Groundwater irrigation management in the Kingdom of Saudi Arabia: A case study of Al-Wajid aquifer*

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Abstract: Groundwater is the primary source for water irrigation in the Kingdom of Saudi Arabia. As a result of lack of basic knowledge on irrigation practices, massive abstractions of groundwater occurred in 1980s. A decision support linear programming (LP) model was developed to help in allocation of optimal groundwater irrigation use, to assess policies implication for water management efficiency, and to estimate welfare impact on producer surplus is developed. Due to massive abstractions occurring in 1980s, Al-Wajid aquifer water levels have dropped in agricultural areas by more than 200 m. The total groundwater of Al-Wajid aquifer that can be saved is equal to 158.7 MCM for the first scenario, 211.9 MCM for the second scenario, and 15,087 MCM for the third scenario. Regarding welfare analysis impact, it is clear that the second scenario alternative is the best alternative, since the value of the producer surplus is the highest for the two study regions and also the two type schemes of modern and traditional irrigation, except the traditional irrigation of Najran region.

Key words: groundwater; Al-Wajid aquifer; abstraction; irrigation; welfare analysis

1. Introduction

The Kingdom of Saudi Arabia is ranked as an arid land, with limited natural water resources. As a result of rapid growth and comprehensive development in all economic sectors, water demand for domestic, agricultural and industrial purposes has dramatically increased. Agriculture is the major water consumption which consumes about 85% of total national water use (Ministry of Water and Electricity [MOWE], 2008). Groundwater is considered as nonrenewable, stock resource that is mined by water users over time, although groundwater stocks are clearly rechargeable by both natural and artificial means, the potential benefit of recharge in use decisions tends to be small relative to aquifer capacity (Provencher, 1995). The sedimentary deep aquifers are the main sources of irrigation water for Saudi agriculture, there are ten principal and five secondary aquifers, based on their real extent, groundwater volume, water quality and development potential (MOWE, 2008). The abstraction and use of groundwater in arid land is the same as a mining operation (Lloyd, 2002). Since groundwater is the primary source of water for irrigation, and massive abstractions occurred in 1980s, a signal was released by the government of Kingdom of Saudi Arabia in 1993 and 1994 to make use of groundwater resources more

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sustainable and prevent massive groundwater consumption (Water Watch, 2006; World Bank, 2006).

The policy challenge is predictable groundwater resources for the purpose of assuring continued availability in the future. The success of the policy depends on the ability to accurately value the water resources being used. Developing the institutions for this valuation process, and determining the impact of changing valuation on allocation of water to various users, is the primary role the economics profession plays in the creation of water policy (Whittlesly & Huffaker, 1995).

Al-Wajid aquifer is one of the principal aquifer in the Kingdom of Saudi Arabia, which suffered from massive irrigation abstractions. Wadi Ad Dawasir and Najran regions are the major irrigation water abstraction from Al-Wajid aquifer. The total volume of groundwater abstracted for irrigation in this relatively small region has increased from 23 MCM in 1973 to 2,051 MCM in 2006, while the annual recharge dose not exceed 10% (GTZ, 2007). In fact, most economic researches have treated groundwater recharge as either invariant with respect to the current stock of groundwater or variable only as the aquifer approaches maximum capacity (Brown & Deacon, 1972; Feinerman & Knapp, 1983; Gisser & Sanchez, 1980; Moncur & Pollock, 1988). The annual irrigation abstraction of Al-Wajid is in the range of total annual residential water consumption of the entire Kingdom of Saudi Arabia, and 10 times of two regions in Al-Wajid area which are estimated to be 200 MCM/a (GTZ, 2007). This case study can serve as a pattern for other aquifers.

The objectives of this study are to increase groundwater irrigation management efficiency for Al-Wajid aquifer through minimizing water use under the optimal allocation concept, and to assess the impact of agricultural policy reforms on farm income and groundwater resources use.

2. Geographical overview

Al-Wajid area encompasses a variety of geomorphologic units that are characteristic for the southwestern part of the Kingdom of Saudi Arabia. From east to west the main units are: the Rub' Al-Khali desert, the Tuwayq Escarpment, the Wajid Plateau, the Hijaz Plateau and the Najd Peneplain on the Arabian Shield, and the Asir Highlands (GTZ, 2007).

The climate in the study area ranges from hyper-arid in Rub' Al-Khali desert to semi-arid in the Asir Highlands. About 80% of the study area receives less than 100 mm/a, mostly during the spring months. The area of Wadi Ad Dawasir, situated at an altitude of around 650 m.a.s.l., is characterized by very hot summers, average monthly maximum/minimum in July: 43.9 C/27.7 C, and mild winters, average monthly maximum/minimum in January: 24.7 C/9.8 C. The calculated annual potential evapo-transpiration ET_0, Penman-Monteith approach (FAO, 1998) for Wadi Ad Dawasir is 2,643 mm/a. Najran, at an altitude of around 1,250 m.a.s.l., does not suffer the extreme heat of the summer, average monthly maximum/minimum in July: 39.2 C/24.8 C, and mild winters, average monthly maximum/minimum in January: 25.2 C/8.7 C. Resulting in a lower annual potential evapo-transpiration of 2,168 mm/a (MOWE, 2008).

