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Efficient water conservation in agriculture for growing urban water demands in Jordan

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Abstract

A significant worldwide challenge is to increase the food supply to accommodate a population growing to 9,000,000,000 in the face of climate change. Per capita water supply in Jordan is among the world's lowest. Despite this scarcity, three-quarters of Jordan's water use is consumed by irrigated agriculture, while producing low economic values from additional water used compared to urban uses. However, irrigated agriculture supports Jordan's food security, so its policymakers continue to examine measures to produce more crop per drop in irrigated agriculture, to permit scarce water to meet growing urban demands. This paper examines economically efficient measures to conserve water in irrigated agriculture to sustain growing urban water demands. Using a sample of one-third of the farms in Jordan's Mafraq Basin, an econometric model is formulated to identify factors influencing irrigation water use and economic productivity. Findings show that the price of water is the overarching factor influencing both. A low water price discourages water conservation even if other institutions promote it. A high price of water encourages conservation even in the presence of other discouraging factors. Results suggest that water-conserving policies in Jordan's irrigated agriculture can be more effectively implemented where water institutions and programs are designed to be compatible with the underlying economic scarcity of water. Results carry significant implications for the design and implementation of development programs affecting the use of water in the world's dry areas.

Keywords: Aquifer; Irrigation; Jordan; Mafraq Basin; Urban water use; Water conservation

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1. Background

Political leaders and the research community currently face the challenge of increasing the world's food supply to accommodate a world growing to 9 billion by 2050 or more (1 billion $= 10^9$), while also facing a less reliable water supply resulting from climate change. A water problem exists where water is not supplied in the right quality, amount, time, or place. Much of the world's food production depends on water for irrigation. Natural ecosystems are adapted to stream discharge, precipitation, and evaporation patterns. Therefore, adjustments in the water cycle to climate, weather, and land-use change will have large and complex effects on economic, ecological, cultural, and legal systems.

Many countries in the dry parts of the world have inadequate water supplies to meet their current urban, environmental, and agricultural needs. In the face of increased water scarcity, population and water demands continue to grow. The challenge is to produce enough food for 2 billion more people than the current world population of 6.8 billion over the next 40 years while supplying growing urban and environmental needs for water. Some analyses have estimated that 60% of the added food required will come from irrigation. So, raising food production to support this larger world population requires sustaining the improved technical and economic performance of irrigation. As pressure grows for irrigated agriculture to produce more crop per drop, there is a widespread belief in environmental and water policy circles that if irrigators made more efficient use of water then there would be more water for environmental uses and for cities. According to the World Health Organization (WHO, 2010) an estimated 1.1 billion people worldwide lack safe affordable drinking water.

All the forces described above are increasing the competition for fresh water (Aggarwal, 2000; Akpabio, 2007; Ward, 2007). Nowhere is this more striking than in the dry Middle East (Arar, 1991; Al-Weshah, 1992; Al Salem, 1996; Al-Weshah, 2000; Salman, 2005; Salman *et al.*, 2008). Water demand in this region continues to increase because growing irrigation water requirements are needed to support food security to feed growing populations. In agriculture, various water conservation measures are being scrutinized and debated, such as increased irrigation efficiency, subsidies for water-conserving measures, reduction of water-intensive crops, recycling and reuse, and water pricing reform.

Jordan has been plagued by water scarcity since ancient times (Brooks, 1993; Abu-Shararr & Battikhi, 2002; Beaumont, 2002; Scott *et al.*, 2003; Mohsen, 2007). Throughout its history, Jordan's people have suffered from water shortages due to its dry climate and scant rainfall. Water scarcity is still a serious environmental challenge facing Jordan. Water is a central factor defining, promoting, and limiting Jordan's population, resources, and economy. While water resources in Jordan have varied from year to year around a constant or falling average, its population continues to rise. A high rate of natural population growth, combined with sporadic large inflows of refugees, has altered the old balance between population and water. That old balance, which lasted to 1950, has gradually changed to a chronic and worsening imbalance. Jordan's water situation is challenged by the constraint that Jordan shares much of its surface water resources with neighboring countries, whose control limits Jordan's supplies.

These trends have resulted in increased demand from urban users with no offsetting demand reductions from irrigated agriculture. Jordan is currently among the world's ten most water impoverished countries (Al-Assaf *et al.*, 2007). Water is currently delivered only once a week to Amman's residents. Nationwide, Jordan's annual water use is 890 million cubic meters (MCM), with a need for 1,600 MCM per year to meet its 2015 forecast requirements (Gama Enerji, 2009). Other recent analyses have forecast supply shortages of one-third of total forecast demand, unless non-conventional sources are used (Abu-Taleb & Murad, 1999; World Bank, 2001; Abu-Sharar *et al.*, 2003). Jordan's major water resources are groundwater, surface water, and treated wastewater effluent. The total renewable safe yield of groundwater resources in all of Jordan is an estimated 275 MCM per year. Water use from these renewable sources has exceeded the safe renewable supplies by more than 200 MCM per year in recent years, a use pattern that cannot be sustained without water imports, recycling, reuse, or reduced demand. Moreover, the Dead Sea level has continued falling since the 1960s (Akash & Mohsen, 1998; Salman *et al.*, 2001), mostly as a result of upstream surface water diversions and industrial evaporation ponds.

Jordan's water scarcity will present growing scientific and policy challenges over the next two decades as the forecast population doubles, living standards rise (Alkhaddar *et al.*, 2005; Jordan Ministry of Water and Irrigation (2009)) and climate change risks making precipitation more uncertain and variable[1]. Furthermore because many of Jordan's poor are migrating to urban areas, these people face growing food and water insecurity (Faruqui & Al-Jayyousi, 2002). More than 90% of Jordan's land area receives less than 200 mm of rainfall per year (Al-Weshah, 1992; Chebaane *et al.*, 2004; Al-Kharabsheh & Ta'any, 2005).

Under one recent proposal, the amount of water delivered to Jordan's farmers for irrigation would be reduced significantly, with only water-conserving crops allowed. High domestic water demands result from large numbers of foreigners in Jordan. According to a March 2008 report by the Integrated Regional Information Networks of the United Nations (IRIN, 2008) the arrival of 500,000 Iraqi refugees since 2003 has compounded Jordan's water problem. Jordan also hosts nearly 300,000 Egyptian guest workers, 200,000 Syrians, and other expatriates, including an estimated 167,000 Palestinian refugees who are not Jordanian citizens. Jordan has recently examined numerous measures for coping with these shortages: in April 2007, it announced several large projects to tackle the chronic water shortage, including the US $1-10 billion Red-Dead Canal Project, which would convey water by canal from the Red Sea to the Dead Sea and provide 850 MCM of potable water.

