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Irrigation Water Costs and Management Practices Among Farms in Northern Oman

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تكلفة مياه الري وأساليب الإدارة في مزارع شمال عمان

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خلاصة: يورد هذا البحث نتائج الدراسة التي أجريت على أساليب إدارة المياه في شمال عمان. فبالرغم من وجود عدد من التقارير الواصفة لذلك، إلا أن الأبحاث الكميّة التي تتناول أساليب إدارة المياه وتكلفة مياه الري محدودة جداً. لهذا السبب لا يعرف إلا القليل عن الأداء التقني والاقتصادي لأساليب الري السائدة في القطاع الزراعي. بناءً على نتائج الأبحاث المستقاة من المسح الميداني والمراقبة المباشرة لاستخدام المياه في المنطقة، فقد جرت محاولة للتعرف على تكلفة مياه الري للمزارع ومستويات الأداء لاستخدام المياه. ويحاول البحث إثبات وجود علاقة عكسية بين تكلفة المياه بالنسبة للمزارع وأسلوب إدارته لها. فعندما يكون الحصول على المياه الجوفية سهلاً وبسعر متدن، تزيد قابلية استخدام المياه بصورة أكبر وتقل كفاءة إدارتها. وينتج عن ذلك عواقب بيئية كبيرة تهدد استمرارية الإنتاج الزراعي في المنطقة. في هذه الأحوال لا بد من اللجوء إلى البدائل المتاحة للحد من سهولة الحصول على المياه الجوفية قليلة التكلفة. كما يناقش البحث البرامج الحالية ويقترح الأولويات التي تؤدي إلى تطوير الخطط الفعّالة وتأسيس البرامج الملائمة للري وإدارة المياه .

ABSTRACT : This paper reports on findings from an irrigation water management study conducted in northern Oman. Although numerous descriptive accounts exist, quantitative research on the management and costs of irrigation water has been limited. As a result, very little is understood about the technical and economic performance of dominant irrigation practices within the agricultural sector. Based on research results from farmer surveys and direct monitoring of water use in the region, an attempt is made to provide a more thorough understanding of the costs to the farmer for irrigation water and related levels of water use performance. This paper argues that there is an inverse relationship between the cost to the farmer for irrigation water and the way that the water is managed. When access to ground water is available at relatively low costs, there is a tendency for the resource to be used excessively and managed inefficiently. This, in turn, results in serious environmental consequences and threatens the sustainability of irrigated agricultural production in the region. In such cases, alternatives must be sought by which unrestricted access to low cost water can be limited. The paper also discusses existing programs and suggests priorities which will serve to facilitate effective development planning and the establishment of appropriate water management and irrigation programs.

According to official estimates, there are some 60,200 ha under cultivation in the Sultanate of Oman (MAF, 1995). Most crop producing areas receive only 100-200 mm of rainfall annually. Therefore, virtually all cultivation in Oman is dependent on irrigation. Approximately half of the cultivated area is irrigated by traditional community *falaj* systems which access ground water by gravity flow from underground galleries or surface springs on neighboring mountain slopes (Abdel Rahman and Omezzine, 1996). The remaining half is irrigated under individual farms that utilize wells and pumps to extract ground water (MAF, 1995).

Farm size generally remains small in Oman (among individual farms and in community *falaj* systems), with mean holdings of 0.5-2.5 ha (Ministry of Information, 1992; MAF, 1995). Traditional land preparation and surface irrigation methods are used to distribute water in most farms, although the government has been involved in a modernization program to encourage the use of more efficient irrigation technologies. At present, irrigation of agricultural lands accounts for 85-95% of the nation's fresh water use (George, 1996; Abdel Rahman and Abdel Majid, 1993).

In an attempt to better understand how water is used among irrigated farms, a water management field study was initiated in northern Oman in 1995. The study primarily addressed the cost to the farmer for irrigation water and related levels of on-farm water use, through means of farmer surveys and direct measurements of water use. The objective of this paper is to provide a preliminary evaluation of these costs among surveyed farms and to examine farmer irrigation performance in response to the costs. In this context,

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only those costs incurred by the farmer, in getting water from its source to the crop, are considered. Economic and water use data from 26 farms using wells and surface irrigation are examined. Data from four farmer holdings within a *falaj* system are also used for comparative purposes. Costs are given in Omani Rials (RO), with an RO/£ exchange rate of 0.6.

