantity (Eq. 3.1, a fixed reduction will have a greater percentage effect on a smaller quantity than a larger quantity). In other words, parameter variability will have a relatively consistent effect on water use at different prices but an increasing effect on price elasticity as the total quantity becomes smaller.

Conclusions

Social and environmental variability is shown to have a large effect on price elasticity as a function of price. The range of likely price elasticity values increases significantly with price. Given (1) its reasonable performance over a large range of water prices, (2) its simpler form (compared to the polynomial model), and (3) the significant variability associated with higher water prices, the linear model is shown to be a reasonable method for approximating price elasticity of irrigation water demand.

Chapter 4, Accounting for Uncertainty in Water Infrastructure Planning

In this chapter, the impact of variability in the price elasticity of irrigation water demand is explored for different allocations of water and infrastructure planning decisions for the West Bank. Scenarios for the year 2010 with and without the possibility of building infrastructure are evaluated with price elasticities ranging from values found in the literature for agriculture (-0.5) to values observed in the previous chapters.

Background

Economics can be a valuable tool for water resources planning and management. Fisher et al. (2002) introduced an economic optimization program which can guide the resolution of transboundary water disputes, the development of public policies towards water, and the optimal placement of water related infrastructure. This is done by simultaneously accounting for demand, supply, existing and potential future infrastructure and social policies to maximize social welfare. The tool, known as the Water Allocation System (WAS), is an annual steady-state model which partitions a region into a set of districts. Demand for water in each district is sub-divided into three sectors or 'users': domestic, industrial, and agricultural. Available supply is connected to users via infrastructure. Districts can also be connected by conveyance lines for inter-district transfers.

Shadow values are central to the analysis of constrained systems such as water allocations in the West Bank. They represent the increase in system-wide benefits that would occur if a constraint (such as water) was relaxed by one unit. In WAS, higher shadow values indicate higher levels of water scarcity. Districts with high shadow values are willing to pay more for water than users in districts with lower shadow values. If inter-district water transfers are possible between districts with different shadow values, it is beneficial to both parties to transfer water.

Though generally constrained, the availability of water varies widely in the West Bank. There are currently no conveyance lines between districts. As a result, some areas suffer from much greater water scarcity than others. Additionally, the exploitation of additional water sources is politically constrained. However, there are two alternate water sources immediately available to Palestinians; wastewater treatment for reuse in agriculture and desalination (in Gaza). WAS is able to evaluate the optimal placements of new water sources and infrastructure with the goal of relieving water scarcity and improving social welfare.

Fisher et al. (2005) evaluated the benefits of new water related infrastructure in the West Bank and Gaza for the year 2010. Recommendations for the construction and optimal placement of desalination plants, wastewater treatment facilities, and inter-district conveyance lines were made based on the results of the simulation. Here, we seek to improve these recommendations by demonstrating how variability in price elasticity can lead to different optimal infrastructure configurations and ultimately more robust decision-making.

Methodology

In Chapters 2 and 3, it was shown that variability in the influences to farmer decision-making leads to uncertainty in demand and the price elasticity of demand for irrigation water. The goal of this study is to make infrastructure-planning decisions that function well over a range of conditions. This will be done by evaluating changes in infrastructure configuration that result from uncertainty in the estimate of the price elasticity of agricultural water.

In WAS, demand is characterized using the double-log functional form (from Chapter 3) which explicitly assigns constant price elasticity. Each sector is assigned a specific value: -0.2

for domestic use, -0.3 for industrial use, -0.5 for agricultural use. The position of the demand curve in each district is fixed by choosing a price, P_o and quantity, Q_o. In this study, the 2010 scenario is run using constant price elasticity values for agricultural water demand of -1.5 while holding the position of the curve, P_o, Q_o constant (See Figure 4-1). Resulting infrastructure decisions will be compared to the configuration when the price elasticity of agricultural demand is set to -0.5. Infrastructure choices when supply is constrained under typical drought conditions will also be considered.

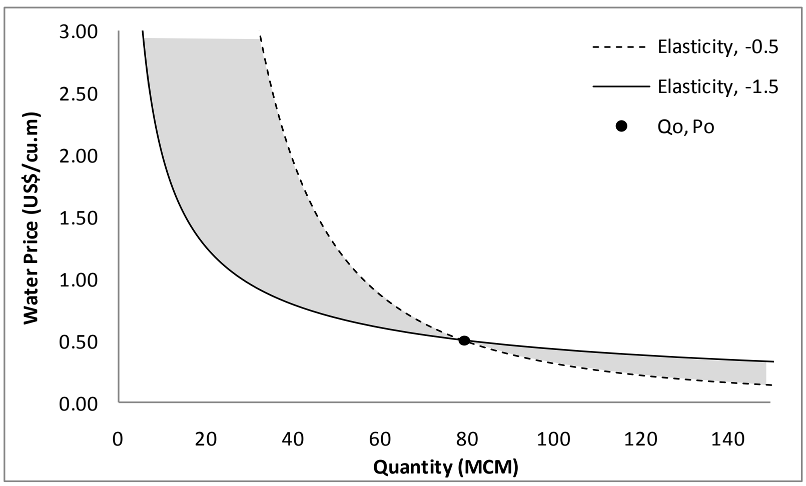

Figure 4-1, Uncertainty in the estimation of price elasticity of agricultural water demand in Jericho.

Baseline Scenario for 2010

In the 2010 baseline scenario, conditions are fixed at their 1995 state with the following changes. Urban and industrial demand is allowed to increase annually by 2.5% and 10% respectively. Secondly, no changes in water transfers are permitted from Israel. Finally, groundwater withdrawals must be pumped at a sustainable rate in Gaza. With the price elasticity of agricultural water demand set to -0.5, the simulation predicts high shadow values in most West Bank districts – an indication of severe water scarcity (See Figure 4-2). Urban and industrial demand continues to grow but no additional supply is available. Importantly, shadow values are extremely high in Ramallah, Jerusalem, and Hebron without the possibility of inter-district transfers from less water-scarce districts.

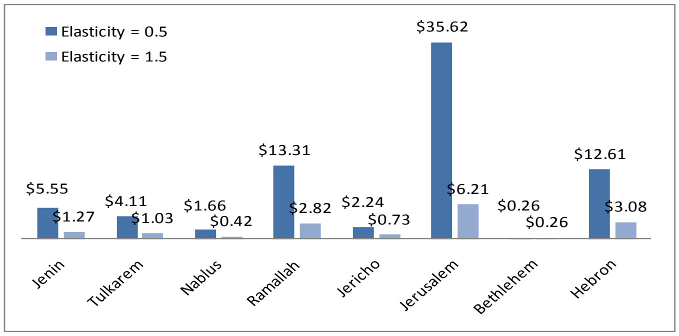

Figure 4-2, Comparison of shadow values for West Bank districts in the baseline scenario.

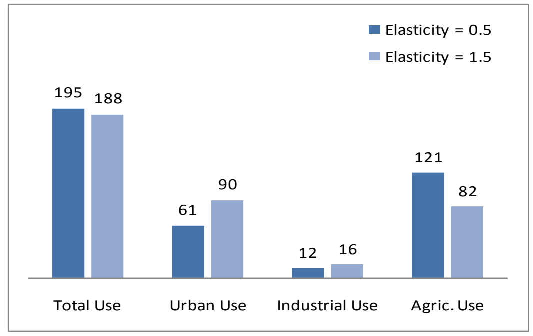

Figure 4-3, Comparison of water use by sector in the baseline scenario.