Most of the study area is covered by typical desert soils, which are pedogenetically underdeveloped and were formed mainly by mechanical weathering rather than chemical alteration. The parent material of those soils consists of the metamorphic and granitic rocks of the Arabian Shield. As would be expected for desert soils, they have a low field capacity and cation exchange capacity due to the rather coarse texture and lack of organic and inorganic colloidal complexes. Also, these soils are rather alkaline due to an elevated calcium-carbonate content in the upper layer that at some places develop into a caliche horizon.

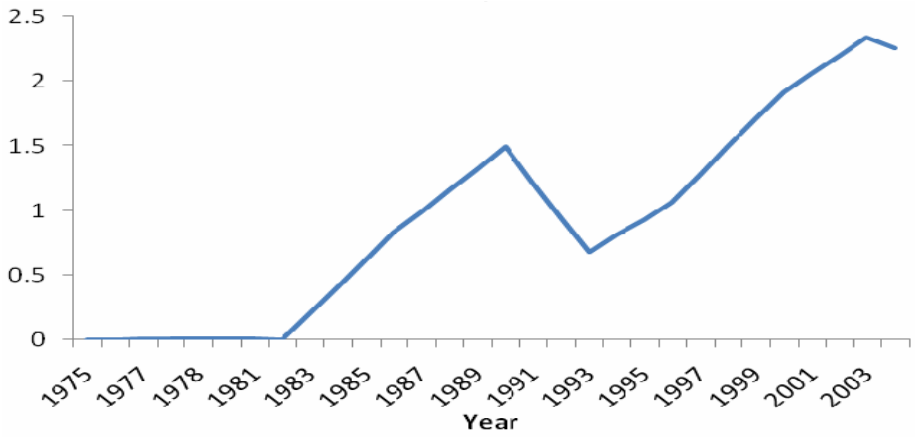

Figure 1 Groundwater abstractions of Al-Wajed aquifer

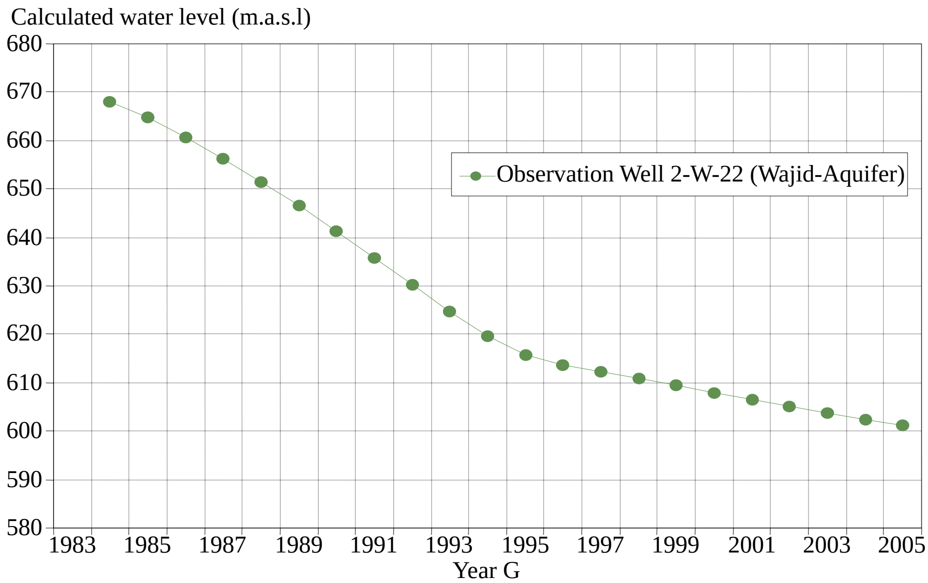

Figure 2 Al-Wajid aquifer water level

Before the beginning of the agricultural expansion in early 1980s, the agricultural activities in the study area were confined to areas where more abundant annual precipitation allowed rain-fed crops to be cultivated or where shallow groundwater for irrigation was easily accessible by traditional means. The crops of these wadi oases were mainly date palms, followed by winter and summer cereals, alfalfa and vegetables. The agricultural production during that time was largely in equilibrium with available water resources and the output was sufficient to meet the needs of the population living in the area. With the advent of modern large-scale (center pivots) irrigation schemes during the 1980s, supplied by deep wells mainly tapping the Wajid aquifer, the agricultural land use within the study area increased significantly. Today's agriculture in Wadi Ad Dawasir area consists of technically highly developed farm enterprises that operate modern center pivot irrigation system. The size of center pivot range from 30 ha to 60 ha with farms managing up to 100 of them with the corresponding number of wells. The main crop grown in winter is wheat and occasionally potatoes, tomatoes or melons. All year fodder consists of alfalfa, which is cut up to 10 times a year for hay. Typical summer crops for fodder are sorghum and Rhodes grass, which is perennial, but dormant in winter. The shallow alluvial aquifers could not sustain the high groundwater abstraction rates for a long time and groundwater level declined dramatically in most areas (see Figure 1 and Figure 2).