Methodology

SITE SELECTION: The water cost survey was conducted among farms of the Batinah, Dhahirah, and Sharqiyah regions in northern Oman, where 80% of the nation's agricultural land is found. The primary criteria for selection were to obtain representative farms from the major crop growing areas and to have as wide a range of representative water table depths as possible among the selected farms. Secondary criteria included the avoidance of absentee farmers (where the farm owner leaves management in the hands of expatriate laborers) and the identification of farmers willing to be surveyed. The focus was on selecting those with whom sufficient rapport could be established to assure greater accuracy in the acquisition of economic information. In the case of absentee farm owners, it was often found that hired farm management was reluctant to release (or ignorant of) necessary economic information. The logistical difficulties of locating and securing interviews with owners usually precluded further survey efforts. Individual farm surveys usually required 1-3 site visits of 3-6 h each. Site visits involved some field measurements of water use and the completion of the survey questionnaire. All surveys were conducted by Omani nationals trained in survey techniques and under the supervision of the authors. *Falaj* farm holdings were selected from those that are presently being evaluated in an on-going water management study in Wadi Bani Kharus (located in northern Oman).

IRRIGATION SUPPLY AND DEMAND: Most farmers cultivate a diverse number of crops on their farms. For farms surveyed, a standard crop was selected (usually alfalfa) and the amount and frequency of irrigation was assessed in order to determine seasonal or annual irrigation supply (i.e. water use). Crop area and the associated pumping rate were measured directly. Seasonal and/or annual irrigation schedules were obtained during farmer interviews. The pumping rate, crop area and irrigation schedule were then used to determine the annual volume of irrigation supply (I_s). Rainfall was not included in the supply component since it is negligible during most of the year and irrigation schedules were given by farmers for no-rain conditions. Using the monitored crop type from each site and climatological conditions for northern Oman, estimated crop water requirements were obtained from published sources (Doorenbos and Pruitt, 1977). These estimates were then applied to crop areas to obtain the annual volume of irrigation demand (I_d). Before irrigation, the static head (i.e. depth to the natural water table) was measured. When possible, the dynamic (i.e. operational) head was also measured after 1-4 h of pumping (Table 1). Among the *falaj* holdings, all irrigations were monitored directly in the field using flow measuring flumes throughout a complete season. Irrigation demand was estimated for the cultivated crop (wheat) from climatological data taken directly in the field.

FIXED COSTS: Fixed costs (FC) were derived from the principal investment and depreciation costs related to accessing water for irrigation. These include the construction of wells, storage tanks, canals and/or pipes for water conveyance, and the cost of pumps (including electrical installations for electric pumps). A straight-line depreciation was applied with a life of 20-30 y, 20 y, 10-20 y and 10-15 y respectively, for each of the above-listed investments. The life applied for these investments varied among farms depending on the method of construction or the type of equipment.

OPERATING COSTS: Monthly expenditures on diesel or electricity were obtained together with annual maintenance costs for pumps and system infrastructure. These were combined to obtain a value for annual operating costs (OC).

LABOR COSTS: Only the portion of farm labor applied to the lifting and distribution of irrigation water was considered as part of the water cost assessment. Wage rates, as well as associated housing and boarding costs, were obtained in the frequent cases of hired (expatriate) labor. For farmers who invested their own time and labor, equivalent labor wage rates for Omanis in the local vicinity were used. Wage rates were then applied to the annual labor time allotted to irrigation (derived from the farm irrigation schedule) to obtain annual labor costs (LC).