One important new source of water to help alleviate water shortages in Amman is the US $1 billion Disi Water Project. Originally contracted in October 2007, it includes construction of a 325 kilometer pipeline that will pump water from the Disi aquifer to Amman (Gama Enerji, 2009). Jordan's Mafraq aquifer accounts for a large part of its underground water resources (Bajjali & Al-Hadidi, 2006). As of 2010, most of the extraction was devoted to irrigation through pumping, as previously approved by Jordan's government. While the government may have legal authority to rescind some or all of the pumping permits, farmers view the permits as long-term water rights. In the light of these debates, policymakers have considerable interest in any information concerning what factors influence water use and water use efficiency by farmers who pump from this aquifer. They also need information that can help meet the needs of individual farmers, as well as help inform better water policy choices.

Because the Mafraq aquifer is close to Amman, a major policy objective in regard to the aquifer is to examine the economic feasibility of water transfers by reallocating pumping from irrigation to urban

[1] Jordan has a land area of 91,971 km^2, a population of about 6 million, a per capita GDP of about US $3,000 and a real GPD growth rate of 6.4% (Hashemite Kingdom of Jordan Department of Statistics, 2003). Jordan is a small but prosperous Middle Eastern country. That prosperity, however, is increasingly threatened by the prospect of reduced water availability for its economic growth, especially manufacturing, wholesale and retail trade, hotels and restaurants, transport, storage and communications, finance, real estate, insurance, business services, and construction. A significant share of this economic activity supports a thriving tourism sector.

water use to support Amman's growth[2]. This increased pressure on agricultural water use in Jordan comes at a time when rural poverty reduction and national food security are major national goals[3]. An important water policy aim of Jordan is to minimize the economic impact on farmers and on the overall economic welfare of this region's people resulting from the increased water conservation that will be required by irrigated agriculture (Doppler *et al.*, 2002). Nevertheless, little quantitative analysis has been conducted to date that could inform policy choices for reducing water use in Jordan's irrigated agriculture. The objective of this paper is to fill this gap by identifying economically efficient measures that could conserve water in irrigated agriculture and sustain growing urban water demands.

2. Methods of analysis

A survey instrument was designed to secure information that would identify the essential factors influencing irrigation water use by farmers in the Mafraq aquifer and affecting economic returns earned from that water use. This instrument was designed to test our hypotheses, described below.

2.1. Hypothesis

An underlying hypothesis driving this research was that the price of water is the overarching factor influencing both water use and economic returns: a low price was expected to discourage water conservation even if other institutions promoted it; a high price was expected to encourage water conservation even in the presence of other discouraging factors. We also hypothesized that several other non-price factors influence the use of water and its economic returns. Testing hypotheses on impacts of these other non-price factors is important both for their own sake and for securing better information on the partial impact of water's price. In particular, we expected that the farmer's demographic profile, the farming system, importance of farming as an income source, farmer access to information, and well tenure all have significant impacts on irrigation water use and on economic returns. For these reasons, survey questions were designed to address all these predictors of irrigation water use and economic returns.

2.2. Need for a survey

There were no data available from any existing source on irrigation water use or economic returns in the Mafraq Basin. Moreover, irrigator demographic profiles, farming system characteristics, contribution of farming to family income, availability of information and expert advice to farmers, well tenure and characteristics, and water prices facing producers were also not available from existing sources. Surveys are one reliable and commonly used method for securing such farm-level information. They have been used for many years to address similar questions, as described for example by Schuck *et al.* (2005) and Maton *et al.* (2005).

[2] Amman has more than half of the country's population and two-thirds of its economic activity.
[3] Hope *et al.* (2008) identified similar policy conflicts between irrigation and urban water uses for South Africa, while Giordano (2007) and Han & Zhao (2007) observed this kind of conflict in China.

2.3. Data

Data collected for this research took place in summer 2006, through a survey of 105 farmers in the Mafraq Basin. Farm surveys as a method of identifying irrigator behavior patterns have been used successfully in previous studies by Moore *et al.* (1994a,b), Do & Egashira (2002), Chebaane *et al.* (2004) and Senthilkumar *et al.* (2008). The survey sample was stratified by farm size so that it represented the population of the region's farmers (approximately 300 families). Stratification groups members of the population into more homogeneous classes before sampling in order to reduce sampling error. Reduced sampling error permits greater precision in parameters estimated.

The survey instrument was administered by a team of three people from the local area with technical training in agriculture and strong ties with the local culture. Local assistance was secured to ensure that questions were framed in such a way that they were compatible with local cultural sensitivities: questions were clear, understandable, and relevant. The pace of posing the questions was slow enough to give farmers adequate time to deliberate and to produce reliable responses. Two people with local cultural ties who held college degrees were secured to train the survey team. Training was accomplished by permitting each member of the team to conduct a preliminary round of five interviews. The data collected in these interviews were evaluated and used to refine both the survey instrument itself and to formulate a culturally acceptable method of administering the survey.

The survey contained about 50 questions and took an average of two hours to administer. The reason for this long duration was that the survey team followed a protocol designed to set the stage for the farmer to achieve a comfort level sufficient to answer the questions in an unstressed environment. One team member was charged with posing questions and recording answers. Another was tasked with maintaining the flow of conversation. The third was responsible for quality control, guarding against unclear, ambiguous, or inconsistent responses. Appointments were made in advance so that farmers could take the survey at a time of their choice. After the preliminary round of interviews, the survey team achieved a level of competence in the administration of the instrument, and for these reasons we have confidence that the data secured were reliable and valid.

2.4. Model

Quantitative analysis has been long recognized to offer important insight into difficult policy questions surrounding the connection between water and economic development (Pretty & Ward, 2001; Clarke *et al.*, 2002; Sullivan, 2002; Fay *et al.*, 2005; Prokopy, 2005; Hope, 2006, 2007; Deichmann & Lall, 2007; Basani *et al.*, 2008). For our analysis, econometric models were developed to explain factors that influence two important measures of irrigation activity in the Mafraq Basin: water use per unit area and total revenue per unit water used[4].

[4] Salman & Al-Karablieh (2004) showed how marginal income from additional water influences the willingness of Jordanian irrigators to pay for water.

The model explaining the irrigation water application rate was specified as:

$$\text{Irrigation Application Rate}_i = \beta_0 + \sum_j \beta_j X_{ij} + e^1_{ij} \tag{1}$$

where

Irrigation Application Rate, for the i-th farm, is measured in millimeters depth;

β_0 = intercept, value of the dependent variable if all independent variables take on a value of zero.

β_j = parameter for j-th explanatory variable, marginal impact of a change in the dependent variable resulting from a unit change of the independent variable

X_{ij} = i-th of 105 observations on j-th of 19 explanatory variables shown in Table 1.

e^1_{ij} = error term for i-th observation on j-th explanatory variable for the first model.

A similar regression model was also estimated to explain the second model, gross revenue per unit water applied. It was specified as:

$$\text{Gross Revenue Per Unit Water}_i = \alpha_0 + \sum_j \alpha_j X_{ij} + e^2_{ij} \tag{2}$$

where

Table 1. Variables used to characterize irrigation in Jordan's Mafraq-Azraq Basin.

