Irrigation and Drainage

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Journal:	*Irrigation and Drainage*
Manuscript ID:	IRD-10-0107
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	20-Sep-2010
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Keywords:	groundwater aquifer life, reducing losses, water savings, irrigation efficiency, Yemen

TO WHAT EXTENT DO IMPROVED IRRIGATION TECHNOLOGIES EXTEND AQUIFER LIFE?[1]

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Abstract At least until 2008, donor policy in Yemen supported improved irrigation technology as the primary means to reduce the rate of over-exploitation of Yemen's aquifers. In this paper the impact of such investments on cumulative water abstraction, water savings and the life of an aquifer are assessed, and found to have limited potential to extend aquifer life. The returns to such investments are highest in areas with significant remaining resources, and are not attractive in the most severely stressed areas. The analysis also shows that improved irrigation technologies increase the profitability of pumping for the farmer, exacerbating problems of over-abstraction. Finally, it is shown that water savings depend on the hydro-geological situation. The implications of these findings for policy are discussed on the basis of the case of Yemen—an exceptionally water-short country where most of the aquifers in groundwater-irrigated areas are severely over drafted.

Key words: groundwater aquifer life; reducing losses; water savings; irrigation efficiency; Yemen

1. Introduction

Subsidies for improved irrigation technologies are currently a substantial component of donor policy in a number of countries. Donor projects subsidize as much as 70% of the capital costs of investments in drip under the groundwater and soil conservation project (World Bank, 2004) in Yemen. Such programs are usually promoted on the basis of water savings, and extended the aquifer life.

Yemen is an extremely water-short country, ranking lowest in per capita availability. Only 200 cubic meters of water is available per capita per year in Yemen, well below the international water scarcity threshold of 1,700 cubic metres (FAO, 2007). The Sana'a basin, where rainfall rarely exceeds 25mm/yr depends primarily on groundwater for domestic, agricultural and industrial uses. Historically, water was drawn from shallow aquifers that were replenished by rainfall and lateral inflows from the surrounding mountains. From the 1970s onwards, however, the introduction of tubewells and submersible pumps allowed the exploitation of even deeper sources of water, largely putting the shallow wells out of service, and eventually drawing on deep, confined aquifers that are either fossil water or only slowly replenished from lateral inflows.

[1] This paper has been written in the framework of a study "Options for Changing the Economic Incentive Structures for Groundwater Extraction in Yemen" (Hellegers et al., 2008) funded by the National Water Resources Authority'.

Predicting how aquifers will respond to over-exploitation is very difficult, specialized, and frequently inexact science. The JICA report (2007) anticipates depletion of Sana'a's basin aquifers within 15 years even with improved irrigation technologies. Such estimates, which relate current levels of abstraction to total recoverable reserves are a simplification: aquifers are rarely homogeneous and of uniform thickness; some small areas may receive relatively abundant recharge while most areas get very little; and clearly abstraction will be possible "forever" at the rate that recharge occurs. Nevertheless the concept of overdraft and aquifer life are useful indicators of the sustainability of water use, and the extent of the changes to current consumption patterns that are required for long-term sustainability, and these provide the framework for the analysis presented here. Within this simplified framework, the objective of this paper is to assess the extent to which modern irrigation technology can be expected to extend the life of an aquifer; to consider how areas with varying remaining reserves should be prioritized; and to point to additional considerations that come into play when irrigation technology is improved.

The paper is in five parts. Following this introduction, the second section demonstrates the impact of improved irrigation technology on cumulative water abstraction and consequently on the life of an aquifer assuming a simplified aquifer, based on the "Joint Vision" statement prepared by donors to Yemen's water sector (2007). In the third section the implications of this analysis are further refined, focusing on the kind of areas where investments should be concentrated, situations where claimed savings may not be fully realised, and the impact on farmer incentives (profitability of pumping) of the new technologies. In the fourth section it is shown how the rate of return of investments in improved irrigation technology varies with aquifer life in Yemen. Finally some concluding remarks are drawn.