The 2010 baseline scenario is repeated with price elasticity of agricultural demand changed to -1.5 for all districts. A large decrease in shadow values occurs (Figure 4-2), because for the same percent change in price, there is a larger percent change in quantity of agricultural water demanded. As a result, there is a large reduction in the agricultural use of water (Figure 4-3). Significant quantities are instead allocated to meet domestic demand because it is so much more price inelastic.

Infrastructure Planning for 2010

In this scenario, the possibility of building infrastructure is introduced in the form of wastewater treatment and reuse, inter-district conveyance and desalination in Gaza. This results in significant reductions to shadow values compared to the 2010 baseline scenario which implies that constructed conveyance lines are relieving localized water scarcity by transferring water from locations with less scarcity. Available supply is increased through the construction of wastewater treatment plants in each district (63 MCM total) and desalination plants in Gaza (34 MCM total).

Water scarcity in several districts, notably Jerusalem, Hebron, and Ramallah, is relieved through inter-basin transfers.

Significant changes to the optimal infrastructure configuration occur when the price elasticity of agricultural demand in all districts is changed from -0.5 to -1.5. As with the baseline scenario, the shadow prices of water in each district are less because water is less valuable to agriculture (See Figure 4-4). Allocations to agriculture are reduced by 59 MCM. The optimal quantity for domestic use however, only increases by 17 MCM. In total, 40 MCM less water is used.

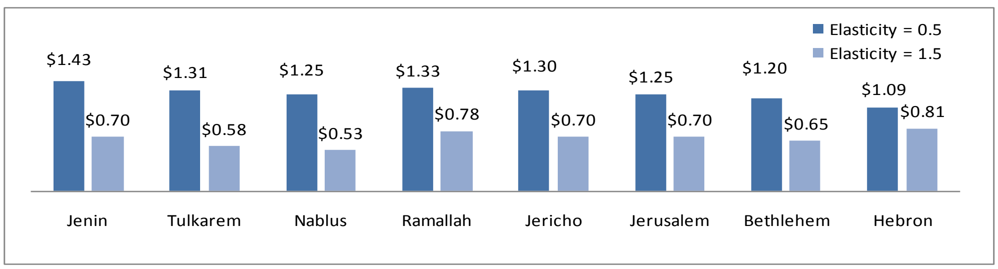

Figure 4-4, Comparison in Shadow Values ($/MCM) for West Bank Districts for 2010 Scenario.

As a result, there is less need for new supply and conveyance capacity in order to achieve maximal social welfare. The most notable change occurs with respect to optimal desalination capacity which is reduced from 34 MCM to 0. Inter-district transfers are also reduced (See Figure 4-5) and the transfer reverses direction between Bethlehem and Hebron. This is because the shadow value of water in Bethlehem becomes less than that of Hebron (See Figure 4-4). It is interesting to note that the treatment and use of wastewater in agriculture changes very little with price elasticity (See Figure 4-6).

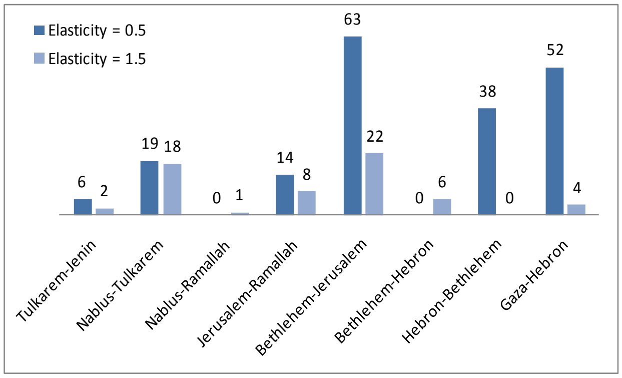

Figure 4-5, Comparison of inter-district conveyance (MCM) for the West Bank and Gaza, 2010 Scenarios.

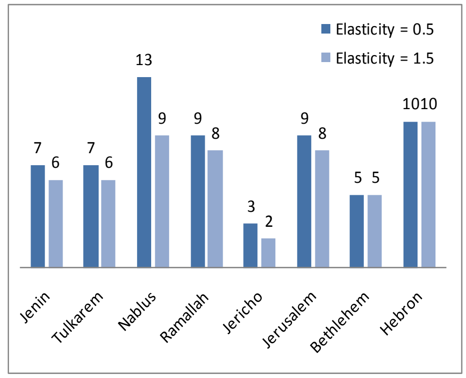

Figure 4-6, Comparison of treated wastewater Capacity (MCM) in the West Bank, 2010 Scenario.

Infrastructure Planning for 2010 under Drought Conditions

Palestine suffers from frequent and sometimes multi-year droughts in which water supplies are constrained beyond average conditions. Infrastructure needs are different under such circumstances. Fisher et al. (2005) report "droughts of a 30% reduction in supplies are not uncommon". In this scenario, the price elasticity of agricultural demand remains -1.5 and supplies are constrained to 70% of that used in the previous scenario.

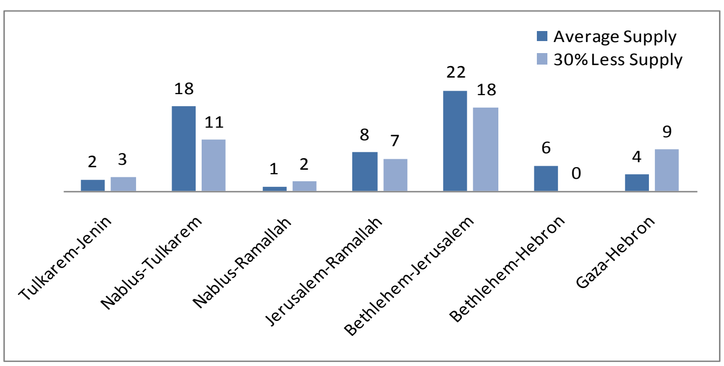

Figure 4-7, Comparison of inter-district transfers (MCM) for the West Bank and Gaza under different supply scenarios. Elasticity is -1.5.

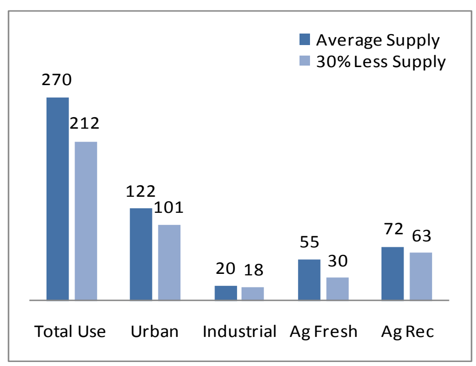

Figure 4-8, Comparison of water use in West Bank and Gaza for alternate supply scenarios.

Shadow values in all districts increase when supply is further constrained. Total water use is reduced by 58 MCM and agricultural water use is reduced by 34 MCM (See Figure 4-8). Desalination becomes cost effective and it is optimal to build 7 MCM of capacity in Gaza.

Production of treated wastewater remains significant but is reduced by 9 MCM. This is primarily driven by reduced domestic water allocations. Water transfers are reduced between several districts but are increased between Gaza and Hebron with the additional supply from desalination plants.