Variables	Units
Dependent variables	
Irrigation application rate	m^3/donum = mm depth
Gross revenue per unit water*	JD/m^3
Explanatory variables	
Hired farm manager makes decisions	1 if true, 0 if false
Farming is main profession	1 if true, 0 if false
Farmer lives on farm	1 if true, 0 if false
Farming is main income source	1 if true, 0 if false
Outside expert advice used for crop selection	1 if true, 0 if false
Outside expert advice used for irrigation	1 if true, 0 if false
Received irrigation training	1 if true, 0 if false
Owns well	1 if true, 0 if false
Well discharge rate	m^3/hr
Casing size	Inches diameter
Water cost	JD/m^3
Falling water table	1 if true, 0 if false
Well depth to water table	m
Total area irrigated†	Donums
Uses mulch	1 if all crops, 0.5 if some, 0 otherwise
Land area in vegetables	Proportion
Land area in water conserving crops‡	Proportion
Age	Years
Post secondary education	1 if true, 0 if false

* 1 JD = 0.70 $US.
† In Jordan 1 donum = 1,000 m^2 = 0.1 hectare.
‡ If crop water use < 500 mm/season.

Gross revenue Per Unit Water, i-th farm, Jordanian Dollars (JD) per m^3 applied.

α_0 = intercept
α_j = parameter for j-th explanatory variable
X_{ij} = i-th observation on j-th explanatory variable
e_{ij}^2 = error term for i-th observation on j-th explanatory variable for second model.

Water use per unit area was measured in m^3 per donum[5], while crop revenue[6] per unit of water was measured in JD per m^3. Econometric models have been used for some time in the economic analysis of crop irrigation decisions. Some of the better known examples include the works of Gunawardana & Oczkowski (1992), Kanazawa (1992), Moore & Negri (1992), Shrestha & Gopalakrishnan (1993), Moore *et al.* (1994a,b), and, more recently, the analyses of Hussain *et al.* (2004), Recio *et al.* (2005), Scheierling *et al.* (2006), Schlenker *et al.* (2006) and He *et al.* (2007).

Standard multivariate regression techniques were used to estimate the presence and strength of factors that affect irrigation water use and economic returns. Regression models were initially estimated by Ordinary Least Squares (OLS), with residuals tested for heteroskedasticity and non-normality using the White test and the D'Agostino–Pearson test, respectively. The null hypotheses of homoskedasticity and normality of the residuals from both models were both strongly rejected ($p < 0.001$)[7].

We took steps to correct for both problems. The first step was to find weights for the residuals to become homoskedastic (constant variance). This was accomplished by regressing the squared OLS residuals on the explanatory variables and using the square roots of the reciprocals of the predictions from that auxiliary regression to weight the values of the dependent and explanatory variables in the original model. The residuals from this Weighted Least Squares (WLS) regression were re-tested for heteroskedasticity. If the null hypothesis of homoskedasticity is still rejected after applying the initial set of weights, modifications are made to the auxiliary regression; the modifications exclude statistically insignificant independent variables and explore non-linear functional forms with respect to some of those variables, so that the resulting weights solve the heteroskedasticity problem. This process is continued until the hypothesis of constant variance in the residuals can no longer be rejected.

Once the weights are identified, a procedure is applied to the weighted model to address the case where normality is rejected by the data. This involves maximum likelihood estimation for an error term that follows a Su distribution, which generalizes a normal error term (Ramírez, 1997). That distribution is sufficiently flexible to approximate most non-normal error term distributions encountered in practice.

[5] donum = 0.10 hectares = 1,000 m^2, so m^3 per donum (1,000 m^2) = millimeters depth.

[6] Gross revenue from farm sales was analyzed rather than net income because the collection of detailed production cost data was beyond our means. Net return information is more informative than gross revenue. Good data on the costs of production for irrigated agriculture should be used where available. Farmers subtract costs from gross revenue to earn net income. For this reason information on net income can be expected to predict irrigator behavior better than information limited to gross revenue. Moreover, irrigators rarely embrace a policy that increases only the gross value of farm sales without also increasing net income.

[7] In the presence of heteroskedasticity, OLS yields inefficient parameter estimates in addition to biased and inconsistent estimated standard error. While non-normality in the error term does not bias the OLS standard error estimates, it reduces the efficiency of the parameter estimates compared to a Maximum Likelihood (ML) estimator based on a more suitable error term distribution.

Table 2. Characteristics of irrigators on 105 farms who pump groundwater from Jordan's Mafraq-Azraq Basin.

	Farms		Regional water use (1,000 m^3/yr)		Regional area irrigated (1,000 Donums)		Regional revenue (million JD/yr)				
Characteristic	Quantity	%	Quantity	%	Quantity	%	Quantity	%	Irrigation application rate (m/yr)	Gross water value (JD/m^3)	Gross land value (JD/Donum)
Residence											
On farm	38	36	4.6	31	6.8	26	4.00	28	0.68	0.87	0.59
Mafraq	46	44	7.0	47	12.6	48	7.15	50	0.56	1.02	0.57
Amman	21	20	3.3	22	6.8	26	3.10	22	0.49	0.94	0.46
Income											
Farming	65	62	9.1	61	13.2	50	8.98	63	0.69	0.98	0.68
Non-farming	40	38	5.8	39	13.2	50	5.27	37	0.44	0.90	0.40
Employment											
Farming	73	70	10.6	71	11.4	43	9.80	69	0.93	0.92	0.86
Non-farming	32	30	4.3	29	15.0	57	4.40	31	0.29	1.02	0.29
Education											
Advanced	33	31	4.9	33	11.4	43	4.80	34	0.43	0.94	0.42
Secondary or less	72	69	10.0	67	15	57	9.40	66	0.67	0.98	0.63
Farm operator											
Owner or family	83	79	6.9	46	14.5	55	7.20	51	0.48	1.04	0.50
Hired manager	22	21	8.0	54	11.9	45	7.00	49	0.67	0.88	0.59
Water information bought											
None	84	80	12.0	81	18.7	71	10.80	76	0.64	0.90	0.58
Private consultant	21	20	2.9	19	7.6	29	3.40	24	0.38	1.17	0.45
Age											
> 60	35	33	5.4	31	9.5	30	5.10	27	0.57	0.94	0.54
> 50	60	57	8.2	47	15.6	48	8.70	47	0.53	1.06	0.56
< 50	25	24	3.9	22	7.1	22	4.80	26	0.55	1.23	0.68
Well tenure											
Owned	86	82	12.8	86	22.2	84	12.40	87	0.58	0.97	0.56
Leased	19	18	2.1	14	4.2	16	1.80	13	0.50	0.86	0.43

Ramírez *et al.* (2003) show that this method considerably increases estimation efficiency when the error term is found to be significantly non-normal.