2. The impact of improved irrigation technology on extension of aquifer life

It is assumed, based on estimates in projects documents and the donors' *Joint Vision* statement (2007), that losses from irrigation systems in the Sana'a basin can be reduced from 65% to 40%. It is further assumed that once the technology is installed, it is properly utilised, that farmers immediately reduce deliveries to fields, farmers do not expand their irrigated area, and that maintenance is adequate to keep the new technology fully functional and performing to the design potential.

To trace the impact of this program, the analysis is presented in terms of a single unit of pumping. This will result in 0.35 units of crop evapotranspiration (ET) if losses are 65%. With the improved irrigation technology and losses reduced to 40%, the same level of crop ET will require only 0.58 units of pumping (0.35/0.6=0.58). These basic data are summarized in Table 1—pumping is reduced while crop ET is maintained constant, as foreseen in the *Joint Vision*.

Table 1: Losses, ET and water use

	Now	Potential
Losses %	65	40
Beneficial use	0.35	0.35
Water use (pumping)	1.00	0.58

Table 2 traces the impact of investment programs introducing the improved technology, on the basis of a 10 year investment program (i.e. it will take ten years to cover the entire irrigated area with the new technology), and a slower, 20 year investment program.

Table 2: Annual Abstraction for 10 and 20 year investment programs.

Year	10 year	20 year
1	1.00	1.00
2	0.96	0.98
3	0.92	0.96
4	0.88	0.94
5	0.83	0.92
6	0.79	0.90
7	0.75	0.88
8	0.71	0.85
9	0.67	0.83
10	0.63	0.81
11	0.58	0.79
12	0.58	0.77
13	0.58	0.75
14	0.58	0.73
15	0.58	0.71
16	0.58	0.69
17	0.58	0.67
18	0.58	0.65
19	0.58	0.63
20	0.58	0.60
21	0.58	0.58

These data are most easily understood by first looking at the year when implementation is complete (year 11 for the ten year program, year 21 for the 20 year program) and noting that pumping in each case is at the reduced level of 0.58 compared to 1 in the first year. Interim years are linear interpolations between these two points, reflecting steady, continuous project implementation and impact.

Figure 1 plots the cumulative abstraction (assuming there are no return flows from excess irrigation deliveries) that results from three scenarios: first, if no changes are made—the "Do nothing" scenario when abstraction will continue at 1 unit per year; second, the "10-year investment program" is followed, cumulative abstractions will (for example) in year 3 be equal to 2.88 (1+0.96+0.92). The cumulative abstraction for the "20-year program" is derived similarly. The graph shows a progressive divergence between the "Do nothing" scenario and the 10- and 20-year programs, with the 10-year program producing larger, quicker divergence.

Estimates of the period of time that the Sana'a aquifer can support existing levels of pumping are uncertain, but 10 years is sometimes suggested. An interesting observation from this simple analysis is that cumulative pumping for the "20-year investment program" will reach the 10 year "Do nothing" level around year 11, and even the "10-year investment" program only extends the aquifer life by about three years.

Clearly this analysis is simplistic, though the conclusions are rather similar to the recent JICA report (2007), which anticipates depletion of Sana'a's aquifers within 15 years even with improved irrigation technologies.