TOTAL VOLUMETRIC COST OF WATER: The total cost to the farmer for each unit of irrigation water delivered to the field is given as follows:

$$TC = \frac{(FC + OC + LC)}{I_s} \tag{1}$$

TABLE 1

Summary of cost and water use data from 26 surveyed well farms

Farm No.	Farm Size (ha)	Pump (diesel = 1) (elec. = 2)	Stastic Head (m)	Dynamic Head (m)	Pumping Rate ($m^3 \cdot hr^{-1}$)	Annual Water Use ($m^3 \cdot ha^{-1} y^{-1}$)	Surveyed Crop Type	D/S Ratio $m^3 \cdot m^{-3}$	Fixed Costs (10^{-3}OR·m^{-3})	Operating Costs (10^{-3}OR·m^{-3})	Labour Costs (10^{-3}OR·m^{-3})	Total Costs (10^{-3}OR·m^{-3})
1	2.5	2	10.1	10.3	34.7	52,009	alfalfa	0.45	3.5	1.4	3.3	8.2
2	4.2	1	10.2	13.1	43.8	24,662	alfalfa	0.95	3.7	3.6	7.7	15.0
3	2.1	1	11.3	11.9	36.0	58,705	alfalfa	0.40	3.4	2.7	2.0	8.1
4	6.3	2	12.0	12.1	30.3	29,667	alfalfa	0.79	2.0	2.4	5.5	9.9
5	3.8	2	12.9	15.3	36.5	46,351	alfalfa	0.51	7.3	0.7	7.0	15.0
6	5.9	2	13.0	16.0	70.8	55,434	alfalfa	0.42	3.0	2.1	4.4	9.5
7	2.9	2	13.0	15.6	50.4	57,582	alfalfa	0.41	3.5	4.2	8.2	15.9
8	2.1	2	13.2	--	78.3	133,308	alfalfa	0.18	2.1	0.7	3.4	6.2
9	5.2	2	13.3	14.4	50.4	50,184	alfalfa	0.47	3.7	1.8	1.2	6.7
10	3.8	1	14.9	--	59.0	37,116	peppers	0.43	3.6	5.1	4.6	13.3
11	1.9	2	15.0	--	63.4	90,024	alfalfa	0.26	2.7	0.6	5.7	9.0
12	2.9	1	15.1	--	33.4	52,452	alfalfa	0.45	1.6	4.6	8.0	14.2
13	1.3	1	17.0	18.2	23.4	73,135	alfalfa	0.32	6.9	5.5	7.7	20.1
14	1.3	1	18.0	19.3	35.3	83,310	maize	0.23	5.0	4.8	6.3	16.1
15	12.6	1	18.3	20.3	68.1	73,766	alfalfa	0.32	2.2	1.2	3.4	6.8
16	4.6	1	19.6	20.4	15.1	36,910	alfalfa	0.64	6.3	11.3	18.5	36.1
17	2.1	1	20.5	--	14.1	28,116	alfalfa	0.84	6.5	9.3	24.6	40.4
18	1.7	1	21.0	--	14.1	15,588	alfalfa	1.51	14.6	11.8	19.4	45.8
19	4.6	2	23.2	26.3	45.5	46,943	alfalfa	0.50	6.0	1.4	9.2	16.6
20	2.0	1	23.5	--	11.8	19,560	alfalfa	1.20	17.1	7.1	33.4	57.7
21	2.5	1	24.1	--	12.0	16,152	alfalfa	1.45	6.8	7.8	28.8	43.5
22	1.1	2	24.2	24.6	31.4	30,417	alfalfa	0.77	12.6	5.2	13.2	31.0
23	3.4	2	26.2	27.3	17.5	45,097	alfalfa	0.52	5.1	2.5	21.9	29.5
24	4.6	2	27.0	27.8	19.5	52,827	alfalfa	0.44	3.9	1.0	19.7	24.6
25	1.7	2	27.4	28.5	29.2	23,987	alfalfa	0.98	10.1	3.1	11.1	24.3
26	1.1	1	29.5	30.5	19.9	20,863	alfalfa	1.13	13.0	20.6	21.3	54.9
MEAN	3.4	--	18.2	--	36.2	48,237	-	0.64	6.0	4.7	11.5	22.2

where, TC = total cost of water, RO·m^{-3}
FC = fixed costs, RO·$ha^{-1}y^{-1}$
OC = operating costs, RO·$ha^{-1}y^{-1}$
LC = labor costs, RO·$ha^{-1}y^{-1}$
I_s = irrigation supply, $m^{-3} \cdot ha^{-1}y^{-1}$

The variable total cost describes the actual cost which the farmer incurs, as a function of observed irrigation supply. Total cost (TC), and its individual components, were not assessed for individual *falaj* holdings. Rather, overall estimates were obtained from water share prices and maintenance requirements among the *aflaj* (*Aflaj* is the plural rendering in Arabic, while *falaj* is the singular) of Wadi Bani Kharus, as well as from irrigation labor times monitored within selected holdings. The assumption is also made in this study that during a typical irrigation season the need or incentive to recuperate invested capital has a more critical and immediate effect on farmer performance than does the forgone opportunity of the investment (Ellis, 1988). For this reason, opportunity costs are not included in the principal estimate of water costs (Equation 1) in this study.