3. Results

3.1. Overview

Table 2 summarizes the characteristics of farmers and the irrigation system. The table includes farmer demographic profiles, farming system characteristics, significance of farming for income, source of farm information, and well tenure.

3.1.1. Farming dependency. An important issue explored through this survey was the degree of dependence of the farmers on agriculture and, therefore, on pumping water from the Mafraq aquifer. This issue was explored through several questions. Taken together, responses to these questions shed light on the issue. Table 2 shows that responses to the first question indicate that only 36% of the farmers surveyed live on their farm, while the remainder live elsewhere (44% in the city of Mafraq and 20% in Amman). The people living on their farms pump 4.6 million m^3 (31%) of water from the aquifer each year. They use this water to irrigate 6,884 donums (26%) of crop land and generate nearly JD 4 million (28%) in revenues from the sale of their agricultural products[8].

The table shows that many who live in the small city of Mafraq also depend on farming for their livelihoods. These people pump close to 7 MCM (46%) of the water and use it to irrigate 12,628 donums (48%) of crop land and generate over JD 7.2 million (50%) in agricultural sale revenues. Amman farmers are the least likely to rely on their farm income for a living.

Another question explored the dependency of farmer incomes on agriculture. About 62% of respondents indicated that their family derived the majority of its income from farming. About 38% earn the majority of their family income from other sources. The 62% that derive the majority of their income from farming hold about half of the area irrigated, use 61% of the water pumped from the aquifer each year, and generate 63% of the total agricultural sales. The 38% who earn the majority of their income from other sources hold the other half of the area irrigated, use 39% of the water, and generate 37% of the total sales. In total, about 5.75 MCM of water per year could be put to other uses if these people left farming.

Table 2 shows that the reported main occupation is related to the degree of economic dependence on agriculture. Nearly 70% report farming as their primary income source. While these farmers only irrigate 59% of the area, they pump nearly 71% of the water and generate 69% of crop sales. Education can indicate the opportunity cost of farming by showing what farmers can earn outside agriculture. Just under 70% of farmers surveyed had no more than a secondary education. They hold 57% of the irrigated crop area, use 67% of the water and generate 66% of agricultural sales. Unless they already have another occupation that provides for adequate income, transferring water from them risks jeopardizing their livelihood. Less than 5 MCM of water is held by farmers who are college educated. This fact suggests to us that this water is held by people who are educated sufficiently well to earn adequate income outside agriculture.

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[8] JD = 0.708 U.S. dollars.

The final factor included in the survey that sheds light on the dependence of the farmers on agriculture is who manages day-to-day farm activities. We found that most farms are managed by the farm owner or family member (79%). Only 21% are operated by a hired manager. However, on a per-farm basis, considerably more water is used when the farm is managed by a hired manager and these farms operate on more land. As a result, 8 MCM (54%) of the water pumped from the Mafraq aquifer each year is used in farms operated by a hired manager.

Each of the previously-discussed factors is a partial indicator of the extent to which a farmer can sustain a family without income produced by irrigated agriculture. We examined responses by a combination of categories corresponding to these factors (not shown in Table 2). From this analysis, we discovered that 34 farmers (32%) live on farm or in the city of Mafraq, report that farming as their main income source, indicate that farming is their primary work, have no more than a secondary education, and manage their own farm. These people irrigate 6,346 donums of land (24% of the area), pump 4.67 MCM of water (31%) and generate JD 4.84 million, which is 34% of the basin's value of crop sales. Farmers fitting this profile will have the most difficulty making a living outside agriculture.

3.1.2. Information sources. Knowledge of farmers' information sources is essential for the design and implementation of training and extension programs. Table 2 shows that most farmers (80%) rely on self experience for water use decisions. About 20% receive help from an agricultural engineer, while none cited the Ministry of Agriculture extension agents as an information source. The area irrigated by those who rely on self experience is 18,707 donums (71%), but they use just under 12 MCM of water per year (81% of total). The remaining 20% who rely on an agricultural engineer for irrigation advice cultivate 7,590 donums of land (29%) and use 2.9 MCM water (19%).

3.1.3. Age. Age can affect farm behavior. In addition, age might play an important role for improved water policy in light of age-related policy decisions that could be implemented in connection with water rights. A third of farmers were found to be 60 or older, while over 57% are at least 50. About 47% of the water is pumped by farmers who are 50 or over. This information is relevant for policy decisions involving possible water purchases by the government. Older farmers may sell or rent their water or water rights for a lower price than younger ones, since the younger ones have more years of water income earning power in their futures[9]. However, age effects may work in the opposite direction, too. Older people are generally less able to find alternative work, so their opportunity cost of forgoing water use may be higher.

3.1.4. Employment and income. Employment and income are foundations for assessing the potential economic impact of a decline in agricultural production activities resulting from irrigation water use restrictions on Jordan's rural communities. The 105 farms surveyed in the Mafraq Basin provide permanent jobs for 729 people (not shown in Table 2). Of these permanent workers, only 67 (9%) are Jordanians, while 650 (89%) are Egyptians, 6 (1%) are Syrians and 6 (1%) are from other countries. About 25% of Jordanian employees receive benefits, mostly in the form of housing. Less than 15% of

[9] Where capital markets are efficient, farmers of all ages will find an equal discounted net present value of water as a resource contributing to a farm's selling price; i.e. a loss of a water right has the same effect on a farm's asset value regardless of the farmer's age.

guest workers of foreign nationalities receive housing or other benefits. The total salaries paid to all 729 workers amount to JD 932,000 per year, of which JD 93,318 goes to Jordanians and JD 838,741 accrues to guest workers.

In addition to permanent employees, just over 3,500 temporary workers are hired to work these 105 farms. Nearly two-thirds are female. While 15% of the temporary workers are Syrian, most are Jordanians. Benefits received by temporary workers are negligible regardless of nationality. According to our survey, the temporary workforce is employed on these farms for an average of only three months per year. Therefore, four temporary workers are equivalent to one permanent worker and the 3,500 temporary employees are equivalent to only a quarter as many permanent workers. So the 105 farms surveyed provide approximately 1,600 full-time equivalent jobs, about 15 per farm. Each full-time equivalent job is associated with the pumping of 9,300 m^3 of water and produces just under JD 9,000 in agricultural sales revenue. In addition to providing third-party employment, the income derived from these farms helps support a large number of dependents. In fact, an average of just over 10 family members are supported by the families surveyed.

What these details add up to is that Jordanians make up only a small part of full-time farm workers, and that most Jordanians working in agriculture who were surveyed did so on a part-time basis. Low water prices may effectively be supporting foreign workers, so raising the price of water may put many out of work. Most of those workers displaced would be foreign workers who would return to their own countries[10]. This point is particularly important since keeping Jordanians in agriculture is a central national goal to support employment and food security.