Robust and Resilient Infrastructure Planning

The three scenarios demonstrate how optimal infrastructure placement and capacity change with changes in price elasticity and the availability of supply. In Chapter 3, the estimate of price elasticity was shown to be uncertain. For this exercise, we assume price elasticity varies between -0.5 and -1.5 and craft infrastructure choices that work best given this uncertainty. Reported capital investment costs and value of benefits from infrastructure are taken from Fisher et al. (2005).

Critical to note, the production and use of treated wastewater is remarkably independent of the price elasticity of agricultural water demand and the availability of supply. Annual benefits of treatment facilities are $242 million in 2010. By assuming a discount rate of 5% and a 25-year life of the plants, the expected present value of benefits is $2.5 billion for 2010. This study demonstrates those benefits are only slightly impacted by variability of price elasticity and drought conditions. Thus the investment in treatment plants is shown to be highly robust given the uncertainties explored here.

Investments in several inter-district conveyance lines are also shown to be robust. Price elasticity has minimal impact on transfers from Nablus to Tulkarem. Transfers from Tulkarem to Jenin, Jerusalem to Ramallah, and Bethlehem to Ramallah are modestly affected by price elasticity. For example, transfers from Jerusalem to Ramallah are predicted to vary between 8 and 14 MCM per year. The difference in benefits resulting from the 7 MCM variation in quantity transferred is not likely to more than double the payback period. Thus, these conveyance systems are also shown to be robust with variable but realistic payback periods.

Decisions to invest in the other conveyance lines are not as clear. Optimal transfers from Nablus to Ramallah vary from 0 to 2 MCM depending upon price elasticity and supply availability. The required capital investment is $120 million, which is large because of the change in elevation. This investment may not be worthwhile. The conveyance lines from Hebron to Bethlehem and Gaza to Hebron are shown to depend greatly on price elasticity and frequency of droughts.

When produced in large quantities, desalinated water is distributed from Gaza to Hebron, and onward to Jerusalem, Bethlehem, and Ramallah. When it is not produced, these transfers are not necessary. The decision of how much desalination capacity to build is a tradeoff of frequency of drought or other possible political charges in water availability versus robustness and resilience. Building capacity closer to 34 MCM means the system will be optimal a greater percentage of the time. Decisions regarding the capacity conveyance systems that carry desalinated water to Hebron and northward are interconnected to this decision. If less desalination capacity is built, the conveyance lines become less cost-effective. The resilience of the system can be increased by accounting for drought conditions which occur regularly in the West Bank. This can be done by building at least the minimum 7 MCM of desalination capacity in Gaza.

Conclusion

The presented methodology leads to infrastructure planning that can function well under a range of conditions. This is demonstrated by solving a general water allocation model with two different price elasticities, -0.5 and -1.5. If the demand for water is not precisely known, this technique can be useful for making more robust and resilient decisions. Such uncertainty has been shown to result from parameter model uncertainty in agricultural water demand estimation methods that are not unique to the West Bank.

The impact of infrastructure choices for the West Bank was shown to range in robustness and resiliency. Wastewater treatment plants with re-use and certain inter-district conveyance lines were shown to perform well regardless of the assumed price elasticity estimate. Other choices were less clear. This was especially true for desalination plants and associated conveyance lines that transfer water from Gaza to the West Bank. Under nominal supply conditions (no drought), increasing desalination capacity results in optimal supply availability a greater percentage of the time. Perhaps more importantly, a minimum of desalination capacity is shown to improve the resilience of the system because desalinated supply is optimal under drought conditions. The final decision must weigh the costs associated with increased capacity against the gains made from when the infrastructure configuration is minimally optimal and losses incurred when supplies are sub-optimally available.

Chapter 5, Coupled Pricing Policies that Stimulate the Agricultural Use of Treated Wastewater

In the previous chapter it was shown that treated wastewater can be a robust source of water. In this chapter, an application of the steady-state mathematical program introduced in chapter 1 is used to evaluate coupled freshwater and treated wastewater pricing policies. The model is used to demonstrate how appropriate pricing can stimulate the agricultural use of treated wastewater.

Background

Often, rural populations in semi-arid regions are highly dependent upon groundwater (GW) for domestic consumption and agriculture because surface water is both spatially and temporally inadequate. Unchecked growth in water utilization often causes extractions to exceed natural recharge capabilities of underground aquifers. Under such conditions, it is necessary to limit or reduce use in order to prevent significant loss or contamination of GW resources. Many technical solutions have been developed to support such efforts by improving the efficiency of water use and exploiting alternate sources such as rainwater or seawater. Technical innovations, however, are often not adopted unless supported by policies which stimulate consumers to change their behavior (Varela-Ortega, 2011).

One such technical innovation is the use of treated wastewater (TWW) for agriculture. The use of TWW can effectively increase the number of times a given unit of freshwater is used, which results in greater agricultural production 'per unit' of extracted GW. Typically, TWW used for agriculture is not treated to drinking water standards because it is cost prohibitive and is therefore used with a specific sub-set of crops such as cotton, barley and fruit trees (FAO, 1992). TWW is of particular interest in the Middle East where most countries suffer from high levels of water scarcity and many rural agricultural communities depend upon limited groundwater resources for their livelihoods. The world leader in the use of TWW is Israel which treats 92% of its total wastewater and uses around 75% of that water for agriculture (Mekorot, 2007).

The availability of TWW alone has not resulted in its wide-spread adoption (Abu-Madi et al, 2008). This is the case in the West Bank where 31 MCM of wastewater is collected per year but no systematic use of TWW exists (McNeill et al., 2009). However, small pilot projects have demonstrated its potential. For example, a 600 m^2 green house is irrigated using a small portion of the 5,750 cubic meters per day of TWW generated by the Al Bireh treatment plant in Ramallah (EMWATER, 2004).

Problem Statement

To stimulate agricultural use of TWW as more municipalities connect sewer systems to treatment facilities, it will be necessary to enact policies that encourage farmers to adopt its use. Recent work by Abu-Madi et al., 2008 has demonstrated the adoption of TWW for agriculture depends in part upon the difference in price between freshwater and TWW. They found that freshwater prices must be increased *relative* to TTW prices in order to entice farmers to use TWW in the Middle East and North Africa (MENA) region. However, a methodology for evaluating the effects of coupled freshwater and TWW pricing schemes on regional water utilization has yet to be developed.

The decision-support tool described below is designed to quantitatively evaluate the effects of combined GW and treated wastewater pricing schemes based upon the value of water used for agriculture. The results of the analysis not only indicate the farmers' willingness to pay for TWW based upon a hypothetical GW price, but also estimate how much of each type of water will be used. It is established that the effects of water policies are highly dependant upon the unique characteristics of a given region such as yields, crop profitability, land availability, and historic cropping patterns (Varela-Ortega, 1998). The proposed methodology is intended to aid policy makers in evaluating (1) the potential for TWW use and (2) the quantifiable effects of coupled GW and TWW pricing policies on the utilization of groundwater and treated wastewater in a regionally specific context.

Coupled Price Policy Evaluation Methodology

Mathematical Programs (MPs) have previously been employed to evaluate the effects of either freshwater pricing (Varela-Ortega et al., 1998; Al-Weshah, 2000) or treated wastewater pricing (Segara et al., 1996; Darwish et al., 1999) individually on regional farming systems. Amir and Fisher evaluated multiple qualities of water with AGSM, however they assumed a single or aggregate price for each type (Amir and Fisher, 1999; Amir and Fisher, 2000). Here, we consider the use of both GW and TWW on the same system and allow each to be individually priced. Coupled GW and TWW price policies are evaluated together to determine the extent to which different coupled price policies entice farmers to use GW in place of TWW. This is done by using the model formulation described in Chapter 1.