IRRIGATION DEMAND/SUPPLY RATIO: A standard variable used to describe irrigation performance is one which relates crop water demand to the actual amount of water supplied to the field (Burman *et al*, 1983). This demand/supply ratio (D/S) is given as:

$$D/S = \frac{I_d}{I_s} \qquad (2)$$

where, I_d = estimated crop water demand at the field level, $m^3 \cdot ha^{-1}y^{-1}$

A minimum D/S value of 0.6 (or 60%) is often included in the design of most surface irrigation systems to accommodate for crop water needs and anticipated losses. Demand/Supply values below this would normally be considered unacceptable, and indicate that significant over irrigation is occurring and excess water is being lost below the crop root zone. Values above 1.0 may indicate that maximum potential crop yields are not being attained.

Results and Discussion

FIELD STUDY: The 26 surveyed farms range in size from 1.3-12.6 ha, with a mean of 3.4 ha. A variety of

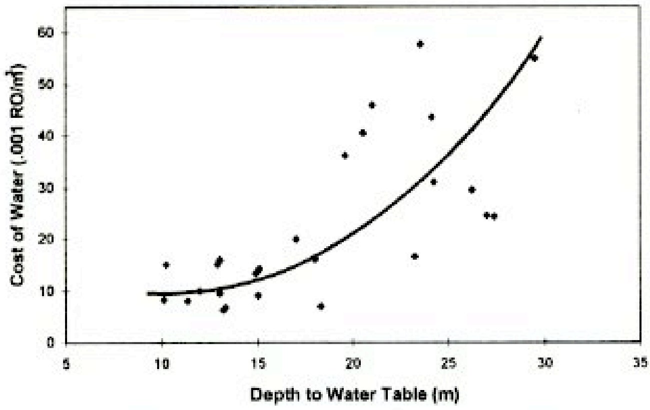

Figure 1. Cost of irrigation water and depth to the water table

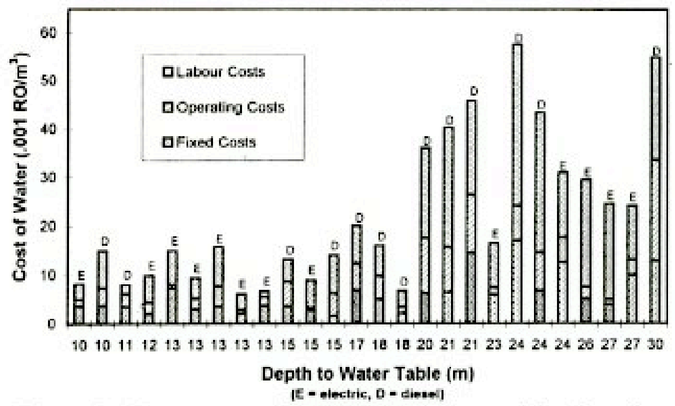

Figure 2. Farmer costs for irrigation water and depth to the water table

three or more crops are cultivated in all farms, with the majority using only one well and pump. Open wells and tube-wells are equally common. Half of the surveyed farms use diesel powered pumps, the remaining use electric-powered pumps. The difference in static and dynamic heads draw-down ranges from 0.1-3.1 m, with a mean difference of 1.4 m. All farms employ gravity flow and surface irrigation for field water distribution. The primary results of the water cost survey are compiled in Table 1.