3.1.5. Well tenure. Well tenure is an important factor affecting both irrigation water use and impacts of potential water pumping restrictions. Curtailing or rescinding pumping rights on leased wells may be more politically acceptable than a similar curtailment on wells used by permit holders. However, our survey data indicated that most (82%) of the farmers own the well from which they pump water to irrigate crops. These people use 86% (12.8 MCM/year) of the water pumped annually, versus 2.1 MCM from leased wells.

An interesting result of the surveyed well information relates to the difference between well depth and water table depth from which the well draws. The average depth of the 105 wells included in the survey is 347.9 meters (not shown in Table 2). The average water table depth for those wells is 267.3 meters, a difference of about 80 meters. Only three of these differences are less that 20 meters, suggesting that few wells are in danger of drying up soon.

3.1.6. Cost and value of water. Our data show that the maintenance and operation cost per m^3 of water pumped is higher for leased wells (JD 0.32) than for owned wells (JD 0.25). Well lease costs average JD 0.18 per m^3 pumped. Surprisingly, the data showed that most farmers (29 out of 40) paid no mandated government fee for water pumped in excess of 150,000 m^3. Excluding government fees, the average cost per m^3 of water pumped is JD 0.25 for owned wells and JD 0.50 for leased wells. Since all wells sampled were in use, the economic value to those farmers at the margin was at least as high as these costs.

Table 2 shows that only 18% of the farmers lease wells, so the average lease charge of JD 0.18 per m^3 of water yield is a lower-bound estimate of the marginal economic value of water in the region. Any well

[10] By reducing imports of water-intensive foreign workers, raising water prices has the characteristics of virtual water.

owner currently pumping water values their pumped water for agricultural use at more than JD 0.18 per m^3. This means that well owners receive an unpriced value by holding a pumping permit. What has been described elsewhere as permit value[11] is the discounted value of additional income produced by holding the permit. At an average pumping rate of 0.14 MCM per year, this economic value of the unpriced resource amounts to at least JD 25,660 annually, averaged over the 86 permit holders sampled.

3.1.7. Regional water use. The total amount of water pumped by the farmers surveyed is nearly 14.9 MCM, used to irrigate 26,400 donums. The survey sampled about 1/3 of the farmers in Mafraq Basin, so basin-level pumping is estimated at about 45 million m^3 to supply about 80,000 donums of irrigated agriculture. A total of JD 14.25 million in gross revenues from crop sales are generated by the farmers surveyed, resulting in a basin-level estimate of JD 42.72 million. This is about 10% of the annual value of the total agricultural production of Jordan.

Agricultural activity in the Basin is estimated to employ $3 \times 729 = 2{,}187$ permanent and $3 \times 3{,}505 = 10{,}515$ temporary workers paying over JD 6 million/year in salaries and supporting $3 \times 1{,}129 = 3{,}387$ dependent family members. Total water cost (including well rent or opportunity cost) is estimated at JD 0.5 per m^3 pumped, or JD 22.35 million for the Basin. Labor costs and sales revenues are estimated at JD 0.15 and JD 0.96 per m^3 of water, respectively. While data on other production costs were not collected, those costs are likely important. Most farmers, for instance, use a tractor (99%) and apply fertilizer (100%), mulch (58%), herbicides (87%), insecticides (100%) and fungicides (100%); and either hire a farm operator or devote a significant part of the family's time to manage the farm.

3.2. Model

Table 3 shows descriptive statistics for the various measures of irrigator behavior and the predictors of that behavior. It includes averages, standard deviations, maximums, and minimums for both of the models' dependent variables. It also includes the same statistics for the independent variables used to predict water use and revenue per unit water applied.

3.2.1. Water price. Table 4 shows an important discovery uncovered by this analysis. Water's price has a significant, large, and policy-relevant effect on the depth of irrigation water applied, with a reduction in more than 360 mm depth of water applied for each additional one JD added to the price per cubic meter. Table 5 shows that water's price also has a large effect on revenue generated per unit of water, more than JD 2 per m^3 [12]. Calculations made from Table 4's results show that a doubling of the price of water reduces water use by just over 100 mm depth. It also increases revenue generated per unit of water used by over JD 0.60 per m^3, as shown in Table 5.

The finding on impacts of price on use translates to a lower bound estimated price elasticity of demand for water of −0.28. It is lower bound because it ignores additional water savings that would occur if

[11] In some countries, permit value can be an important economic asset held by ranchers who have a private property right to graze livestock on government-owned range and forest lands. The permit value comes from the price charged to the holder of the grazing right being less than its market value capitalized into the price of the private ranch.

[12] Liao *et al.* (2007) present similar findings for three large irrigation districts in China.

Table 3. Summary statistics of variables used to characterize irrigation in Jordan's Mafraq-Azraq Basin.

Dependent variables	Mean	Std Dev	Max	Min
Irrigation application rate	756.84	498.28	3,000	75
Gross Revenue per Unit Water	1.43	2.46	21.08	0.03
Explanatory variables				
Hired farm manager makes decisions	0.21	0.41	1	0
Farming is main profession	0.70	0.46	1	0
Farmer lives on farm	0.36	0.48	1	0
Farming is main income source	0.62	0.49	1	0
Outside expert advice used for crop selection	0.30	0.46	1	0
Outside expert advice used for irrigation	0.20	0.40	1	0
Received irrigation training	0.27	0.44	1	0
Owns well	0.83	0.38	1	0
Well discharge rate	64.10	20.75	150	0
Casing size	7.00	2.82	16	4
Water cost	0.30	0.47	3.43	0.02
Falling water table	0.70	0.46	1	0
Well depth to water table	80.64	50.49	260	10
Total area irrigated	251.11	181.77	820	30
Uses mulch	0.51	0.47	1	0
Land area in vegetables	0.54	0.48	1	0
Land area in water conserving crops	0.52	0.43	1	0
Age	50.73	13.19	75	22
Post secondary education	0.31	0.47	1	0

higher water prices resulted in irrigators fallowing land or leaving agriculture altogether[13]. At the aquifer level, this savings translates into nearly 7 MCM, or over 6% of Amman's annual demand. Interestingly, such a measure is also predicted to raise the value of sales generated per unit of water used by over JD 0.60 per m^3. These results suggest implementing a policy that charges farmers for the water that they pump to irrigate, consistent with the findings of Easter & Liu (2007) and of many other economists in recent years.

3.2.2. Water use. Table 4 shows results for the model explaining irrigation water application depth. Several factors were found to have a significant and positive effect on farm water use rates. Higher water use rates occurred for farmers who hired a professional manager, full-time farmers, and resident farmers. These results certainly make sense: all of those predictors of higher water use rates suggests that a full-time farmer sees deficit irrigation as a risky activity. By contrast, non-commercial farmers may worry less about income certainty from crop water use with more attention given to a satisfying lifestyle. Two other factors were also important predictors of a higher water use rate. Table 4 shows that these include well discharge rate and well casing diameter. These two terms indicate the importance of greater pumping capacity as a predictor of higher water use rates.