3. Methodology and data source

The problem of evaluating irrigation water demand and management, and water regulations assessment are not recent and has become a growing field of research in the last few years (Christophe, et al., 2001), two approaches on irrigation water demand and management estimation exist. If data relating to observed water consumption exist then econometric models are used (Ogg & Gollehon, 1989; Moore, et al., 1994; Christophe, et al., 2001), while if the data are imprecise on consumptions, then standard mathematical techniques such as linear programming (Shunway, 1973; Montginoul & Rieu, 1996) or quadratic programming are applied (Howitt, 1995; Mila & Ganacio, 2009). However, the programming methods are based on the mathematical formulation of the farmer's behavior to maximize his gross margin, thus, for variations in water prices induce different levels of optimal water quantities (Christophe, et al., 2001). The weaknesses of these models are due to formalization of the farmer's program and the necessarily simplifying assumptions. Also, most of the previous studies are based on the unrealistic assumption that the farmers are risk-neutral, while it is recognized in the literature that farmers are risk adverse (Bouzit, 1995). The studies based on maximizing the objective function of farmers' gross margin are in the short run and at production unit level; therefore, risk factor is related to farmers' gross margin not to water sustainability.

In fact, all previous studies in Saudi Arabia (such as Safar, et al., 1996; REF, 2009) used linear programming technique for irrigation water management through maximizing farmer's gross margins, assuming that the average amount of water used in a certain period is available, accessible, stable and sustainable. Of course, these assumptions are not valid. In reality, there are remarkable signs of serious decline in aquifers water levels in the Kingdom of Saudi Arabia.

This study tries to overcome the weaknesses of previous studies (maximizing problems) by altering to minimizing and rationing water use. Because water resource is the most scarce important and limited factor for sustainable agriculture development. Therefore, the method of this study is considered more objective in dealing with the development of non-renewable groundwater in Saudi Arabia. It is based on water efficiency oriented rather than production efficiency of all production factors, and it relies on the intensification of available items such as capital and reduces scarce factors such as water.

Linear programming approach is applied for only two regions that rely on water abstraction from Al-Wajid aquifer (namely Wadi Ad Dawasir and Najran; M_j, j = 1, 2). The study includes 17 commodities (N_i, i = 1, 2 … 17). These commodities were classified into 4 groups (cereals, fodder, vegetables and fruits, I = 4). Farmers implement two types of irrigation schemes (modern (center pivot) and traditional (flood) schemes, k = 1, 2). The LP model has been stated as follows:

The objective function:

$$\min z = \sum_{i=1}^{N}\sum_{k=1}^{L}\sum_{j=1}^{M} X_{ikj}W_{ikj} \tag{1}$$

Subject to:

$$\sum_{i=1}^{N}\sum_{k=1}^{L}\sum_{j=1}^{M} X_{ikj}Y_{ikj} \geq \text{YB} \tag{2}$$

$$\sum_{i=1}^{N}\sum_{k=1}^{L}\sum_{j=1}^{M} X_{ikj} \prec BLH(j) \quad (3)$$

$\forall_j$; j = 1, 2 i = 1, 2, … , M

$$\sum_{i=1}^{I_n}\sum_{k=1}^{L}\sum_{j=1}^{M} X_{ikj} \prec BCA(j,i) \quad (4)$$

$$\sum_{i=1}^{I_n}\sum_{k=1}^{L}\sum_{j=1}^{M} X_{ikj} * C_{ikj} \prec TC(j,i) \quad (5)$$

$$\sum_{i=1}^{I_n}\sum_{k=1}^{L}\sum_{j=1}^{M} X_{ikj} * F_{ikj} \prec TF(j,i) \quad (6)$$

$$\sum_{i=1}^{I_n}\sum_{k=1}^{L}\sum_{j=1}^{M} X_{ikj} * L_{ikj} \prec TL(j,i) \quad (7)$$

$$Barea1(i) = \sum_{j=1}^{M} X_{i1j} \quad (8)$$

$$Barea2(i) = \sum_{j=1}^{M} X_{i2j} \quad (9)$$

$$Barea2(i) \prec Barea1(i) * R(i) \quad (10)$$

$$X_{i2j} \geq 0$$

where: X_{ikj} is decision variables, W_{ikj}, C_{ikj}, F_{ikj} and L_{ikj} are water, capital, fertilizer and labor requirements respectively (technical coefficients), Y is the productivity per hectare, YB is the production quantity, BLH is the total cultivated area, TC is total cost, TF is total fertilizer, TL is total labor force, Barea1 is traditional irrigation, Barea2 is modern irrigation, R is ratio between modern and traditional irrigation. The separability among commodity groups is assumed, this assumption allows competitions among commodities in each group based on water efficiency, therefore equation (1) and inequations (2)-(4) are added to the LP model. Equation (8) and equation (9) represent the sum of traditional and modern irrigation in region (M_j) respectively. For high water efficiency use, equation (10) is used to ensure that traditional water use should not exceed actual water use for LP solution.

Water requirement, land, production level data were obtained from Ministry of Agriculture [MOA] (2008). Other data such as labor, fertilizer, operating costs were obtained from agricultural strategy survey, 2005.

4. Results

Table 1 illustrates the basic data for LP model. The highest total operating cost among all products in Wadi Ad Dawasir was the squash (10,440 SR/ha), while among grains was the wheat (7,050 SR/ha) for modern irrigation. The large amount of water requirement is for palm dates which are equal to 32.5 and 29.2 thousand m^3 for modern and traditional irrigation respectively. Wheat is the largest amount of water requirement among grain group. The current water use according to area production and water requirements in both regions and for all commodities (N_i, I = 1, 2… n) for 2008 year was 1.3 billion m^3. The LP feasible solution for minimizing water use is 1.23 billion m^3 which save about 70 million m^3.

Table 2 illustrates the optimal area production for both type of irrigation systems. The columns 5, 6, 7 and 8 show the reduced cost, which indicates the saving of water requirement as a result of increasing one unit of n commodity. For example in Najran region, increasing one unit of grapes will result in water requirement saving by 700 m^3 for modern irrigation.