Figure 1 demonstrates the volumetric cost of irrigation water as a function of the depth to the water table. In this case, the static head is used instead of the dynamic head since the variation between the two is not excessive for the surveyed farms. Furthermore, use of the static head facilitates comparisons with geographic regions in northern Oman which are generally characterized by different depths to the ground water table (primarily, coastal aquifer regions versus those in the interior of the country). The trend of increasing water cost with depth is typical and is influenced by several factors. Fixed costs increase with depth due to the increased cost of well development. The pump size (and therefore the cost) may also increase but is usually secondary to the effect of depth on well development. Operating costs may increase due to the increased energy requirement for lifting water from greater depths. Some farmers with deeper wells, however, opt to pump at lower flow rates in order to minimize costs. When flow rates are lower, farmers must increase field labor input for field water distribution. Most small farms in Oman are operated in areas with water table depths between 10 and 15 m. As seen in Figure 2, the cost of water tends to increase significantly beyond 15 m.

The components of TC for each farm are given in Figure 2. In general, cost components among farms are highly variable up to about 15 m, after which there is an evident tendency for each to increase with depth. The increase in operating and fixed cost components for farms beyond 15 m may not be as significant among larger farms as it is with those having smaller areas. The relative proportions of each cost component fluctuate from farm to farm largely as a function of the farmer's choice of equipment and system management practice. No significant difference is noted between the use of electric versus diesel pumping. Beyond 17-20 m, increases in labor and fixed costs are the most notable.

As volumetric costs and water table depth, increase, farmers tend to use lower pumping rates during irrigation, as demonstrated in Figure 3. With lower rates, however, farmers must increase the level of field labor input in order to assure proper and complete field water distribution among basins and/or furrows. Some farmers having extremely low pumping rates have constructed storage tanks, which are filled and the water subsequently released at a higher application rate to the field. Figure 4 demonstrates the relationship between operational flow rates and labor input for field water distribution. This tendency among small irrigated and labor-intensive farms to substitute labor for water and vice-versa has been documented in other countries (Norman and Walter, 1997). Often where there is