[13] One possible implementation of such a water pricing program, described in more detail in the discussion, is a water market arrangement in which water or water rights are purchased from farmers.

Table 4. Results of the regression model predicting irrigation application rate by irrigators who pump from Jordan's Mafraq-Azraq Basin; Dependent variable measured in mm depth of water applied. Each parameter estimate is the change in the dependent variable from a one unit change in the independent variable.

Explanatory variable	Parameter estimate	Standard error	*T*-Value	Prob | > | *T*
Hired farm manager makes decisions	110.180	34.113	3.230	0.002
Farming is main profession	98.252	48.839	2.012	0.048
Farmer lives on farm	80.455	39.084	2.059	0.043
Farming is main income source	− 106.002	59.997	− 1.767	0.081
Outside expert advice used for crop selection	33.377	26.477	1.261	0.211
Outside expert advice used for irrigation	− 84.615	35.651	− 2.373	0.020
Received irrigation training	− 27.620	30.504	− 0.905	0.368
Owns well	− 87.369	40.515	− 2.156	0.034
Well discharge rate	1.180	0.585	2.017	0.047
Casing size	12.094	5.443	2.222	0.029
Water cost	− 360.492	56.346	− 6.398	0.000
Falling water table	60.406	34.947	1.729	0.088
Well depth to water table	− 0.914	0.301	− 3.038	0.003
Total area irrigated	− 0.868	0.099	− 8.798	0.000
Uses mulch	18.850	29.095	0.648	0.519
Land area in vegetables	46.083	51.905	0.888	0.377
Land area in water conserving crops	119.609	41.370	2.891	0.005
Age	− 1.029	1.235	− 0.834	0.407
Post secondary education	− 0.719	12.541	− 0.057	0.954

Table 4 also shows a greater water application rate found for farmers who believe the water table is falling. These people use more water per unit of area (60 mm added depth). While this result may seem counterintuitive, it makes economic sense: supplies of groundwater are a common property resource to all producers in the basin who draw from the Afraq. The perception that the aquifer is finite and is being economically depleted motivates farmers to use more water by maximizing their short run returns before others deplete the common pool. This is yet another example illustrating Hardin's celebrated tragedy of the commons (Hardin, 1968). This finding has important policy implications in connection with the need for establishing private property rights for use of the aquifer, or possibly for the government of Jordan establishing more restrictive pumping limits.

Several factors have significant and negative effects on water use rates, all of which could offer potentials for water conservation. Irrigators for whom farming is the main income source apply more than 100 mm less depth than part-time farmers. This finding points to the potential for greater water conservation by full-time farmers. Similarly, those who hire expert advice on irrigation use at least 80 mm less water than those who make their own decisions. Farmers who pay for the advice evidently receive advice on the economic payoff from substituting other resources for water whenever possible.

Well tenure affects water behavior. Well owners are also apt to guard against misusing the well, showing at least 80 mm less irrigation depth than tenants. Well owners have a longer-term planning horizon with attendant economic incentives to more carefully use scarce water. Unlike tenants, well owners have a greater incentive to account for well depreciation, and to apply only additional water from a well when the marginal returns exceed the marginal costs including the cost of depreciation. Well tenants have little incentive to account for well depreciation and therefore little incentive to reduce water

Table 5. Results of regression model predicting gross revenue per unit water in agriculture by irrigators who pump from Jordan's Mafraq-Azraq Basin; Dependent variable measured in JD/m3 water applied. Each parameter estimate is a change in revenue per unit water from a one unit change in the independent variable below.

Explanatory variable	Parameter estimate	Standard error	*T*-Value	Prob | > | *T*
Hired farm manager makes decisions	0.282	0.105	2.680	0.009
Farming is main profession	−0.098	0.137	−0.714	0.477
Farmer lives on farm	0.097	0.067	1.451	0.151
Farming is main income source	−0.060	0.100	−0.600	0.550
Outside expert advice used for crop selection	0.071	0.088	0.812	0.419
Outside expert advice used for irrigation	0.252	0.128	1.967	0.053
Received irrigation training	0.052	0.054	0.965	0.338
Owns well	0.324	0.136	2.374	0.020
Well discharge rate	−0.001	0.002	−0.374	0.709
Casing size	0.021	0.011	2.005	0.048
Water cost	2.032	0.089	22.825	0.000
Falling water table	−0.169	0.065	−2.584	0.012
Well depth to water table	−0.001	0.001	−1.178	0.242
Total area irrigated	−0.025	0.015	−1.685	0.096
Uses mulch	0.210	0.080	2.622	0.010
Land area in vegetables	−0.070	0.190	−0.370	0.712
Land area in water conserving crops	−0.217	0.098	−2.221	0.029
Age	0.004	0.003	1.285	0.202
Post secondary education	0.030	0.106	0.283	0.778

use where it would reduce depreciation. The price of water is of singular importance in promoting water conservation, and will be discussed subsequently.

Depth to water is a negative predictor of water use, as is expected. Greater depth to water increases lift and provides the economic inducement to conserve water in many ways. These include planting water-conserving crops, deficit irrigation, substituting land for water, and in some cases fallowing land. Finally, the total land irrigated that is served by a pump also shows a similar kind of substitution of land for water. As the amount of land area increases, a given amount of water is spread over more land. Especially where institutional constraints preclude expanding of well capacity proportional to land in production, one would expect to see reduced water use per unit land.

Other measures could be implemented to reduce water use in irrigated agriculture. Providing expert advice and formal training on irrigation, for example, is estimated to reduce the amount of water used by about 112 m^3 per donum [−84.6 plus −27.6]. Since almost 80% of the farmers receive no such training and advice, addressing this issue could provide for another 5.5 MCM of available water and meet an additional 5% of Amman's needs.

3.2.3. Returns to water. Table 5 shows that hired managers produce more revenue per unit of water (JD/m^3). They also plant more water-using crops. Table 5 also shows that whether or not the producer identifies himself as a professional farmer has no significant effect on the revenue produced per unit water applied. So, professional farmers earn no more revenue for each unit of water used. We conclude that these farmers could benefit from a manager's expertise with regard to gross revenue produced by water.

Table 5 also shows the effects of on-farm residence on revenue per unit water. For this predictor, it is important to recognize that families who live on the farm devote a significant part of their total water use for household consumption, particularly for small farms. This explains why overall water use per unit of area is higher than those who live off the farm. However, revenue per unit of water is not statistically different from those who live off farm. Therefore, these findings suggest no significant impact on revenue generation from a policy that differentiates farmers by residence. Commercial farmers are as efficient as those who farm part time measured in sales revenue produced per unit water.