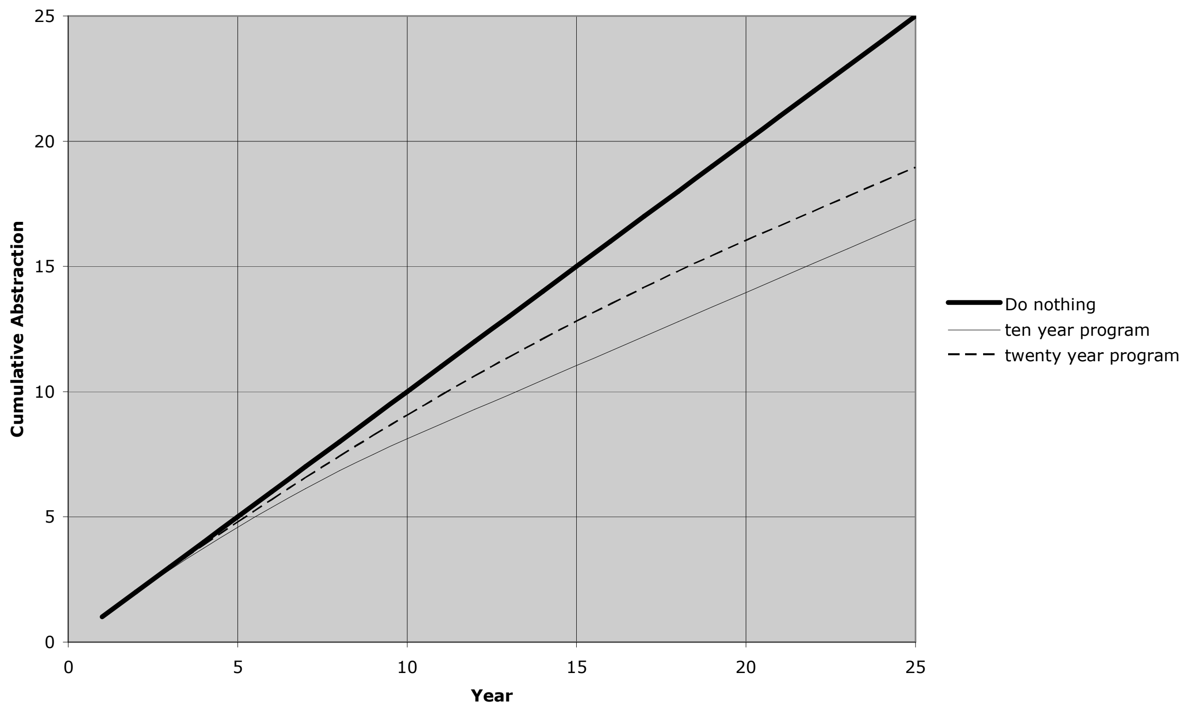

Figure 1. Cumulative abstraction over time from three scenarios

3. Implications of the analysis

Priority areas for investment

Two quite separate considerations should govern the selection of areas for program implementation.

First, as already noted the aquifer is not in fact uniform; some areas have already been exhausted, some are already close to exhaustion, while other areas still have relatively plentiful supplies remaining. A presumption might be, since the entire investment program is aimed at addressing severe scarcity and over-exploitation, that priority should be given to those areas most at risk, but the implication of the analysis above is that those who are most at risk will benefit little from investments of several thousands of dollars per hectare because water will run out in just a few years with or without the investment.

Second, the analysis so far has been based on the assumption that any water supplied to the crop in excess of its needs is "lost", so that an increase in efficiency from 35% to 60% implies that the excess water previously applied has been lost and is no longer available to the system. The extent to which this is true is best understood by defining more clearly the terminology.

Perry (2007) has set out terminology based on the use of "fractions". The adopted terms avoid the word "efficiency" (which is often ill-defined and leads to misleading conclusions), relying instead on the hydrological framework that defines component flows. The terms are:

1. *Water use*: any deliberate application of water to any specified purpose, comprising:

2.1 *Consumed fraction*: Water evaporated and transpirated, comprising:
- 2.1.1 *Beneficial consumed fraction*: Water consumed for the intended purpose
- 2.1.2 *Non-beneficial consumed fraction*: Other evaporation or transpiration

2.2 *Non-consumed fraction:* Water not lost to the atmosphere, comprising:
- 2.2.1 *Recoverable fraction*: Water that can be recovered and re-used
- 2.2.2 *Non-recoverable fraction*: Water that cannot be economically recovered

The benefits of this framework include: identification of consumptive uses; clarity in identifying how water can most effectively be saved (by reducing *non-beneficial* consumption and the *non-recoverable* fraction); and making sure that the accounts are done properly[2].