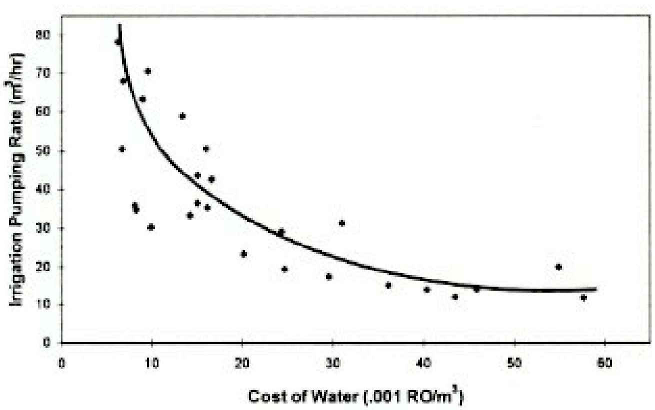

Figure 3. Irrigation pumping rate and cost of irrigation

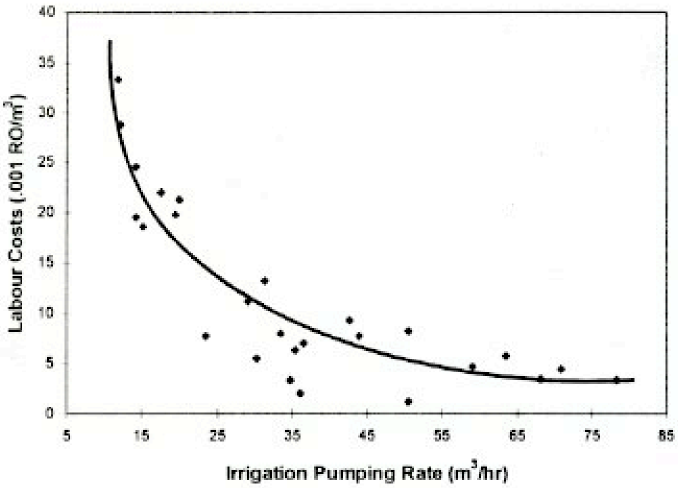

Figure 4. Water distribution labor costs and irrigation pumping rate

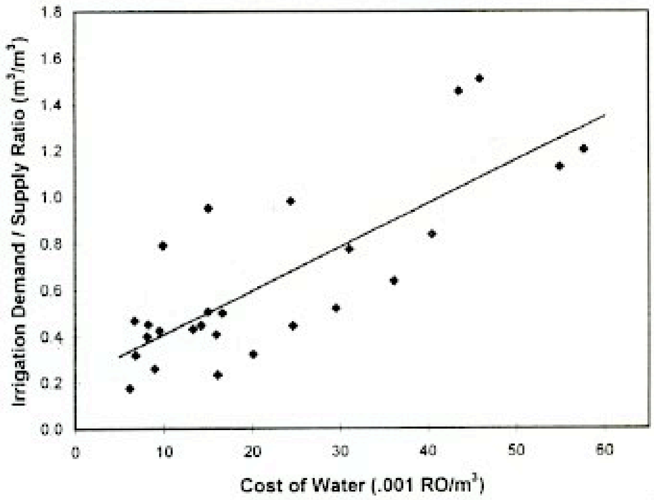

Figure 6. Irrigation demand/supply ratio (D/S) and cost of irrigation water. (The slope of linear regression line is statistically greater than zero)

unrestricted access to low-cost water, farmers will exchange more valuable labor, with higher operational flow rates. The usual result is that greater volumes of water are applied incurring an increase in losses (Norman, 1991; Young, 1986). Among the studied farms, an increase in water use is evident as volumetric costs to the farmer decrease (Figure 5). When the cost of water is compared to the D/S ratio, there is a high variability in water use among farmers (Figure 6). However, it also becomes evident that there is a tendency to utilize water less efficiently as water costs decrease. The slope of the linear regression line in Figure 6 is statistically greater than zero. In general, small farms of this size, in which water application rates and schedules are entirely in the hands of the farmer, should be able to operate at D/S ratios of at least 0.6-0.8. Of the surveyed farms, 70% are irrigated at D/S ratios below this level (i.e. they are irrigated in excess of farm crop need). In a water metering project initiated in recent years by the Ministry of Water Resources (MWR) within 27 farms,

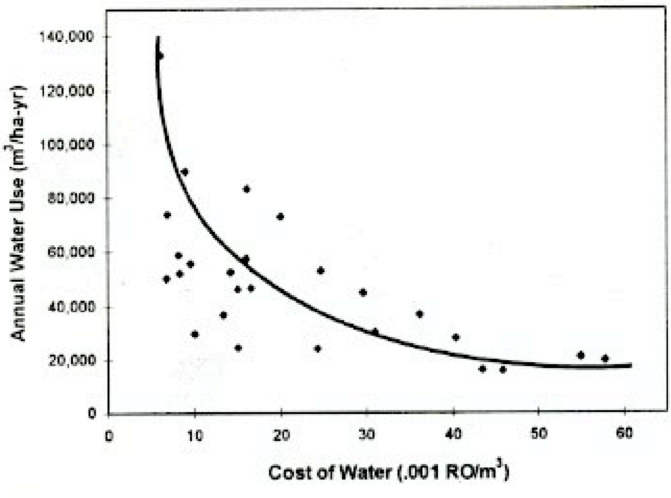

Figure 5. Annual irrigation water use and cost of irrigation water

it was found that 55% were irrigated at D/S ratios of 50% or less (Rout, 1995).

As recently as 20-25 years ago, many of these farmers were still using animal traction methods to lift water. Such methods incur very high volumetric costs to the farmer (Norman and Walter, 1997). More fortunate farmers at the time may have operated small diesel pumps, but at purchase and operating costs well in excess of today's equivalent costs. As Oman's economy developed and greater access to pumps and fuel came about, traditional farmers having well systems reduced water costs by switching to diesel and electric-powered pumping. In this way farmers were able to increase the margin between water costs and returns to production. As relative affluence continued to increase, many new farmers and wells began to appear as access to water became less costly. Consequently, an increasing percentage of high water- consuming crops began to appear on farms and the total area under irrigation from wells began to expand area under irrigation from wells began to expand rapidly, with the demand for water soon exceeding aquifer recharge capacity in many areas. A large number of farm owners today are simply absentee managers whose primary income is from employment or business in urban communities (Rout, 1995; Allan, 1995). At the same time as these changes came about, the efficiency with which water was used probably began to decline as well, based on the trend in Figure 6. Results from similar studies among small farms in arid regions of West Africa compare well with Figure 5 and confirm this trend as one moves from traditional water-lift systems to fuel-powered pump systems. It was shown that farmers employing traditional, labor-intensive methods to lift water incur costs of about 0.100 RO·m^{-3} of water with D/S ratios of 0.95-1.10.. Small, portable fuel-powered pump systems incur costs of about 0.055 RO·m^{-3} and use water at D/S ratios of about 0.70-0.90

(Norman and Walter, 1993; Norman and Walter, 1997).