Recall the objective function (Eq. 1.1) of the optimization model which seeks to maximize regional net profits by selecting the optimal mix of rain-fed and water-consuming activities:

$$Maximize: \qquad \sum_{a}\sum_{wq} X_{a,wq}\left[\left(Pc_a \cdot Y_a\right) - \left(Pw_{wq,} \cdot W_{a,wq}\right) - NWC_a\right] \qquad (5.1)$$

where the decision variable, $X_{a,wq}$ is land area devoted to rain-fed or irrigated activity, *a,* using water of quality, *wq*, Pw_{wq} is water price per dunam, and $W_{a,wq}$ is water use per dunam. Net benefits are constrained by available land and local market conditions (historic cropping patterns). In Chapter 1, only one water quality, *wq* was considered. Here, two water qualities, GW and TWW are considered.

When the model is run at specific GW and TWW prices, the resulting allocations of agricultural land and used quantities of GW and TWW water determine optimal net agricultural benefits. By running it systematically using all possible combinations of GW and TWW prices, an array of resulting GW and TWW quantities are generated. This array can be used by decision makers to evaluate the effect of various coupled pricing schemes on GW and TWW use. The method is demonstrated in the following example using data for the Jericho Governorate gathered as described in Chapter 1.

Coupled Policy Analysis of Jericho

The Government of Japan has recently signed an agreement with the Palestinian Authority to finance a $32 million dollar wastewater treatment plant in Jericho. One of the established goals is to increase the quantity of water available for irrigation through the use of TWW. Freshwater supplies in Jericho are not constrained, but future population changes will strain available water resources (See Chapter 1). Alternate sources of reliable irrigation water will be important for the continued economic resilience of the region. The average price of freshwater is approximately $0.27.

The proposed policy analysis tool will therefore evaluate (1) the maximum quantity of TWW Jericho can potentially utilize and (2) how the decision support tool can be used to identify coupled pricing policies that stimulate the use of TWW. The application is built using the data from Chapter 1.

Figure 5-1 shows the demand or *the willingness of farmers to pay* for GW and TWW by running the model separately using only GW and TWW respectively. The plot gives insight into the extent to which GW can be replaced by TWW in agriculture.

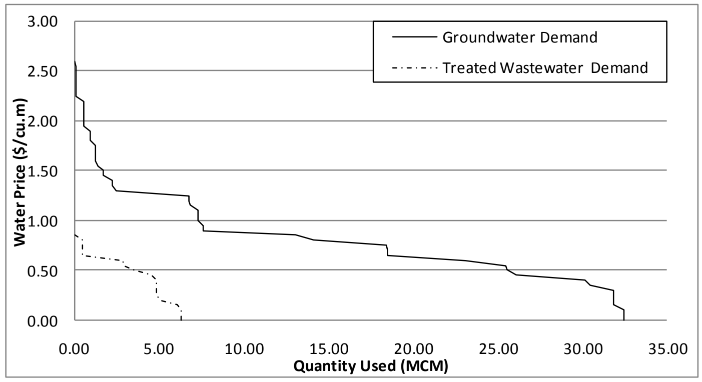

Figure 5-1, Demand for Treated Wastewater and Groundwater

The demand curves show the upper bounds of potential GW and TWW use. Due to region specific conditions, use of TWW cannot exceed 6.3 million cubic meters (MCM) of TWW. On the other hand, GW use can reach 32.5 MCM. Maximum use of each is constrained by total available land, historic cropping patterns and the number of crops that can use each type of water. The difference results from large historic land allocations to vegetable crops that cannot use TWW. Secondly, the TWW demand curve y-intercept is lower than that of the GW demand curve, which indicates there are a number of high value crops that cannot be grown with TWW. Therefore, based on regional agricultural conditions, the use of GW will always exceed TWW use. However, there still exists potential for TWW to replace significant quantities of GW enabling greater agricultural production while conserving large quantities of GW for other uses.

With a better understanding of how regional characteristics affect the potential replacement of GW with TWW, different coupled pricing policies can be evaluated with various policy objectives in mind (See Table

TWW Price = $0.10			
GW Price	**WW Used**	**Tot Wat. Used**	**Tot GW Red.**
0.25	0.66	32.46	0.66
0.30	0.70	31.87	0.66
0.35	1.27	31.70	2.03
0.40	1.42	31.53	2.35
0.45	2.84	28.94	6.36
0.50	3.37	28.94	6.89
0.55	3.44	28.94	6.96
0.60	5.84	28.94	9.36
0.65	5.83	24.32	13.97
0.70	5.83	24.32	13.97
0.75	5.84	24.24	14.06
0.80	6.26	20.37	18.35

Table 5-1, GW and TWW allocations at various GW Prices

TWW Price = $0.15			
GW Price	**WW Used**	**Tot Wat. Used**	**Tot GW Red.**
0.25	0.66	32.46	0.66
0.30	0.66	32.46	0.66
0.35	1.23	31.66	2.03
0.40	1.55	31.66	2.35
0.45	2.63	28.73	6.36
0.50	3.16	28.73	6.89
0.55	3.23	28.73	6.96
0.60	5.63	28.73	9.36
0.65	5.62	24.11	13.97
0.70	5.62	24.11	13.97
0.75	5.63	24.03	14.06
0.80	6.05	20.16	18.35

Table 5-2, GW and TWW allocations at various GW Prices

The data show the extent to which appropriately priced TWW and GW combinations can induce farmers to use TWW in place of GW, enabling conservation of finite GW resources. Tables 5-1 and 5-2 are two sub-sets of the results from the complete simulation of all possible combinations of GW and TWW prices. The model predicts the effect of TWW use induced by increases in GW prices starting with the current GW price of $0.26. We consider two likely candidate price points for TWW of $0.10 (Table 5-1) and $0.15 (Table 5-2) and use the resulting allocation values to evaluate different coupled GW and TWW pricing options. TWW use increases steadily as GW become more expensive until the GW price reaches $0.60. GW prices greater than this induce diminishing TWW use. If GW is priced at $0.60, then GW use would decrease by 9.4 MCM. However if treated wastewater were available at $0.10 or $0.15, than 5.6 to 5.8 MCM of TWW would be used, compensating for the decreased use in GW. The resulting net decrease in total agricultural water use is therefore decreased by only 3.6 to 3.8 MCM. Thus, quantified shortfalls in GW use and induced compensating quantities of TWW can be evaluated at different coupled price points. The proposed analysis technique is a flexible tool that allows decision makers to make policy decisions that fit specific objectives such as a target reduction in the use of GW, targeted increase in the use of TWW, or some combination thereof.

Limitations

Many simplifications are made in the Jericho case study, which can be improved in a number of ways. First, yields are assumed to be fixed and identical for crops irrigated with GW and TWW. More precise TWW yield estimates will provide more accurate results. Secondly, a single average GW price is assumed to be charged to all users in the system. In reality there is a distribution of prices and this distribution is simplified to the expected average value of $0.26. Future applications should explore the effects of this simplification further. Finally, average agricultural parameter values are used in this model formulation. It would be prudent to evaluate the effects of variability in agricultural characteristics for future applications.