Situations where claimed savings may not be fully realized

For example, the climate may be such that the crop consumes 5mm/day in transpiration. To meet this need, the farmer may supply 50mm every week. In fractions terminology, the *water use* of 50mm would lead to 35mm (7 days * 5mm/day) of *beneficial consumption* leaving some 15mm unaccounted for. To complete the accounts, we need to know whether the

[2] No data are available to separate beneficial transpiration from non-beneficial evaporation; however, much of the irrigation is of "closed canopy" qat, where evaporation losses are likely to be low.

additional water went to *non-beneficial consumption*, to the *non-recoverable fraction*, or to the *recoverable fraction*. In general, in situations where there is an exploited, relatively shallow aquifer in the area, percolation losses are largely recoverable. In assessing this, it is important to consider water quality: if the local soil or underlying aquifer is saline, percolation water will pick up salts and may not be reusable. Similarly runoff that goes back to a water system upstream of irrigation or other intakes will be *recoverable*, while drainage that go to the sea or a salt sink is *non-recoverable*. Recovery will often require additional energy inputs—a real cost—but our primary interest here is water, not energy.

The main impact of improved irrigation technology is thus a reduction in *water use*. The extent to which this reduction translates into *water savings* that will be available for use elsewhere depends, however, entirely on the hydro-geological situation, which determines whether excess deliveries are *recoverable* or *non-recoverable*.

A local analysis is always required to determine the extent of water savings in the specific hydro-geological context is needed to justify investments in improved irrigation technology.

In the case of Yemen, these considerations suggest that priority for investment in improved technologies should be in areas with considerable remaining reserves, where there is no shallow aquifer, and percolation is not readily recoverable.

Impact of improved technology on farmer incentives

To understand possible outcomes beyond the analysis presented so far—which indicates that the impact on aquifer life may be rather limited—it is essential to understand how farm-level incentives are affected by the new technology. With the new technology, based on the assumptions set out in Table 1, the farmer only needs to pump 58% as much water to achieve the same level of crop production as with the traditional technology. This saving in energy costs of 42% will be welcome—but the farmer also has the far more attractive option of maintaining the same level of pumping and increasing the irrigated area by some 70% (1/0.58)! For the farmer, given that the energy costs of pumping are not high in relation to the productivity of water, the main potential gain will be to increase the irrigated area, increase crop consumption, and thus—to the extent that any of the former excess water deliveries were recoverable—to increase net abstractions.

The project designers were mindful of this possibility and included measures to control the expansion of irrigated area. However, given that farmers routinely share wells, and buy, sell and trade sell water, this would be hard to police. In any event, the reduced energy demands for pumping with new technologies will make pumping from even deeper wells profitable.

In Hellegers et al. (2009) options for changing the incentive structure to reduce unsustainable groundwater consumption in Yemen are evaluated, including subsidies on improved irrigation technology. In that paper it is concluded that priority should not be given to subsidizing improved irrigation technology—which will expand through private financing anyway because it is financially profitable for farmers. Leaving aside the question of whether water is saved or not, it is accepted that improved irrigation technology delivers more water to the field per unit of water pumped—and thus delivers a private benefit to the farmer. . Paradoxically, then, improved irrigation technology makes pumping more profitable for the farmer, so that the current situation—where water abstractions are largely uncontrolled—becomes even more difficult to manage.

From the perspective of a farmer who has either a limited entitlement to surface water or limited ability to pump from an aquifer, the incentive to improve irrigation technology is clear. The farmer will be able to increase the *beneficial consumed fraction*—which is the water that his crops consume—and hence increase production and income. For every unit of water available to his farm, he can grow more crops. If the farmer has limited land resources and cannot sell water to others, consumption will remain more or less constant; however, if the option exists to intensify irrigation, then improved irrigation technology facilitates this and consumption is likely to increase. Such a scenario is well documented in parts of the North China Plain (IWMI, 2006). Over recent decades, gross water abstraction has *declined* as irrigation technology has improved; the irrigated area has *expanded*—thus increasing consumptive use so that the rate of decline of the underlying aquifer has increased.

This increase in demand will be more severe if the farmer is able to increase crop yields by more precise and timely irrigation—further increasing the profitability of pumping—though generally such increases in yield are associated with increased crop consumption (Perry et al., 2009), allowing the farmer to increase net abstraction without increasing the area irrigated..

4. The rate of return on investments in improved irrigation technology

The internal rate of return (IRR) is commonly used to evaluate the profitability of investments. The higher a project's internal rate of return, the more desirable it is to undertake. The IRR is the discount rate at which the net present value of costs (negative cash flows) of the investment equals the net present value of the benefits (positive cash flows) of the investment.