Table 1 Water requirements and total operating costs in Wadi Ad Dawasir and Najran regions

Commodity	Water requirements (m^3/ha)				Total water use (000 m^3)	Total operating costs (SR/ha)			
	T1	T2	M1	M2		T1	T2	M1	M2
Wheat	7,309	9,514	7,258	7,419	4,521	10,390	2,830	11,770	7,050
Barley	6,614	8,610	6,568	6,714	365	10,390	1,860	11,770	7,980
Other grain	6,961	9,038	6,613	7,408	56	10,390	4,800	11,770	3,520
Alfalfa	20,373	23,550	20,106	19,053	432,212	10,390	5,480	11,770	4,120
Other fodder	24,935	24,452	23,707	19,053	398,132	13,280	14,950	5,610	5,610
Tomato	8,128	8,337	7,315	7,503	8,582	13,280	14,950	4,290	4,290
Squash	5,553	5,953	4,998	5,358	1,778	13,280	14,950	7,940	7,940
Eggplant	8,298	7,625	7,468	6,863	1,734	16,370	6,230	13,280	8,340
Potato	9,194	10,583	8,275	9,525	6,675	16,720	5,810	8,350	10,440
Onion	7,565	9,852	6,809	8,867	1,716	16,550	6,510	10,820	7,370
Mellon	9,676	5,454	8,708	4,909	9,242	16,550	7,500	10,820	3,330
Water melon	9,676	5,572	8,708	5,015	6,252	16,550	5,210	10,820	8,970
Other veg.	8,298	7,625	7,468	6,863	9,987	16,550	4,100	10,820	6,310
Dates	32,470	25,160	29,220	22,644	233,607	16,550	4,100	10,820	6,310
Citrus	37,318	34,756	33,586	31,280	61,768	16,550	5,640	10,820	7,300
Grapes	31,283	23,992	28,155	21,593	1,674	9,040	6,220	12,030	4,050
Other fruits	32,251	25,672	29,026	23,105	42,403	12,440	6,060	12,030	2,330
Total					1,261,504				

Notes: T_j: stands for traditional irrigation, T_1 for Wadi Ad Dawasir region and T_2 for Najran region; M_j: stands for modern irrigation, M_1 for Wadi Ad Dawasir region and M_2 for Najran region; ha: Hectare; 000 m^3 stands for thousand cubic meter of water.

Source: MOA, 2008.

Table 2 LP optimal solution in Wadi Ad Dawasir and Najran regions

Commodity	Area (ha)				Reduced water (000 m^3)				Current demand (ton)	Water margin (m^3/ton)
	T1	T2	M1	M2	T1	T2	M1	M2		
Wheat	160	7,719	50,819	1,138	0	0	0	0	29,895	6,517
Barley	0	0	320	0	0	0.3	0	0.3	207	5,097
Other grain	0	59	0	0	1.7	0	1.7	0	29	4,962
Alfalfa	0	0	188,335	23,418	0.1	0.4	0	0	404,033	1,179
Other fodder	3,045	0	159,416	4,565	0	0.5	0	0	303,312	1,616
Tomato	0	0	5,723	0	0	0.5	0	0.4	23,375	225
Squash	0	0	0	3,161	0.1	0.1	0.1	0	4,739	357
Eggplant	0	0	1,677	0	0.1	0.1	0	0	2,743	558
Potato	0	0	0	5,922	0.4	0.1	0.2	0	17,937	314
Onion	0	0	0	2,221	0.1	0.1	0.1	0	6,474	304
Mellon	0	0	10,613	0	0	0.5	0	0.5	20,345	528
Water melon	0	0	7,172	0	0	0.3	0	0.2	13,785	527
Other veg.	0	0	1,020	3,095	0	0.1	0	0	26,179	438
Dates	0	18,135	48,832	14,247	0.3	0	0	0	47,912	5,337
Citrus	0	0	0	19,237	1.1	0.4	0.7	0	23,430	3,399
Grapes	0	0	613	0	0.3	1	0	0.7	1,024	1,701
Other fruits	0	0	0	11,554	2.6	0.3	2.3	0	20,405	1,882

Notes: T_j: stands for traditional irrigation, T_1 for Wadi Ad Dawasir region and T_2 for Najran region; M_j: stands for modern irrigation, M_1 for Wadi Ad Dawasir region and M_2 for Najran region; 000 m^3 stands for thousand cubic meter of water.

Source: LP results.

The least amount of irrigation water that can be added for increasing (decreasing) wheat crop output by one ton is about 6,517 m^3(-6,517 m^3) and by 5,337 m^3 (-5,337 m^3) for dates production. Table 3 shows the slack area that is not used is equal to 6,699 ha for Wadi Ad Dawasir and 7,128 ha for Najran. In Wadi Ad Dawasir region, the grain area has been used which is the slack equal to zero, while water is -2.64 (m^3/ha), this means that Ad Dawasir region has comparative advantages of growing grains, so that increasing grain area by one hectare will result in decreasing total water consumed in the region by 2,640 m^3. At Najran region, there is no surplus water of use which means Najran region has no comparative advantages of water use (Table 3).