Conclusions

The agricultural use of treated wastewater has significant potential to decrease the human use of increasingly strained groundwater resources in water scarce regions. However, it has been shown that availability alone does not result in its wide-spread adoption. The proposed coupled pricing policy evaluation method significantly improves the options available to water planners by including treated wastewater in a holistic policy analysis. This is necessarily done within a region specific context such that results fit the particular agricultural conditions of interest. The proposed novel decision-support tool provides decision makers with specific estimates of groundwater and treated wastewater use stimulated by various pricing policies. The efficacy of this methodology is demonstrated with a case study of Jericho, Palestine where groundwater price increases are shown to quantifiably stimulate the use of treated wastewater.

Limitations

There are a number of limitations to the various model formulations in this thesis. First, the inclusion of capital costs could allow planners to better understand how policies will be enacted. AGSM is a steady-state formulation. Second, a multi-year analysis will elicit more insight into how farmers in water constrained districts like Bethlehem and Jenin use additional land and how farmers in less constrained districts like Jericho react over time to water pricing policies.

There are a number of aspects of farmer behavior not included in the model. Perhaps most fundamentally, the model does not include mechanisms that simulate a farmer's aversion to risk. Agricultural water use predictions will continue to become more reflective of actual farm-level decisions as risk aversion, for example, is incorporated into water allocation models.

Finally, the infrastructure analysis is limited to somewhat arbitrary price elasticity bounds. The logical next step in this work is to estimate the likely bounds of agricultural demand for the remaining West Bank districts and input all of them directly into WAS. This would elicit a more precise range of optimal infrastructure choices to evaluate.

Conclusions

The responsiveness of the agricultural water allocation model presented in chapter 1 was improved by accounting for historical social and environmental variability using Monte Carlo simulation. Likely ranges of water allocations as a function of price were estimated to predict year to year uncertainty in agricultural water demand for three West Bank agricultural districts, Bethlehem, Jenin, and Jericho. Results of the Monte Carlo simulation also produced likely ranges of price elasticity as a function of price for Jenin and Jericho.

The importance of considering uncertainty in agricultural demand for water was demonstrated with an infrastructure planning analysis. Variability in the estimate of price elasticity of agricultural water demand was shown to lead to different optimal infrastructure configurations for the West Bank. This information led to the development of robust and resilient infrastructure configurations.

Resources must be managed efficiently when highly constrained. In developing countries such as the West Bank this is as true financially as is it for water resources. It is vital that investments in infrastructure provide maximum social welfare per dollar spent. The methodology is designed to provide decision support that guides policy makers as they consider how to allocate limited financial resources. The analysis shows it is possible to identify specific infrastructure investments such as wastewater treatment plants that operate well under a range of conditions.

The methodology can also identify investments that improve the resiliency of social welfare. This protects society against disturbances such as prolonged periods of drought. The social and economic costs of ill-preparation for such events can range from catastrophic to the perpetuation of the poverty trap. Investments in infrastructure that improve resilience must be carefully weighed against such costs.

Decision support tools that can guide the effective development of water related infrastructure in a highly variable world are desperately needed. Effective investment decisions are vital to improving the social welfare of developing countries such as Palestine.

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Appendix B: Optimization Program for Irrigation Water Variability Simulation