Although many *aflaj* in Oman have suffered from declining flows as a result of declining water tables, on-farm water management within these systems has changed very little in comparison to well systems. *Falaj* systems are managed by the community, water shares may be purchased by individuals when available, and field water distribution is done in much the same way as it was in past centuries (Wilkinson, 1977). As previously mentioned, traditional irrigation systems are often characterized by high volumetric water costs to the farmer and correspondingly high levels of water use performance. Among *falaj* systems in Wadi Bani Kharus, the cost of water in 1995 and 1996 was around 0.10-0.15 $RO{\cdot}m^{-3}$. This figure can be derived either from local water share rental rates, or from local water share purchase prices applied over a 20-40 y farming life of the share holder. The components of fixed costs (i.e. initial water share purchase), operating costs (i.e. system maintenance) and labor costs for field water distribution are approximately 50%, 20% and 30%, respectively, of the total volumetric water cost. Among the four farm holdings monitored in one of these *falaj* systems, seasonal D/S values ranged from 0.70-1.10 with a mean of 0.93. These cost and D/S values can be compared with the well and pump systems in Figure 6.

The relatively high water costs among the *aflaj*, coupled with returns to production that have changed little over the years, account for the declining state of many systems across the Sultanate. Many of the youth in rural communities are forgoing the option of continuing the maintenance of their family *falaj* holdings for the greater returns to investments and labor which can now be found elsewhere. As is now found among many farms with wells, increasing numbers of *falaj* holdings are managed by hired, low-cost expatriate labor. This crisis facing *falaj* systems and their communities is discussed in detail by Dutton (1995). In an effort to reverse declining flows among *aflaj*, the Ministry of Agriculture and Fisheries (MAF) and Ministry of Water Resources (MWR) have financed rehabilitative measures among nearly a third of Oman's 3,000-4,000 systems. Most of these efforts have involved infrastructural improvements to underground galleries and delivery channels. In additon, the MAF provided some 117 wells to augment flow among some of the lowest yielding *aflaj* (MAF, 1995).

THE SEARCH FOR SOLUTIONS: Two problems facing irrigated production among farms with wells in Oman should perhaps be distinguished at this point. One is the overuse of shallow aquifers (i.e. extraction rates which presently exceed those of natural recharge). The second is that of excessive irrigation doses where irrigation supply is in unnecessary excess of true crop demand (i.e. D/S ratios significantly less than 1.0). The first problem largely occurs in agricultural areas when the annual crop demand for water, a function of cultivated area and crop type, exceeds annual recharge of the aquifers from which irrigation water is withdrawn. The second, while inefficient and costly to the farmer, does not necessarily contribute significantly to net aquifer depletion. While some of the excess irrigation that occurs will be lost to evaporation, the greater portion may return to the aquifer in the form of excess drainage below the active crop root zone. This is particularly true for farms with D/S ratios of 0.50 or less (Figure 6). Thus, an increase in the efficiency of on-farm use may not necessarily result in a proportional reduction of net ground water extraction.

In 1993, the Directorate General of Agricultural Research completed an integrated study of the South Batinah coastal region, one of Oman's more important agricultural areas, of which irrigation and water use was a component (MAF, 1993). It was reported that not only would continued expansion of agricultural lands have to cease, but also existing farm land would have to be reduced by 19% to achieve an equilibrium in ground water recharge. The Directorate went on to propose a two-step measure. First, as a measure to reduce continued expansion, the government would buy back from land owners some 5,100 ha presently fenced in preparation for cultivation, but not yet cultivated. Secondly, the government would buy back an additional 4,900 ha of farm land most affected by salinity, a result of saltwater intrusion into depleted aquifers, and/or owned by absentee farmers who have another source of income. The government has already imposed strict limitations on the placement of new wells, through the implementation of a well permit program overseen by the MWR. The Directorate's report also proposed that water metering be used to control water consumption and that limitations should be placed on the percentage of land cultivated in high water-consuming crops within each farm. Although insightful and perhaps an effective solution for the water resource problem, a proposal of this nature carries with it significant social, financial and logistical ramifications. To date, it has not been translated into an existing program or policy.