To show how the IRR on investments in improved irrigation technology varies with aquifer life in Yemen insight is required in the following information on costs and benefits:

- Investment in improved irrigation technology of US$3,000/ha in year 1 (World Bank, 2003)

- Postponed expenditure on power: from year 1 until the current estimated life of the aquifer power will be saved (if the same area is irrigated with less water applied), which will be spend during the extended life of the aquifer to pump water. The diesel costs to pump groundwater in the Sana'a Basin from a depth of 180 m are US$0.11/m^3 (Hellegers et al., 2008).

- During the extended lifetime of the aquifer there will be benefits from irrigation water. The economic value of agricultural water consumed in the Sana'a basin is estimated at US$0.26/m^3 by the World Bank (2003) and US$0.95/m^3 by Hellegers et al. (2009). An average value of US$0.60/m^3 of net irrigation water consumed is therefore assumed in this analysis. Reductions in water use in the Sana'a basin are valued by the World Bank (2003) according to their expected future use. As water gets scarcer, more will probably be reserved for domestic and industrial (higher value) usage. Since the desalination option is not available for Sana'a at reasonable cost, a sensitivity analysis for a value of US$0.80/m^3 will be presented as well. Though these are extremely high values for water by international standards. The value of water for irrigated agriculture often varies between US$0.50/m^3 and US$0.15/m^3. A sensitivity analysis for a lower value of US$0.30/m^3 will therefore be presented as well.

It is assumed, based on estimates in project documents (a.o. World Bank, 2003), that water use can be reduced by 7 MCM per year through improved irrigation on 4,000 ha in the Sana'a Basin. This means an annual reduction in water use of 1,750 m^3/ha. The initial capital costs of investments to achieve this are US$3,000/ha. Annual costs of maintaining the infrastructure are assumed to be unchanged.

Based on a reduction in water use of 1,750 m^3/ha, then pumping–based on the figures presented in Table 1—is 4,187 m^3/ha before investment and 2,428 m^3/ha after investment in improved irrigation technology. This allows for constant crop consumption (ET) of about 1,450 m^3/ha. (see Table 3)..

Table 3: Losses, water consumption and water use (m^3/ha)

	Before	After	Water use saving
Losses	2,721	971	1,750
Beneficial use	1,465	1,457	
Water use (pumping)	4,187	2,428	

Table 4 shows the accumulated water balance and the costs and (net) benefits for an aquifer with a 5 year lifetime at current abstraction rates. In years 1-5, water "accumulates" annually in the aquifer with 1,750 m^3, because withdrawals are reduced. This is drawn down by 2,428 m^3 annually in years 6-9 (in year 9 there is not enough for full irrigation).

Table 4: Water balance and annual costs and (net) benefits of an aquifer with a 5 year lifetime

Year	Water balance (m^3)	Investment costs (US$)	Power savings and costs (US$)	Irrigation benefits(US$)	Annual net benefits(US$)
1	1,750	-3,000	193		-2807
2	3,500		193		193
3	5,250		193		193
4	7,000		193		193
5	8,750		193		193
6	6,322		-267	874	607
7	3,894		-267	874	607
8	1,465		-267	874	607
9	0		-161	528	366

There are savings in power during the first five years of US$193 (US$0.11/m^3 * 1,750 m^3) annually; whereas there are annually incremental cost of US$267 (US$0.11/m^3 * 2,428 m^3) thereafter (except in year 9). No adjustments are made for the incremental power required as a result of the aquifer declining. The irrigation benefits are US$874 (US$0.60/m^3 * 1,457 m^3) annually in the years 6-8. The IRR of the annual net benefits of an aquifer with a life of 5 year is 1.0 %, which is positive, but low compared to aquifers with a longer estimated lifetime, and far lower than usually required to justify investments.