Written in the General Algebraic Modeling System (GAMS)

```
*           Agricultural Sub-Model (AGSM)
*                   Version 1.0
*                   21 Mar 2011
*
* This model maximizes the quantity of water delivered at a given water price
* agriculture in Jenin, West Bank. The model is steady-state.

* The following lines allow for a maximum of 80000 iterations by the solver,
* and increases the default resource limit.
*
* In this version crop price and intermediate costs are variables for
* a variability analysis. A Monte-Carlo simulation is employed.
*
* To switch districts change activity file, include files, and block additional
* activity equations

OPTIONS ITERLIM   = 80000;
OPTIONS RESLIM    = 100000;
OPTION  SOLVELINK = 5;

*resets the random number generator seed value
*execseed = gmillisec(jnow);

* This allows comments to be made in a line by using the characters: {}
$inlinecom{ }

* The maximum number of characters recognized in a single line is 250
$maxcol 250

SETS
   i       all districts

* This file inputs district names and indices for all nodes
$include district.inc

* Activities include all types of income generating activities including
* crops, orchards, fish ponds, flowers, etc.
   a       activity

* The four types of water that will be modeled will be fresh groundwater,
* fresh surface water, recycled wastewater, and brackish water
   wq      water quality /G/

* Land category accounts for the fact that not all land is equally suitable
* for all types of activities
   lc      land category

* Water prices vary by season. Typically there are 3-4 seasons per year.
   sn      season /sum/

* Iterations for creating a demand curve by varying water price
```

```
   r       water price run/r1*r20/

* Iterations for creating a second demand curve by varying an input parameter
   d       demand curve run/d1*d1/

* The following statements add files which include AGSM set definitions.

*$include jenin_activity.inc
*$include jericho_activity.inc
*$include beth_activity.inc
$include shean_activity.inc

*  The following statement add file includes the land categories of each activity
$include landcat.inc

alias(a,j);

SCALARS
   WCOST   Cost in shekels of water quality wq in year 1 /0/
   LGM     Land Growth Max /100/
   LMR     Land Minimum Growth Rate /.10/

*$include jericho_cv.inc
*$include jenin_cv.inc
*$include beth_cv.inc
$include zero_cv.inc

*$include jericho_land.inc
*$include jenin_land.inc
*$include beth_land.inc
$include shean_land.in;

PARAMETERS

   AGSM(i)          Switch to activate the Agricultural Sub-Model for district (i)
   MAX_YIELD(i,a)    Maximum Yield from activity (a) in district (i) per kg
   YIELD(i,a)        Yield of activity a per area of land
   WREQ(i,a,wq,sn)   The water requirement per dunam per activity
   MAX_LAND(i,lc,sn) Maximum land available per district (d) & land category (lc)
   CROPCAT(i,lc,a)   Indicates which crops are in which land category
   MAX_WAT(i,wq,sn)  Maximum available water of water quality wq in year t
   AG_INIT(i,a)      Initial land allocations per crop
   AG_MAX_P(i,a)     Maximum Allowable present land allocations per crop
   AG_MAX_F(i,lc,a)  Maximum Allowabe future land allocations per irrigated crop
   GROW_COEF_P(i,a)  Present Growth Coefficient for land change constraint
   PCROP(i,a)        Nominal price of crops
   PINT(i,a)         Nominal price of input costs
   ADJ_PCROP(i,a)    Randomized price of crops
   ADJ_PINT(i,a)     Randomized Price of crops
   ADJ_YIELD(i,a)    Randomized Crop Yield
   ADJ_WREQ(i,a,wq,sn) Randomized Crop Yield

* Post-processing parameters
   WP(r)        Water Price
   QT(r,d)      Water Quantity
   NB(r,d)      Net Benefits
```

```
   IR(r,d)      Irrigated Land Allocations
   RF(r,d)      Rain-fed Land Allocations
   GH(r,d)      Green-House Land Allocations
   FT(r,d)      Fruit Tree Land Allocations
   VG(r,d)      Vegetable Land Allocations
   FC(r,d)      Field Crop Land Allocations
   CROP(a,r,d)  Track crop allocations at each water price time-step
   INF_IND(a)   Total influence of each crop on allocation variation
   gg(a)        Counter for sorting crops by influence
   DEM_DER(r,d) Point derivative of demand curve
   E(r,d)       Point Elasticity based upon demand curve
   ShV(r,d)     Shadow Value for run r and demand curve d;

* The following statements imclude files for the AGSM parameters.
{$include jenin_agsm.inc
$include jenin_nwc_fix.inc
$include jenin_maxyield.inc
$include jenin_prof_fix.inc
$include jenin_wreq.inc
$include jenin_cropcat.inc
$include jenin_watmax.inc
$include jenin_init.inc
$include jericho_agsm.inc
$include jericho_nwc_fix.inc
$include jericho_maxyield.inc
$include jericho_prof_fix.inc
$include jericho_wreq.inc
$include jericho_cropcat.inc
$include jericho_watmax.inc
$include jericho_init.inc
$include beth_agsm.inc
$include beth_nwc_fix.inc
$include beth_maxyield.inc
$include beth_prof_fix.inc
$include beth_wreq.inc
$include beth_cropcat.inc
$include beth_watmax.inc
$include beth_init.inc}
$include shean_agsm.inc
$include shean_nwc_fix.inc
$include shean_maxyield.inc
$include shean_prof_fix.inc
$include shean_wreq.inc
$include shean_cropcat.inc
$include shean_watmax.inc
$include shean_init.inc;
* The growth coefficient is used to set the maximum growth rate for allocations

   GROW_COEF_P(i,a)$AGSM(i) = 0.5 * ( 1 + (1 - EXP(0.03*(LMR * sum((wq),AG_INIT(i,a))
            -LGM)))/(1 + EXP(0.03*(LMR * sum((wq),AG_INIT(i,a))-LGM))));