Table 5 shows no evidence that professional advice on crop selection significantly affects sales revenue per unit water applied. In addition, receiving expert advice on irrigation increases gross revenue per unit water applied by JD 0.25 per m^3 when compared to the overall sample average of JD 1.4/m^3. In short, current sources of irrigation advice seem to have a positive impact on revenues per unit water. In contrast, producers who at some point received training on irrigation do not appear to generate more sales per unit of water. This finding suggests that these two sources of irrigation information complement each other. If advice on irrigation can be procured at a lower cost than the extra revenue produced, Table 5 shows that this advice is a good investment in securing additional net revenue.

Since nearly 20% of the farmers irrigate from a leased well, it is important to analyze the effect of the farmer's well tenure status on revenue. Farmers who own the wells from which they pump generate a higher value of sales per unit of water applied, a gain of JD 0.32/m^3. Table 5 also shows that these farmers generate a lower crop revenue value per unit of water (JD 0.025/m^3 for each additional donum of land irrigated).

Often, in developing countries, larger farms use more efficient technologies and have access to better information, management, and marketing resources. In this particular case, however, larger farms simply have less water availability per unit of area than smaller farms, since all producers surveyed are limited to a single well for which there is a regulated upper limit on pumping capacity. As a consequence, farmers with more land stretch their available water to crop more land, making more technically efficient use of their water. The fact that these farmers generate a lower value of sales per unit of water shown in Table 5 can be explained by the counter-balancing effect that large farms tend to grow low-valued field crops, rather than high-valued fruits and/or vegetables.

Another important finding is that much farming advice is provided by pesticide sales people and by privately hired experts, rather than Ministry of Agriculture and Irrigation (MAI) extension agents. Table 5 shows that the advice received has important effects, which means that the MAI agents could contribute significantly to revenue if they receive training and invest the time and connections required to secure farmers' trust. In addition, the guidance and training on irrigation provided by these commercial parties has positive impacts on revenue per unit water applied. MAI agents can play a productive role in focusing on economic performance rather than limiting their advice to technical aspects.

4. Discussion

Our findings have numerous implications for water policies that would efficiently promote irrigation water conservation in Jordan's Mafraq Basin. For example, half the farm land in the basin is held by people who earn most of their income from off-farm work. These people use just under 40% of the basin's irrigation water and account for just over a third of its total farm gate sales. Just under 6 MCM of water annually could be transferred from farm to city uses if these people left agriculture completely and instead earned all their income from off-farm sources. However, the expectation that people might leave agriculture to pursue other employment is debatable.

What may be a more important policy-relevant finding in this study is the importance of water's price as a predictor of irrigation water demand. This single piece of information has major policy implications because it can be used to design market institutions that promote voluntary water transfers. Such institutions could be a low cost way to move water from farm to urban uses by taking advantage of the economic incentive provided by water's price.

In Amman, the economic value of water at the margin for urban uses has recently been estimated at JD 1.05/m^3 (Rosenberg *et al.*, 2008). Compare that to the results shown in Table 3, for which the (average) incremental value of water in irrigated agriculture is a far lower JD 0.30/m^3. That lower value in agriculture is based on the typical farmer's willingness to bear pumping costs[14] of JD 0.30/m^3. The average value of urban water is JD 0.75 higher than the value of water in agriculture (JD 1.05 minus 0.30), so there is considerable economic opportunity to move water from agriculture to urban uses economically, possibly more cheaply than by developing new supplies alone; however, we do not know how much water would be transferred to Amman if a regional water market were established. The implementation of water transfer institutions could produce gains from trade for both farms and urban areas[15] in the Mafraq Basin[16]. A short list of market institutions includes contingent transfers/dry-year options, spot market transfers, water banks, water wheeling, and water salvaging.

Contingent transfers, where needed, could produce a mutually beneficial payoff. This type of transfer could be implemented by Amman contracting to pay a sum of money for the privilege of exercising the right to use water should an emergency occur. It could also arrange to pay the farmers an extra sum if that right is exercised. For the irrigator, advantages of contingent transfers are an immediate infusion of cash

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[14] Table 3 shows the minimum marginal value of water in agriculture (willingness to incur pumping costs) at JD 0.02 per m^3. If Amman enters a water market as a buyer, JD 0.02 is the opportunity cost of the first m^3 transferred from agriculture. The mean opportunity cost in agriculture of JD 0.30 per m^3 will be transferred to the city only after all lower marginal valued uses are taken out of agriculture first. Farmers first take water out of their lowest valued crops, like cattle feed, before reducing irrigation on higher valued crops, such as orchards.

[15] Important conditions must be satisfied before market-oriented water transfers can be implemented effectively in Jordan. These conditions include an adequate political and legal framework, institutional and administrative resources capable of implementing and enforcing the policy, and a water distribution infrastructure providing the level of control and measurement required. In addition, both buyers and sellers must be prepared to comply with the rules for whatever water market arrangement is established. Currently, water markets are not widely practiced in Jordan, as shown in the following Jordanian public law:

> *"Article 25a of Law 18 of 1988 states that all water resources available within the boundaries of the Kingdom, whether surface or ground waters, regional waters, rivers or internal seas are considered state owned property and shall not be used or transported except in compliance with this law. Paragraph C emphasized that all natural and judicial bodies are prohibited from selling water from any source, or granting or transporting it, without obtaining in advance written approval of the Authority and within conditions and restrictions the decided or included in the contracts or agreements concluded between them and the Authority."*

[16] With increased quantities of water traded from farms in the Mafraq Basin to the city of Amman, the marginal value of water in agriculture will increase as water use in agriculture is reduced. The marginal value of water for urban uses in Amman will fall as greater supplies allow the city's population to start using water for lower valued uses such as car washing, street cleaning, and landscape watering. Where the efficient amount of water is moved from agriculture to Amman, the marginal value of water in both uses will be equal except for the cost of water transportation and purification. It should also be pointed out that the Mafraq Basin is not the only source of additional water being examined by the city of Amman. Other possible sources include supplies from the Jordan Valley, in addition to water from other proposed projects described earlier in this paper.

when the contract is made and additional cash if the contingent transfer option is called. Both sources of cash can finance investments in on-farm water conservation measures. Examples of such measures include water-saving technologies like drip irrigation, shifts to water conserving crops, reduced land in production, and increased food imports. The advantage to the seller is income to finance water conservation. The advantage to Amman is access to water when it's most needed.

Spot market transfers are short-term transfers, typically agreed to and carried out within a single year. These transfers can be set up as a bidding process, often with some of the conditions for transfer, such as price or quantity, being set in advance. The advantage of a spot market transfer for agriculture is the immediate infusion of cash when the transfer takes place, which can finance various water conservation measures.

Water banks, a special kind of spot market, can be organized and operated by a central banker, such as the state. The bank is a mechanism for owners of water rights to voluntarily transfer water to the bank for re-deployment to a willing buyer on a short-term basis. The bank is responsible for organizing the contract and for tracking the supply and demand for money and water. A water bank is characterized by flexible, temporary transfers of water while maintaining the original owner's secure water right. Bank participants can vary each time the bank is established.