Table 3 Area and capital cost impacts in Wadi Ad Dawasir and Najran regions

Region	Crop groups	Region area impact			Crops area impact			Capital cost impact		
		Current area (ha)	Slack area (ha)	Water (m^3/ha)	Current area (ha)	Slack area (ha)	Water (000 m^3/ha)	Current cost (SR)	Slack cost (SR)	Water (m^3/ha)
Wadi Ad Dawasir		493,700	6,699	0						
Najran		121,600	7,128	0						
Wadi Ad Dawasir	Grains				51,300	0	-2.64	36,150	21.4	0
	Fodder				351,400	602	0	239,820	3,033	0
	Vegetable				398,000	4,343	0	24,730	0	-220
	Dates and fruits				51,200	1,755	0	30,570	10,701	0
Najran	Grains				9,100	184	0	9,420	0	-1,520
	Fodder				28,000	16	0	35,890	19,127	0
	Vegetable				18,600	4,200	0	25,650	10,850	0
	Dates and fruits				65,900	2,727	0	70,575	0	-840

Note: 000 m^3 stands for thousand cubic meter of water.
Source: LP results.

The efficiency of available total capital can be seen from adding capital constraints. The result shows that at increasing one thousand Riyals, this impact is only for vegetables which will reduce water use by 220 m^3; other commodity groups will not be affected. At Najran region, increasing capital for grain and dates will reduce water use by 1,520 m^3 and 340 m^3 respectively.

5. Policy implications

Water resource problems in many cases are primarily the results of inefficient policy and institutions (Adamowicz & Horbulyk, 1996; Weinberg, 2002; Shahbaz, et al., 2009). Bernardo and Whittlesey (1989) used a mathematical programming model to show that farmers in Washington State substitute water with labor, by switching to more water efficient mode of operation of their irrigation technology. Consequently, under restricted water supply, water use can be reduced up to 35% for surface irrigation and 25% under center pivot schemes, without greatly affecting farmer income. Hoyt (1984) reached similar conclusions on farmer response to increasing pumping cost as a result of declining aquifer levels in Texas, USA. Their modeling results imply that if water supply is restricted by 20%, farmers' profit will not be affected significantly. Increasing water extraction costs and crop prices has no significant impact on the efficiency of water use (Berbel & Gomez-Limon, 2000). However, due to the inelastic demand for irrigation water, reliance on price mechanisms to conserve water has limited impact in the short run (Huffaker, Whittlesen, Michelsen, Tayor & McGuckin, 1998). Only if prices increase dramatically, capital investments in more efficient irrigation technology become viable at considerable profit loss to farmers (Caswell & Wilberman, 1990). There are a wide range of irrigation technologies available for irrigation. Using techniques available today, farmers could cut their water demands by 10%-50% (Postel, 1996). However, both technology diffusion and water allocation efficiency improvement have not been easy without appropriate policy and economic instruments (Lixia, et al., 2005).

A result of the expansion of agricultural policies in the early eighties, which aims to increase self-sufficiency of strategic crops such as wheat, has led to an increase in wheat production in excess of local market and then export in some years. It was from the agricultural policy incentive which is to buy grain silos full of wheat production and pay prices higher than world prices for a long period of time. This was undoubtedly at the expense of depletion of non-renewable groundwater resources and largely. A result, the government issued Decree No. 335 in 2008 aims to reduce water consumption in the agricultural sector through the reduction of bonds to buy wheat from traditional farmers and agricultural companies, by 12.5% per year for eight years. Of course, the resolution will have a direct impact on reducing the cultivation of wheat due to the adoption of the producers to ensure full production of the silos as well as the inability to compete with imported wheat. One of the main pillars which conservation policies are built are water laws. Legislation can help to improve groundwater management plans, facilitate the use and protection of the resources and provide guidelines for future conduct (Mohammed, 2001).

In addition to Decree No. 335 in the context of maintaining the non-renewable groundwater resources, government has encouraged farmers by linking subsidies and direct and indirect loans, using modern irrigation techniques in order to raise the efficiency of water use. Also that the fodder is water consumption crop, therefore, the government is currently studying reducing the area devoted to grow fodder as well as to ensure that wheat producers, especially agricultural enterprises, have not to shift to the cultivation of fodder, which accessible could be marketed to the dairy farms. Based on the foregoing views of the government in the rationalization of water consumption in the agricultural sector and to assess the impact of the new policy on rationalizing water consumption and farm incomes, three alternative scenarios have been prepared based on a fundamental solution to linear programming as follows:

Scenario 1: is to assess the effect of the resolution No. 335 in reducing the purchase of wheat by 12.5% for eight years to conserve the consumption of non-renewable groundwater resources. The Table 4 shows the impacts of Decree No. 335 on the area planted with wheat and the amount of water consumed, at the beginning of the first year of resolution No. 335 for each method of irrigation type (modern, traditional), and total water consumption. The results indicate that the cultivated area will become a modern irrigation of 48 thousand hectares and consume 928 million cubic meters, while the traditional irrigation area is 12.7 thousand hectares which consumed 321.5 million cubic meters of groundwater. In the last year of resolution No 335, the total cultivated area 56.3 thousand hectares is expected to consume 1,222 million cubic meters of groundwater.

Scenario 2: the first scenario in addition to the impact of linking subsidies and loans using the method of modern irrigation technology (high water efficiency). Table 4 provides results of Scenario 2 which shows a greater shift to the use of modern irrigation schemes, where the cultivated area has increased with modern irrigation compared to traditional irrigation scheme and the decline in the total amount of water used. When compared to the last year of Scenario 2 with the first alternative, the total cultivated area reduced by 500 hectares and less quantities of water used by 17 million cubic meters.