The water metering pilot project sponsored by the MWR represents one of the government's attempts to find solutions. As part of the larger objective of assessing alternatives for demand management of irrigation water, this project has been evaluating the use of meters as a potential control mechanism for water conservation in the Batinah region. The installation of a meter would increase volumetric water costs at each farm by about 0.001 $RO{\cdot}m^{-3}$, if farmers were to incur installation costs (Rout, 1995). But this does not include government costs for meter reading and enforcing compliance. If a demand management program using meters was adopted, it could serve to restrict the use of what is otherwise relatively low-cost water. Without such a program, excessive on-farm irrigation will likely continue unabated.

The present MAF irrigation modernization program, in operation since 1991 with a budget 12 million RO, has provided subsidized upgrading from surface to pressurized systems for nearly 2,000 farms. Government subsidies for this program amount to 75% for farms of less than 4.2 ha, 50% for farms of 4.2 to 21 ha, and 30% for farms greater than 21 ha. If a farmer, on a farm with wells, was to incur the entire expense of upgrading his irrigation system, this would result in an increase of about 0.002-0.003 $RO \cdot m^{-3}$ in his total water costs (i.e. a 12% increase) (FAO, 1992). This is based on an FAO estimate of 126 $RO \cdot ha^{-1} yr^{-1}$ (in 1992 prices) for trickle and bubbler systems in Oman, allowing for inflation, and assuming an annual water use of 50,000-75,000 $m^{-3} \cdot ha^{-1}$ (FAO, 1992). As with water metering, an increase in the number of farms using more efficient irrigation technologies will not necessarily guarantee that net aquifer depletion will cease, as long as the same total area of farm land continues to be cultivated in affected areas. However, if such effort is coupled with a metering program and limitations on access to water are imposed, upgrading farm irrigation technologies could be used to effectively increase net returns by increasing productivity per unit volume of water used.

As long as unrestricted access to ground water at costs of around 0.010-0.020 $RO \cdot m^{-3}$ remain, excessive use of the resource will likely continue. While increased net production levels per unit area of land or unit volume of water should continue to be sought, such increases will not necessarily serve to lessen the critical depletion of fresh water aquifers. As is found throughout the Gulf area, agricultural products can often be produced outside Oman and imported at a considerably lower cost than having to produce them locally. Ultimately, as Allan (1995) argues, an understanding of the political economy of world food production and trading systems in food, and national participation in world food markets, will be key elements in bringing about a healthy economic and environmental equilibrium in irrigated agricultural production in Oman.

Conclusions

Data from this study indicate that there is an inverse relationship between volumetric costs and use for irrigation water. The cost of water evidently affects how farmers use the resource. Given today's relatively low water costs, there is a tendency for irrigation water to be used in greater quantities and in excess of crop need. When costs are higher, there appears to be the necessary incentive to manage water more carefully. In order to be environmentally sustainable some regulation of extraction or use will likely be necessary in the future.

The data also indicate that when the necessary incentives do exist, farmers are able to manage their water efficiently. This is true even when using traditional surface irrigation methods, which are often deemed inefficient by irrigation and development specialists. Programs aimed at ameliorating on-farm water management would perhaps be more cost-effective if measures that limit access to low-cost water were prioritized first. Programs aimed at upgrading farm irrigation technologies would serve as viable follow-up or secondary measures.

Finally, measures such as the implementation of control mechanisms and the upgrading of farm irrigation technologies, that can serve to limit overall farm water use and increase irrigation efficiencies, may not necessarily serve to reduce ground water deficits in a significant way. Until viable solutions to this more serious problem are found, the future of irrigated agricultural production will remain threatened despite all other efforts.

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