   AG_MAX_P(i,a)$AGSM(i) = AG_INIT(i,a) + (LGM * GROW_COEF_P(i,a))+ (LMR *
            (AG_INIT(i,a)*(1-GROW_COEF_P(i,a))));

   AG_MAX_F(i,lc,a)$(AGSM (i) and ord(lc) = 7) = ((AG_INIT(i,a)/MLAND_IR) *
            MLAND_F) * (1+LMR)* CROPCAT(i,lc,a);
```

```
{* Additional Cash Crops for Jenin Only
   AG_MAX_F('i5',lc,'a80') = 24508;
   AG_MAX_F('i5',lc,'a81') = 5415;
   AG_MAX_F('i5',lc,'a82') = 5013;
   AG_MAX_F('i5',lc,'a83') = 8072;
* Additional Cash Crops for Bethlehem Only
   AG_MAX_F('i20',lc,'a40') = 821;
   AG_MAX_F('i20',lc,'a41') = 763;
   AG_MAX_F('i20',lc,'a42') = 499;
   AG_MAX_F('i20',lc,'a43') = 499; }

* The following declares the decision variables for the optimization problem
VARIABLES
   Z                    Net Economic Benefit in Million Dollars
   AG_AREA(i,a,wq,sn)  The land area used for agricultural activity (a);

POSITIVE VARIABLES AG_AREA;
* The following statements define the equations that will be used
* in the optimization, both the objective function and the constraints.

EQUATIONS
OBJ             Net Econonomic Benefit in Million Dollars
WAT_MAX(i,wq,sn)    Agricultural water use cannot exceed calculated demand (fresh)
LMAX(i,sn)      Agricultural land use cannot exceed available land
GROW_MAX(i,a)       Limits crop land  beyond growth of 15% of IC or 300 dunam;

OBJ..       Z =E= sum((i,a,wq,sn)$AGSM(i),AG_AREA(i,a,wq,sn)*(1/1000000)*
             ((ADJ_YIELD(i,a)* ADJ_PCROP(i,a))
             - ADJ_PINT(i,a)
             - (WCOST*ADJ_WREQ(i,a,wq,sn))));

* The first equation limits the water allocated to crops to a maximum available
* quantity for each type of water quality; surface, ground, recycled, brackish.
  WAT_MAX(i,wq,sn)$AGSM(i).. MAX_WAT(i,wq,sn) =G=
             sum((a),AG_AREA(i,a,wq,sn)*ADJ_WREQ(i,a,wq,sn));

* The next equation limits the land used of each land category (permenant,
* industrial, vetetable, fish farms) to a maximum available area.
  LMAX(i,sn)$AGSM(i).. MLAND_T =G= sum((a,wq), AG_AREA(i,a,wq,sn));

* The next equation constrains change from initial crop allocation for proper
* crop diversification. Crop allocation increase or decrease by 10% or 50 du,
* whichever is larger. A smoothed step function is employed using the growth
* limit coefficient (previous eqn).
  GROW_MAX(i,a)$AGSM(i).. sum((wq,sn),AG_AREA(i,a,wq,sn)) =L= AG_MAX_P(i,a) +
             sum(lc,AG_MAX_F(i,lc,a));


MODEL WAS /ALL/;

Loop(d,

* Random parameter values driven by input Cv values
  ADJ_YIELD(i,a) = CROPCAT(i,'lc1',a) * CROPCAT(i,'lc7',a) *
            normal(MAX_YIELD(i,a),(MAX_YIELD(i,a) * FT_IR_YIELD_Cv));
```

```
  ADJ_YIELD(i,a)$(ADJ_YIELD(i,a) = 0) = CROPCAT(i,'lc2',a) * CROPCAT(i,'lc7',a)
             * normal(MAX_YIELD(i,a),(MAX_YIELD(i,a) * V_IR_YIELD_Cv));
  ADJ_YIELD(i,a)$(ADJ_YIELD(i,a) = 0) = CROPCAT(i,'lc3',a) * CROPCAT(i,'lc7',a)
             * normal(MAX_YIELD(i,a),(MAX_YIELD(i,a) * FC_IR_YIELD_Cv));
  ADJ_YIELD(i,a)$(ADJ_YIELD(i,a) = 0) = CROPCAT(i,'lc1',a) * CROPCAT(i,'lc4',a)
             * normal(MAX_YIELD(i,a),(MAX_YIELD(i,a) * FT_RF_YIELD_Cv));
  ADJ_YIELD(i,a)$(ADJ_YIELD(i,a) = 0) = CROPCAT(i,'lc2',a) * CROPCAT(i,'lc4',a)
             * normal(MAX_YIELD(i,a),(MAX_YIELD(i,a) * V_RF_YIELD_Cv));
  ADJ_YIELD(i,a)$(ADJ_YIELD(i,a) = 0) = CROPCAT(i,'lc3',a) * CROPCAT(i,'lc4',a)
             * normal(MAX_YIELD(i,a),(MAX_YIELD(i,a) * FC_RF_YIELD_Cv));
  ADJ_PINT(i,a) = normal(PINT(i,a),(PINT(i,a) * PIN_Cv));
  ADJ_PCROP(i,a) = CROPCAT(i,'lc1',a) * normal(PCROP(i,a),(PCROP(i,a) * FT_PCROP_Cv));
  ADJ_PCROP(i,a)$(ADJ_PCROP(i,a) = 0) = CROPCAT(i,'lc2',a) * normal(PCROP(i,a),
             (PCROP(i,a) * V_PCROP_Cv));
  ADJ_PCROP(i,a)$(ADJ_PCROP(i,a) = 0) = CROPCAT(i,'lc3',a) * normal(PCROP(i,a),
             (PCROP(i,a) * FC_PCROP_Cv));
  ADJ_WREQ(i,a,wq,sn) = normal(WREQ(i,a,wq,sn),(WREQ(i,a,wq,sn) * W_Cv));

  WCOST = 0;

  Loop(r,
    OPTION NLP = CONOPT;
    SOLVE WAS MAXIMIZING Z USING NLP;
* Post-processing variable calculations
    WP(r) = WCOST / 3.8;
    QT(r,d) = sum((i,a,sn)$AGSM(i),(AG_AREA.L(i,a,'G',sn)*WREQ(i,a,'G',sn)))/1000000;
    NB(r,d) = sum((i,a,wq,sn)$AGSM(i), AG_AREA.L(i,a,wq,sn)*(1/1000000)*
               ((ADJ_YIELD(i,a)* ADJ_PCROP(i,a))
               - ADJ_PINT(i,a)
               - (WCOST*ADJ_WREQ(i,a,wq,sn))
               ));
    IR(r,d)= sum((i,a,wq,sn)$AGSM(i), (CROPCAT(i,'lc5',a) * AG_AREA.L(i,a,wq,sn)));
    RF(r,d) = sum((i,a,wq,sn)$AGSM(i), (CROPCAT(i,'lc4',a) * AG_AREA.L(i,a,wq,sn)));
    GH(r,d) = sum((i,a,wq,sn)$AGSM(i), (CROPCAT(i,'lc6',a) * AG_AREA.L(i,a,wq,sn)));
    FT(r,d) = sum((i,a,wq,sn)$AGSM(i), (CROPCAT(i,'lc1',a) * CROPCAT(i,'lc5',a)
               * AG_AREA.L(i,a,wq,sn)));
    VG(r,d) = sum((i,a,wq,sn)$AGSM(i), (CROPCAT(i,'lc2',a) * CROPCAT(i,'lc5',a)
               * AG_AREA.L(i,a,wq,sn)));
    FC(r,d) = sum((i,a,wq,sn)$AGSM(i), (CROPCAT(i,'lc3',a) * CROPCAT(i,'lc5',a)
               * AG_AREA.L(i,a,wq,sn)));
    CROP(a,r,d) = sum((i,wq,sn)$AGSM(i), AG_AREA.L(i,a,wq,sn));
    ShV(r,d) = sum((i,a)$AGSM(i), GROW_MAX.M(i,a));
    WCOST = WCOST + 0.19;
    );
);

*Determines the point derivatives and elasticities for each demand curve
DEM_DER(r,d)$(ord(r) ge 2) = (QT(r+1,d) - QT(r-1,d)) / (2 * 0.26);
E(r,d)$(ord(r) ge 2) = (WP(r)/QT(r,d)) * DEM_DER(r,d);

$include output_d_curve.inc
*$include output_var_indicator.inc
*$include output_crop_influence.inc
$include output_crop_allocations.inc
*$include output_pt_elasticity.inc
```