Scenario 3: the second alternative scenario in addition to reducing the proportion of area devoted to growing fodder by 20%. Table 4 provides the results of this scenario, which shows a reduction in areas producing wheat in the last year of resolution No. 335 by 8.1 thousand hectares and less quantities of the water used at least by 193.3 million cubic meters compared to the first alternative.

Table 4 Water management under various scenarios for Al-Wajid aquifer in Saudi Arabia

Year	Irrigation type	Scenario 1		Scenario 2		Scenario 3	
		Act 335		Act 335 + HWE		Act 335 + HWE + FR	
		Area (thousand ha)	Water use (million m^3)	Area (thousand ha)	Water use (million m^3)	Area (thousand ha)	Water use (million m^3)
2009	M	48.0	928.3	49.7	957.0	45.0	850.7
	T	12.7	321.5	10.6	280.8	7.7	211.7
	Total	60.7	1,255.8	60.3	1,237.7	52.7	1,062.3
2010	M	47.6	925.0	48.9	951.5	44.3	845.2
	T	12.4	325.0	10.6	280.8	7.7	211.7
	Total	60.0	1,250.2	59.5	1,232.3	52.0	1,056.9
2011	M	47.3	922.6	48.2	946.1	43.5	839.8
	T	12.0	321.9	10.6	280.8	7.7	211.7
	Total	59.3	1,244.5	58.8	1,226.8	51.2	1,051.5
2012	M	47.0	919.7	47.4	940.6	42.8	834.3
	T	11.6	319.1	10.6	280.8	7.7	211.7
	Total	58.6	1,238.8	58.0	1,221.4	50.5	1,046.0
2013	M	46.5	917.0	46.7	935.2	42.1	828.9
	T	11.2	316.2	10.6	280.8	7.7	211.7
	Total	57.7	1,233.2	57.3	1,216.0	49.7	1,040.6
2014	M	46.0	914.0	45.9	929.8	41.3	823.5
	T	11.0	313.0	10.6	280.8	7.7	211.7
	Total	57.0	1,227.0	56.5	1,210.5	49.0	1,035.1
2015	M	45.8	911.0	45.2	924.3	40.6	818.0
	T	10.5	311.0	10.6	280.8	7.7	211.7
	Total	56.3	1,222.0	55.8	1,205.1	48.2	1,029.7

Notes: HWE: stands for high water efficiency; FR: stands for reduced fodder cultivation by 20%; M: stands for modern irrigation; T: stands for traditional irrigation.

Source: LP results.

Similarly, Table 5 provides estimates of amount of water that can be saved from Al-Wajid aquifer based on the above three scenarios, as is clear that the proportion of water which can be saved in the last year of resolution No. 335 represents 3.1% and the total amount of water which can be preserved during the years of the resolution is 158.7 million cubic meters. While the second alternative, the total water quantities can be preserved by the amount 291.9 million cubic meters and up to 4.5% in the last year. The third scenario with total estimated quantity conservation is 1.5087 billion cubic meters, accounting for 17.9% in the last year. The total quantities of water which is possible to be saved in the third scenario is greater than 7.5 times the amount of water used for municipal, industrial, in Al-Wajid area which was estimated at 200 million cubic meters per year (GTZ, 2006).

Table 5　Water saving under various scenario of Al-Wajid aquifer in Saudi Arabia

Year	Scenario 1		Scenario 2		Scenario 3	
	Act 335		Act 335 + HWE		Act 335 + HWE + FR	
	Water saving (million m^3)	%	Water saving (million m^3)	%	Water saving (million m^3)	%
2009	5.7	0.5	23.8	1.9	199.2	15.8
2010	11.3	0.9	29.2	2.3	204.6	16.2
2011	17.0	1.3	34.7	2.7	210.0	16.7
2012	22.7	1.8	40.1	3.2	215.5	17.1
2013	28.3	2.5	45.6	3.6	221.0	17.5
2014	34.0	2.7	51.0	4.0	226.4	17.9
2015	39.7	3.1	56.5	4.5	232.0	18.4
Total	158.7		291.9		1,508.7	

Source: LP results.

6. Welfare impacts of various scenarios

The welfare impact of various Scenarios is estimated as the changes in producer's surplus in both Wadi Al Dowser and Najran areas. Gross margin of each crop was calculated based on total revenue and total operating cost. Farm gate prices, productivity of each irrigation techniques (traditional and modern), and total operating cost per area unit were assumed to be constant at the level of base period (2008). Table 6 presents producer surplus of main crop groups (grains, fodders, vegetables and fruits) under various scenarios for Al-Wajid aquifer which is calculated by adding up the results of both Wadi Ad Dawasir and Najran areas for simplicity.