Water can sometimes be wheeled or exchanged through water conveyance and storage facilities to improve the performance of the system[17]. An example is the use of a parallel lined canal owned by somebody else rather than incurring considerable water losses by using one's own unlined canal. So, depending on the availability and quality of canals for conveying water in the Mafraq Basin, seasonal wheeling may provide opportunities for Amman to buy or trade water with farmers during reduced irrigation demand periods, such as during Jordan's November to April wet season. Repayment could come in the form of added water and/or cash during the dry irrigation season.

Water salvaging, the purchase of water made available by reclamation, conservation, or reductions in water demands is a form of a water transfer. For example, in the late 1990s the Metropolitan Water District of California set up a 35 year contract to pay the Imperial Irrigation District (Israel & Lund, 1995) several million dollars for canal lining and other system improvements in exchange for the water conserved. Where this kind of water salvaging is technically feasible, the city of Amman could lease, rent, or buy water conserved to compensate and provide incentives for farmers to reduce irrigation in the basin.

Another advantage of market water transfers in Jordan's Mafraq Basin is that, where market forces set the price of water, the price signals the opportunity cost of continuing to use water in irrigated agriculture. Market transfers also promote full cost recovery of water owned by the state. Full cost recovery is an important part of Jordan's irrigation water policy, as described by the Jordanian Ministry of Agriculture and Water (2009):

> *The water price shall at least cover the cost of operation and maintenance, and, subject to some other economic constraints, it should also recover part of the capital cost of the irrigation water project.*

[17] Water infrastructure, like reservoirs and canals to hold and convey water, is needed to support water transfers. Otherwise water cannot be moved from its supply source to its demand location. One important piece of institutional machinery that will be needed in Jordan to support a move from farm to city uses is a water accounting system for tracking water use.

The ultimate objective shall be full cost recovery subject to economic, social and political constraints...

Water's price is an important factor affecting the use and economic productivity of water in irrigated agriculture in Jordan's Mafraq Basin. Still, a policy decision to charge for water, while likely to promote water conservation and lengthen the aquifer's life, is also likely to be controversial and should thus be approached with caution. Even the strongest supporters of marginal cost pricing of water found that it can be politically dangerous[18]. One possible solution to the equity problem posed by charging a marginal cost price to poor farmers in Jordan's Mafraq Basin is to establish a two-tiered pricing system. Under a two-tiered pricing system very low prices are charged for basic water needs, such as water used to supply crops for a household's subsistence[19]. After household subsistence water needs are met, water could be priced at marginal cost for discretionary use levels. This two-tiered pricing structure is one way to combine principles of equity with the desire to maximize the economic power of Jordan's scarce groundwater[20].

5. Conclusions

In a celebrated 1958 study of Jordan's irrigated agriculture, H.R.J. Davies concluded that further extension of Jordan's irrigated agriculture was essential for the country to reduce its trade gap, raise its living standards, and provide for its refugees (Davies, 1958). Half a century later, Jordan assigns irrigation developments to a lower place on the development agenda. Its current water challenge is to find ways to promote sustainable water development and use. Irrigated agriculture consumes 75% of its water (Molle *et al.*, 2008) while contributing to only 4% of national income. This paper has identified cost-effective ways to reduce demands in Jordan's irrigated agriculture with a special emphasis on the institutions relying on the strong effects of price in influencing water use. The overarching importance of price assigns considerable potential to the use of market transfer institutions to move water from farms to cities.

The potential for an irrigator to realize an economic gain by conserving water in agriculture is an overarching factor that can be used to design incentives to promote water conservation by Jordan's irrigators who pump from the Mafraq aquifer[21]. Considerable differences in the marginal value of water used in agriculture compared to urban uses create an opportunity for market institutions to promote water transfers from farms to urban areas. Incentives promoting such water transfers also promote water

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[18] Careless implementation of conservation pricing risks pricing a basic human need so expensively that the poor cannot afford their water requirements without shouldering a politically unacceptable burden. In fact, before 1990 only one major American city (Tucson, Arizona) ever adopted marginal cost rates for water. This occurred after the two-year drought of 1976–77. One year after the adoption of those rates, voters held a recall election over the water rates and voted the entire city council out of office.

[19] For example, irrigation water used to provide basic subsistence food staples could be priced at a low enough level to assure a farm's food security.

[20] Two-tiered water pricing could also produce both equity and efficiency gains for Amman's urban water use, helping to guard against inefficient expansion of its urban water demands.

[21] Other water institutions may have a role to play. While beyond the scope of our analysis, Molden *et al.* (2007) identified the role of several institutional adjustments on two irrigation systems in China in promoting successful irrigation water conservation.

conservation by the basin's irrigators. Our results show that water demands in agriculture by Jordanian pumpers are sensitive to the price they pay. Owners or users of agricultural water rights could use this price sensitivity to their advantage by renting or leasing their water to cities in periods of drought or other shortages with no change in water right ownership.

Legislative or judicial action is needed to guarantee secure property rights for legitimate water right holders. Without such public action, fears of forfeiture for that part of the water right not currently used in irrigation poses a barrier to on-farm water conservation[22]. Common property issues also threaten conservation incentives. A basin irrigator may avoid water conservation because the perception of a dwindling water supply available in a common property aquifer undermines the individual's water right security. High current use is a visible and public demonstration of current beneficial use (non waste). That high use may be viewed by the individual as a way to perfect and sustain a more secure future water right when and if those rights are defined by formal public action. The belief that a future property right could be forthcoming in the face of demonstrated high current use can block conservation incentives just when that conservation is most needed in the face of future drought, climate change, or competing demands by cities.

Our data show that the price of water is the most important factor influencing water conservation in Jordan's Mafraq Basin. A low water price discourages water conservation even if other institutions promote, support, or encourage it. A high price of water encourages conservation even in the presence of other discouraging factors. Overall, our findings suggest that water-conserving policies in Jordanian irrigated agriculture can be more effectively implemented where water institutions and programs are designed to be compatible with water's underlying economic scarcity.

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[22] Security of tenure promotes water conservation in irrigation. One way to raise that level of security is through a general basin adjudication. An adjudication settles all the rights to use water within a particular aquifer or stream system, and is typically conducted through an accepted legal authority, such as a court, to determine the extent and validity of existing water rights. While an adjudication creates no new water, it is a legally binding way to determine who has a valid water right, how much water can be used, what rules surround water transfers, and who has priority during shortages. It provides information essential to using, protecting, planning, and transferring water. It also reduces future disputes over water sources and priority of water rights, while increasing protection of legal water users from impairment by those without rights and those using water beyond their limits. Adjudication facilitates the transfer of water to meet emerging economic and environmental needs and promotes the development of water banks that would promote orderly market transfers. Finally, adjudications could increase Jordan's effectiveness in negotiating its use of transboundary waters with its neighboring countries.

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