Appendix C: Optimization Program for Dual Water Pricing Simulation

Written in the General Algebraic Modeling System (GAMS)

```
*          Agricultural Sub-Model (AGSM)
*              Version 1.0
*              21 May 2011

* This model maximizes the net benefits generated using of water delivered
* for agriculture in Jericho in the West Bank.
* This version simulates combinations of two types of water, such as
* freshwater and treated wastewater.
.
* The model is steady-state.

* In this version crop price, water use, yields, and input costs are random
* variables. Simulations using Monte Carlo simulation allow the user to explore
* the effects of variability on water allocations.

* The following lines allow for a maximum of 80000 iterations by the solver,
* and increases the default resource limit.
OPTIONS ITERLIM   = 80000;
OPTIONS RESLIM    = 100000;
OPTION  SOLVELINK = 5;

* This allows comments to be made in a line by using the characters: {}
$inlinecom{ }

* The maximum number of characters recognized in a single line is 250
$maxcol 250

SETS

   i      all districts

* This file inputs district names and indices for all nodes
$include district.inc

* Activities include all types of income generating activities including
* crops, orchards, fish ponds, flowers, etc.

   a      activity

* The four types of water that will be modeled will be fresh groundwater,
* fresh surface water, recycled wastewater, and brackish water

   wq     water quality /G,R/

* Land category accounts for the fact that not all land is equally suitable
* for all types of activities
   lc     land category

* Iterations for creating a demand curve by varying water price
   r      fresh water price run/r1*r25/
```

```
* Iterations for creating a second demand curve by varying an input parameter
   d        treated ww price run/d1*d10/

* The following statements add files which include AGSM set definitions.

*$include jenin_activity.inc
*$include jericho_activity.inc
$include beth_activity.inc

$include jenin_landcat.inc

alias(a,j);

SCALARS
   LGM      Land Growth Max /50/
   LMR      Land Minimum Growth Rate /.05/
   Cv       Coefficient of Variation /0.00/

*Jenin
{   MLAND_P  Present available Land in dunams/344489/
   MLAND_F  Future available Land in dunams/128366/
   MLAND_IR Present Irrigated Land in dunams/19544/
   MLAND_T  Total Available Land in dunams/515863/

* Jericho
   MLAND_P  Present available Land in dunams/45843/
   MLAND_F  Future available Land in dunams/3296/
   MLAND_IR Present Irrigated Land in dunams/45843/
   MLAND_T  Total Available Land in dunams/49139/}

* Bethlehem
   MLAND_P  Present available Land in dunams/54290/
   MLAND_F  Future available Land in dunams/9977/
   MLAND_IR Present Irrigated Land in dunams/2023/
   MLAND_T  Total Available Land in dunams/64267/;

PARAMETERS

   AGSM(i)       Switch to activate the Agricultural Sub-Model for district (i)
   MAX_YIELD(i,a)    Maximum Yield from activity (a) in district (i) per kg
   YIELD(i,a)        Yield of activity a per area of land
   WREQ(i,a,wq)      The water requirement per dunam per activity
   WCOST(wq)         Cost in shekels of water quality wq in year 0
   MAX_LAND(i,lc)  Maximum land available per district (d) & land category (lc)
   CROPCAT(i,lc,a)   Indicates which crops are in which land category
   MAX_WAT(i,wq)     Maximum available water of water quality wq in year t
   AG_INIT(i,a)      Initial land allocations per crop
   AG_MAX_P(i,a)     Maximum Allowable present land allocations per crop
   AG_MAX_F(i,a)    Maximum Allowabe future land allocations per irrigated crop
   GROW_COEF_P(i,a)  Present Growth Coefficient for land change constraint
   PCROP(i,a)        Nominal price of crops
   PINT(i,a)         Nominal price of input costs
   ADJ_PCROP(i,a)    Randomized price of crops
   ADJ_PINT(i,a)     Randomized Price of crops
   ADJ_YIELD(i,a)    Randomized Crop Yield
   ADJ_WREQ(i,a,wq)  Randomized Crop Yield
```

```
* Post-processing parameters
   WP(r,d,wq)        Water Price
   QT(r,d,wq)      Water Quantity
   NB(r,d)      Net Benefits
   IR(r,d)      Irrigated Land Allocations
   RF(r,d)      Rain-fed Land Allocations
   GH(r,d)      Green-House Land Allocations
   CROP(a,r,d)  Track crop allocations at each water price time-step
   INF_IND(a)   Total influence of each crop on allocation variation
   gg(a)        Counter for sorting crops by influence
   DEM_DER(r,d) Point derivative of demand curve
   E(r,d)       Point Elasticity based upon demand curve
   ShV(r,d)     Shadow Value for run r and demand curve d;

* The following statements imclude files for the AGSM parameters.
{$include jenin_agsm.inc
$include jenin_nwc_fix.inc
$include jenin_maxyield.inc
$include jenin_prof_fix.inc
$include jenin_wreq.inc
$include jenin_cropcat.inc
$include jenin_watmax.inc
$include jenin_init.inc

$include jericho_agsm.inc
$include jericho_nwc_fix.inc
$include jericho_maxyield.inc
$include jericho_prof_fix.inc
$include jericho_wreq.inc
$include jericho_cropcat.inc
$include jericho_watmax.inc
$include jericho_init.inc
$include jericho_watcost.inc}

$include beth_agsm.inc
$include beth_nwc_fix.inc
$include beth_maxyield.inc
$include beth_prof_fix.inc
$include beth_wreq.inc
$include beth_cropcat.inc
$include beth_watmax.inc
$include beth_init.inc
$include beth_watcost.inc;

* The growth coefficient is used to set the maximum growth rate for allocations
   GROW_COEF_P(i,a)$AGSM(i) = 0.5 * ( 1 + (1 - EXP(0.03*(LMR *
            sum((wq),AG_INIT(i,a)) -LGM)))/(1 + EXP(0.03*(LMR *
            sum((wq),AG_INIT(i,a))-LGM))));

   AG_MAX_P(i,a)$AGSM(i) = AG_INIT(i,a) + (LGM * GROW_COEF_P(i,a))+
            (LMR * (AG_INIT(i,a)*(1-GROW_COEF_P(i,a))));

   AG_MAX_F(i,a)$AGSM (i) = (((AG_INIT(i,a)/MLAND_IR) * MLAND_F) *
            (1+LMR)* CROPCAT(i,'lc7',a));
```

```
{* Additional Crops for Jenin Only
   AG_MAX_F('i5',lc,'a80') = 24508;
   AG_MAX_F('i5',lc,'a81') = 5415;
   AG_MAX_F('i5',lc,'a82') = 5013;
   AG_MAX_F('i5',lc,'a83') = 8072;}
* Additional Cash Crops for Bethlehem Only
   AG_MAX_F('i20','a40') = 821;
   AG_MAX_F('i20','a41') = 763;
   AG_MAX_F('i20','a42') = 499;
   AG_MAX_F('i20','a43') = 499;
* Adjusted crop prices and input costs based on the maximum a
* The growth coefficient is used to detllowable
* change set by the user for each.
   ADJ_PCROP(i,a) = PCROP(i,a);
   ADJ_PINT(i,a)  = PINT(i,a);
   ADJ_YIELD(i,a) = MAX_YIELD(i,a);
   ADJ_WREQ(i,a,wq)  = WREQ(i,a,wq);

* The following declares the decision variables for the optimization problem
VARIABLES
   Z                  Net Economic Benefit in Million Dollars
   AG_AREA(i,a,wq)  The land area used for agricultural activity (a);

POSITIVE VARIABLES AG_AREA, GL_COEF;
* The following statements define the equations that will be used
* in the optimization, both the objective function and the constraints.

EQUATIONS
OBJ              Net Econonomic Benefit in Million Dollars
WAT_MAX(i,wq)     Agricultural water use cannot exceed calculated demand (fresh)
LMAX(i)           Agricultural land use cannot exceed available land
GROW_MAX(i,a)       Limits crop land  beyond growth of 15% of IC or 300 dunam;

OBJ..       Z =E= sum((i,a,wq)$AGSM(i),AG_AREA(i,a,wq)*(1/1000000)*
             ((ADJ_YIELD(i,a)* ADJ_PCROP(i,a))
             - ADJ_PINT(i,a)
             - (WCOST(wq) * ADJ_WREQ(i,a,wq))
             ));

* The first equation limits the water allocated to crops to a maximum available
* quantity for each type of water quality; surface, ground, recycled, brackish.
 WAT_MAX(i,wq)$AGSM(i).. MAX_WAT(i,wq) =G=
             sum(a,(AG_AREA(i,a,wq)*ADJ_WREQ(i,a,wq)));

* The next equation limits the land used of each land category (permenant,
* industrial, vetetable, fish farms) to a maximum available area.
 LMAX(i)$AGSM(i).. MLAND_T =G= sum((a,wq), AG_AREA(i,a,wq));

* The third equation constrains change from initial crop allocation for proper
* crop diversification. Crop allocation increase or decrease by 10% or 50 du,
* whichever is larger. A smoothed step function is employed using the growth
* limit coefficient (previous eqn).
 GROW_MAX(i,a)$AGSM(i).. sum((wq),AG_AREA(i,a,wq)) =L=  (AG_MAX_P(i,a) +
              AG_MAX_F(i,a));
```

```
* Fixing Rain-fed and permanent irrigated land allocations at zero for this
* analysis.

*$include jenin_fix_RF.inc

MODEL WAS /ALL/;

*$include "jericho_init2.inc"
$include "beth_init2.inc"

*resets the random number generator seed value
execseed = gmillisec(jnow);

Loop(d,
  WCOST('G') = 0;

  ADJ_PCROP(i,a) = normal(PCROP(i,a),(PCROP(i,a) * Cv));
  ADJ_PINT(i,a) = normal(PINT(i,a),(PINT(i,a) * Cv));
  ADJ_YIELD(i,a) = normal(MAX_YIELD(i,a),(MAX_YIELD(i,a) * Cv));
  ADJ_WREQ(i,a,wq) = normal(WREQ(i,a,wq),(WREQ(i,a,wq) * Cv));

  Loop(r,

    OPTION NLP = CONOPT;
    SOLVE WAS MAXIMIZING Z USING NLP;

* Post-processing variable calculations
    WP(r,d,wq) = WCOST(wq) / 3.8;
    QT(r,d,wq) = sum((i,a)$AGSM(i),(AG_AREA.L(i,a,wq)*WREQ(i,a,wq)))/1000000;
    NB(r,d)= sum((i,a,wq)$AGSM(i),AG_AREA.L(i,a,wq)*(1/1000000)*((ADJ_YIELD(i,a)
               * ADJ_PCROP(i,a))
               - ADJ_PINT(i,a)
               - (WCOST(wq) * ADJ_WREQ(i,a,wq)) ));
    IR(r,d) = sum((i,a,wq), (CROPCAT(i,'lc5',a) * AG_AREA.L(i,a,wq)));
    RF(r,d) = sum((i,a,wq), (CROPCAT(i,'lc4',a) * AG_AREA.L(i,a,wq)));
    GH(r,d) = sum((i,a,wq), (CROPCAT(i,'lc6',a) * AG_AREA.L(i,a,wq)));
    CROP(a,r,d) = sum((wq), AG_AREA.L('i17',a,wq));
    ShV(r,d) = sum((i,a), GROW_MAX.M(i,a));
    WCOST('G') = WCOST('G') + 1; {.19}
  );

WCOST('R') = WCOST('R') + 1;

);

*Determines the point derivatives and elasticities for each demand curve
*DEM_DER(r,d)$(ord(r) ge 2) = (QT(r+1,d) - QT(r-1,d)) / (2 * 0.26);
*E(r,d)$(ord(r) ge 2) = (WP(r,d,wq)/QT(r,d)) * DEM_DER(r,d);

$include output_d_curve.inc
*$include output_var_indicator.inc
*$include output_crop_influence.inc
$include output_crop_allocations.inc
*$include output_pt_elasticity.inc
```