Table 6　Changes in producer surplus under various scenarios for Al-Wajid aquifer in Saudi Arabia

Year	Scenario	Crop	Wadi Ad Dawasir (thousand SR)			Najran (thousand SR)			Al-Wajid (Total) (thousand SR)
			M	T	Total	M	T	Total	Total
2008	Actual	Grains	12,858.1	7.2	12,865.3	-1,841.2	-1,271.0	-3,112.2	9,753.1
		Fodders	378,802.7	6,769.7	385,572.4	10,894.7	10,894.7	21,789.4	407,361.8
		Vegetables	194,199.7	1,088.3	195,288.0	37,697.1	37,694.9	75,392.0	270,680.0
		Fruits	19,290.8	173,596.9	192,887.7	155,847.4	155,831.2	311,678.6	504,566.3
		Total crops	605,151.3	181,462.1	786,613.4	202,598.0	203,149.8	405,747.8	1,192,361.2
2015	1	Grains	15,866.2	5.5	15,871.7	-6,012.1	-1,799.1	-7,811.2	8,060.5
		Fodders	316,478.9	5,655.9	322,134.8	-21,697.9	6,554.5	-15,143.4	306,991.4
		Vegetables	167,844.2	942.8	168,787.0	35,803.9	31,880.7	67,684.6	236,471.6
		Fruits	16,650.2	149,608.7	166,258.9	152,810.7	133,794.6	286,605.3	452,864.2
		Total crops	516,839.5	156,212.9	673,052.4	160,904.6	170,430.7	331,335.3	1,004,387.7
	2	Grains	-14,463.0	130.1	-14,332.9	-5,551.2	-5,457.5	-11,008.7	-25,341.6
		Fodders	382,428.7	2,473.2	384,901.9	-20,906.9	11,078.4	-9,828.5	375,073.4
		Vegetables	196,255.1	-76.3	196,178.8	52,376.7	26,581.5	78,958.2	275,137.0
		Fruits	23,100.1	165,480.5	188,580.6	303,861.6	123,322.3	427,183.9	615,764.5
		Total crops	587,320.9	168,007.5	755,328.4	329,780.2	155,524.7	485,304.9	1,240,633.3
	3	Grains	-14,461.5	-6.7	-14,468.2	-5,445.6	-5,495.9	-10,941.5	-25,409.7
		Fodders	286,212.8	-2,140.5	284,072.3	5,897.1	-23,827.2	-17,930.1	266,142.2
		Vegetables	196,255.1	-76.3	196,178.8	52,376.7	26,581.5	78,958.2	275,137.0
		Fruits	23,100.1	165,480.5	188,580.6	214,378.4	123,322.3	337,700.7	526,281.3
		Total crops	491,106.5	163,257	654,363.5	267,206.6	120,580.7	387,787.3	1,042,150.8

Notes: M: stands for modern irrigation; T: stands for traditional irrigation.

Source: LP results and MOA (2008).

It is concluded from data presented in Table 6 that producer gross margin gained from cropping pattern actually prevailing in the whole agricultural area depending on Al-Wajid aquifer (Wadi Ad Dawasir and Najran) was amounted to 1,192 million Saudi Riyals. Producer surplus was distributed among Wadi Ad Dawasir and Najran in ratios 66% and 34% respectively. It is also distributed among crop groups as shown in the table.

The first scenario would lead to 15.8% reduction in producer surplus. The reduction in producer surplus varies between Wadi Ad Dawasir (14.4%) and Najran (18.3%). The second scenario would lead to 4% net increase in producer and would have distributional effect among Wadi Ad Dawasir and Najran. The producer surplus of Wadi Ad-Dawasir would suffer 4% reduction in producer surplus-while Najran would enjoy 19.6% increase in producer surplus. The third scenario would result in 12.3% reduction in producer surplus. The percentage of reduction would be high in Wadi Ad Dawasir (16.8%), and low (4.4%) in Najran areas.

7. Conclusion

The Kingdom of Saudi Arabia has implemented a series of policies since 1980 to boost agricultural production so as to ensure a higher level of food security and an improved rural standard of living. The problem is that most of the water used for irrigation is of a non-sustainable nature, both from the economical and environmental point of view. Due to massive abstractions occurring in 1980s, Al-Wajid aquifer water levels have dropped by more than 200 m. The total groundwater of Al-Wajid aquifer that can be saved is equal to 158.7 MCM for the first scenario, 211.9 MCM for the second scenario, and 15,087 MCM for the third scenario. Regarding to welfare analysis impact, it is clear that the second scenario alternative is the best alternative, since the value of the producer surplus is the highest of the two regions and also the two type schemes of modern and traditional irrigation, except the traditional irrigation of Najran region. Total value of producer surplus is SR 1,240 million**,** which increases by 4% of the real situation, 19% for the first alternative, and 16% for the third alternative. Therefore, the second scenario is recommended to be taken into account for agricultural policy guidance in the future.

References:

Adamowicz, W. L. & Horbulyk, T. M.. (1996). The role of economic instruments to resolve water quantity problems. *Canadian Journal of Agricultural Economics*, *44*, 337-344.

Berbel, J. & Gomez-Limon, J. A.. (2000). The impact of water-pricing policy in Spain: An analysis of three irrigated areas. *Agricultural Water Management*, *43*, 219-238.

Bernardo, D. & Whittlesey, N.. (1989). Factor demand in irrigated agriculture under conditions of restricted water supplies. *Economic Research Technical Bulletin No. 1765*, US Dept. of Agriculture.

Bouzit, A. M.. (1995). *Mode of lysates compartment of agriculture towards risk: The investigation of utility for organizers*. Ph.D. dissertation, ENS Cachan.

Brown, G. & Deacon, R.. (1972, June). Economic optimization of a single-cell aquifer. *Water Resource*, *8*, 557-564.

Caswell, M. F. & Wilberman, D.. (1990). The effects of well depth and land quality on the choice of irrigation technology. *American Journal of Agricultural Economics*, *68*, 798-811.