Figure 2 shows the rate of return as a function of aquifer life. Aquifers with a remaining lifetime of less than 5 years have a negative IRR, which means that for those that are most at risk it is not worth investing several thousands of dollars per hectare in improved irrigation technology. It shows that the IRR increases with aquifer lifetime at a decreasing rate. For an aquifer with a 7 year lifetime the IRR is 5.8 % and for an aquifer with a 10 year lifetime the IRR is 8.0 %. This means that such investments should be concentrated in areas with aquifers that still have relatively plentiful supplies remaining instead of in areas with the shortest remaining lifetime as in those areas the rate of return on such investments is low.

It is important to note that the IRR is very sensitive to the assumed value of water. If the value of water is US$0.8/$m^3$ (instead of US$0.6/$m^3$) the IRR is 6.7 % for an aquifer with a 5 year current estimated lifetime and 10.8 % for an aquifer with a 10 year current estimated lifetime. If the value of water is US$0.3/$m^3$ (instead of US$0.6/$m^3$) the IRR is 0.6% for an aquifer with a 10 year current estimated lifetime.

Figure 2: Internal Rate of Return as a function of aquifer life for various values of water

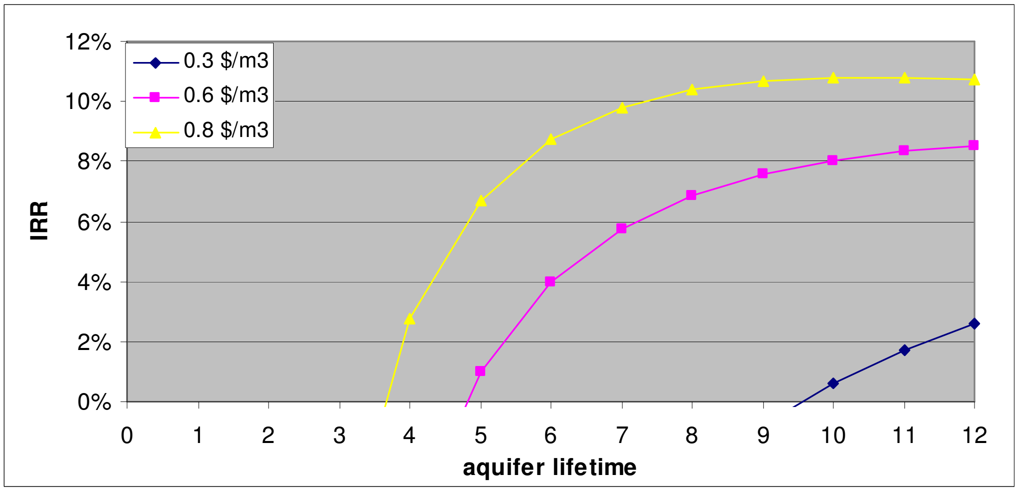

Table 4 shows that the extended lifetime of the aquifer is about 3.6 years for the aquifer with a current estimated lifetime of 5 years, whereas Figure 1 shows a much more modest extension. This is due to the assumed 10-year gradual investment program in section 2. Such gradual programs make investments even less attractive (as the IRR is lower).

This demonstration that the aquifer life can be significantly increased by new technology (from 5 years to more than eight years) may seem at variance with the information presented in Figure 1, where the extension in aquifer life is rather small. The key difference is that Figure 1 presents the impact of a multi-year program of investment, while the analysis here reflects the impact of an "instant" investment.

5. Conclusions

It is widely assumed that improved irrigation technologies save large quantities of water and offer the possibility to extend aquifer life substantially. In this paper it is shown that such interventions, even if they work as planned, may deliver considerably less benefits in terms of aquifer life than is assumed. Furthermore, expected "savings" in water consumption are often exaggerated, and may have the unintended consequence of *increasing* the demand for water because pumping becomes more profitable for the farmer. Such factors may distort policy recommendations and investment priorities. Where the benefits of the investment accrue directly to farmers and can be derived by private, unsubsidised investments, the priority for government is to address extremely difficult challenges of controlling abstractions and consumption to protect future water supplies for essential human uses. Finally it is shown that investments in improved irrigation technology should be concentrated in areas with aquifers that still have relatively plentiful supplies remaining instead of in areas with the shortest remaining lifetime as in those areas the rate of return on such investments is low.

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