Christophe, B., Couture, S. & Favard, P.. (2001). Is the irrigation water demand really convex? *Annual Meeting of the American Agricultural Economics Association*, 1-26.

Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ). (2007). *Agricultural water demand, 6*. Kingdom of Saudi Arabia.

FAO. (1998). *Crop Evapotranspiration guidelines for computing crop requirements*. FAO irrigation and drainage paper 56, Rome, 290.

Feinerman, E. & Knapp, K. C.. (1983). Benefits from groundwater management: Magnitude, sensitivity, and distribution. *American Journal of Agricultural Economics*, *65*, 703-710.

Gisser, M. & Sanchez, D. A.. (1980). Competition versus optimal control in groundwater pumping. *Water Resource*, *16*, 638-642.

Hoyt, P. G.. (1984). *Crop water production functions and economic implication for Colorado*. US Dept. of Agriculture. Economic Research Service.

Howitt, R.. (1995). Positive mathematical programming. *American Journal of Agricultural Economics*, *77*, 329-342.

Huffaker R., Whittlesen, N., Michelsen, A., Tayor, R. & McGuckin, T.. (1998). Evaluating the effectiveness of conservation water-pricing programs. *Journal of Agricultural and Resource Economics*, *23*, 12-19.

Lixia H., Tyner, W. E., Doukkali, R. & Siam, G.. (2005). Strategic policy options to improve irrigation water allocation efficiency: Analysis on Egypt and Marocco. *Annual Meeting of American Agricultural Economics Association*, 1-37.

Lloyd, J. W.. (2002). *Groundwater vulnerability and the reuse of water with particular reference to Saudi Arabia*. White paper, Hydrogeological Research Group, School of Grological Sciences, University of Birmingham, UK.

Meinzen-Dick, R. & Rosegrant, M. W.. (1997). Water as economic good: Incentives, institutions and infrastructure. In: Kay, M., Franks, T. & Smith, L. E. D. (Eds.). *Water: Economic, management and demand*. London: Chapman Hall.

Mohammed, T. H.. (2001). Groundwater rights and legislation for sustainable development in arid regions: The case of Saudi Arabia. *Water Resources Development*, *17*(2), 227-235.

Moncur, J. E. T. & Pollock, R. L.. (1988). Scarcity rent for water: A valuation and pricing model. *Land Econ*, *64*, 62-72.

Mila, B. & Gonzales, I.. (2009). Applying stochastic goal programming: A case study on water use planning. *European Journal of Operational Research*, *196*, 1123-1129.

Ministry of Water and Electricity (MOWE). (2008). *Annual report*. Riyadh, Kingdom of Saudi Arabia.

Ministry of Agriculture (MOA). (2008). *Annual report*. Riyadh, Kingdom of Saudi Arabia.

Ministry of Agriculture (MOA). (2005). *Agricultural future plane study*. Riyadh, Kingdom of Saudi Arabia.

Montainoul, M. & Rieu, T.. (1996). Economic and management instrument of irrigation in France. *The White Coal*, *8*, 47-54.

Moore, M. R., Gollehon, N. R. & Carrey, M. B.. (1994). Multicrop production decisions in western irrigated agriculture economics: The role of water price. *American Journal of Agriculture Economics*, *76*(4), 359-374.

National Research Council. (1997). *Valuing ground water: Economic concept and approach*. Washington, D.C.: National Academy Press.

Ogg, C. W. & Gollehon, N. R.. (1989). Western irrigation response to pumping costs: A water demand analysis using climate regions. *Water Resource Research*, *25*, 767-773.

Postel, S.. (1996). Forging a sustainable water strategy. In: Brown, L. R., et al. (Eds.). *State of the world 1996*. New York: W.W. Norton & Company, 40-59.

Provencher, B.. (1995). Issues in the conjunctive use of surface water and ground water. In: Bromley, D. W. (Ed.). *The handbook of environmental economics*. Oxford: Blackwell.

Riyadh Economic Forum (REF). (2009). *Water and food security and sustainable development in Saudi Arabia*. Riyadh Chamber of Commerce and Industry, Saudi Arabia.

Safar, Al-Kahtani, Sherif, S. & Mansour, M.. (1996). Optimizing production of wheat and barely under food and water security goals in Saudi Arabia. *Journal of King Saud University*, *8*, 35-62.

Shahbaz, K., Hanjra, M. A. & MU, J.. (2009). Water management and crop production for food security in China: A review. *Agricultural Water Management*, *96*, 349-360.

Shunway, C. R.. (1973). Derived demand for irrigation water: The California aqueduct. *Southwestern Journal of Agricultural Economics*, *5*, 195-200.

Smith, L. E. D., Franks, T. & Kay, M.. (1997). Water in economics good? Theory and practice. *International Commission on Irrigation and Drainage Journal*, *46*(20), 1-13.

Whittlesley, N. K. & Huffaker, R. G.. (1995, December). Water policy issues for the twenty-first century. *American Journal of Agriculture Economics*, 1199.

Water Watch. (2006). *Historic groundwater abstractions at national scale in the Kingdom of Saudi Arabia*. Riyadh, Ministry of Water and Electricity.

Weinberg, M.. (2002). Assessing a policy grab bag: Federal water policy reform. *American Journal of Agricultural Economics*, *84*.

World Bank. (2006). *Economic analysis of irrigated agriculture: The water perspective*. Kingdom of Saudi Arabia.

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