The Sana'a Water Issues and Options Study

DRAFT Final Report

Contract Number 7159240
June 2011

This publication was produced for review by the World Bank.
It was prepared by RTI International.

Table of Contents

Page

List of Tables

Page

List of Exhibits

Abbreviations

CIF	cost, insurance and freight (cost of cargo at a port of entry)
cum	cubic meters
EIA	Environmental Impact Assessment
FAO	United Nations Food and Agriculture Organization
FOB	freight on board (cost of cargo at a port of origin)
GTZ	German Agency for Technical Cooperation (now GIZ)
ha	hectare
JICA	Japan International Cooperation Agency
LEI	LEI Wageningen UR
MCM	million cubic meters
NWRA	National Water Resources Authority
NWSSIP	National Water Sector Strategy and Investment Program
PV	present value
RNE	Royal Netherlands Embassy
SAWAS	Sana'a Water Supply (technical report series)
SBWMP	Sana'a Basin Water Management Program
TRMM	Tropical Rainfall Measurement Missions
WEAP	Water Evaluation Application Planning
WEC	Water and Environment Center
WSSP	Water Sector Support Project
WWTP	wastewater treatment plant

Executive Summary

Sana'a Basin is the most water-stressed basin in Yemen. Competing demands for the limited water resource have reached an alarming status. Prior to 1970, the balance between renewable water supply and consumption was in equilibrium. Government agricultural policy in the 1970s led to the introduction of deep well pumping for water, particularly for irrigation, but also for the exploding population of Sana'a City, currently in excess of 2 million inhabitants. The result has been severe aquifer depletion.

Over the years, Yemeni Government officials in the responsible agencies have been presented with many options for addressing water resource issues as well as many analyses of their feasibility, costs, and potential impacts. With such a plethora of reports, it has become difficult to sort through the options and evaluate the relative strength and credibility of the analyses. Some of the studies do not document their assumptions and methodology completely; others propose and evaluate interventions that are not feasible due to technical, social, or environmental constraints. In this study, the World Bank commissioned RTI International to review previous analyses, extract the most viable options and interventions, and prepare a concise and credible comparative analysis of their likely costs and impacts, in collaboration with Yemeni experts and counterparts. Unfortunately, due to the recent political and civil turmoil in Yemen, it has not been possible to work closely with a broad group of Yemeni experts during conduct of this study.

This report presents a specific set of alternative scenarios and their related consequences, characterized in terms of their anticipated effect on extending the time to exhaustion of aquifers in the Sana'a Basin and on reducing the amount of water that must be supplied from other sources ("unmet demand") to the year 2030. This study ranks alternatives based on their contribution toward assuring water provision to the urban population of Sana'a City, which currently draws all of its supply from the Central Plains aquifer. The means to this end and the associated costs are clearly identified. To meet these objectives, to explore impacts of several scenarios of water management options through the year 2030, including:

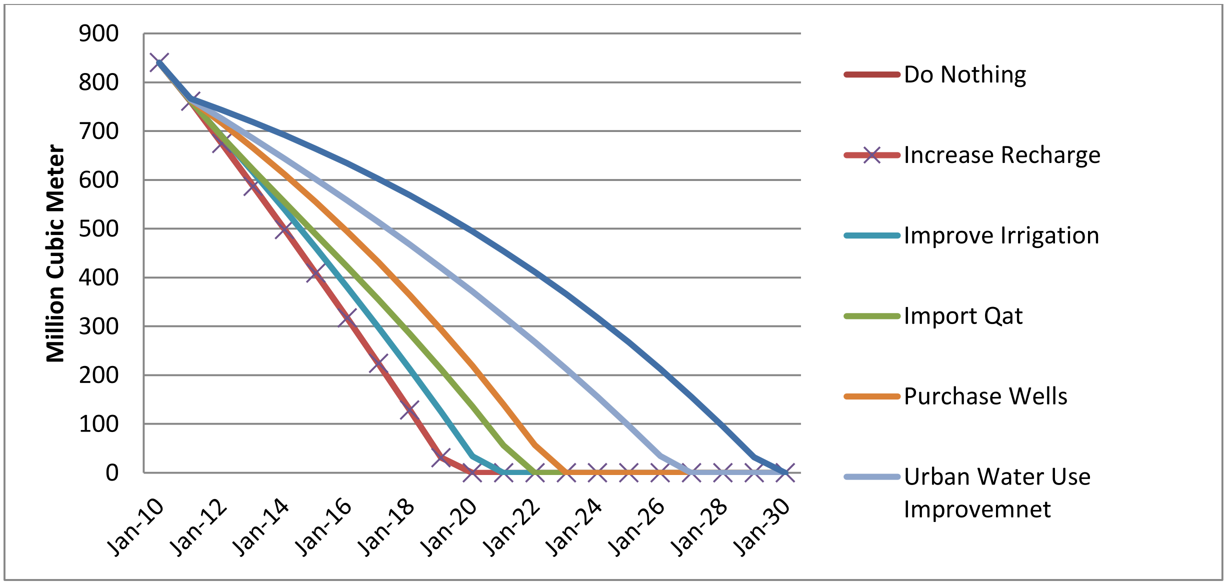
- Using economic tools (importing qat and reducing fuel subsidies) to reduce demand for deep-aquifer pumping;
- Improving irrigation systems to avoid non-beneficial losses;
- Improving urban water delivery and waste water systems to reduce physical losses; Recharging the aquifers from retention facilities;
- Reducing irrigation from deep aquifers by purchasing and removing private wells from service;
- Importing water from other aquifers; and
- Importing desalinated Red Sea water.

RTI used the Water Evaluation Application Planning (WEAP) model originally developed by the Stockholm Environmental Institute and adapted for application in Yemen by the Water and Environment Center (WEC) at Sana'a University. The model covers the entire Sana'a Basin, including 22 major sub-basins identified by the National Water Resource Authority (NWRA) for official planning purposes. In consultation with the WEC director, RTI aggregated the 22 sub-basins into six groups, or aquifer “zones,” for the purpose of this basin-wide evaluation. The RTI team accomplished the following sequence of tasks:

- Grouped the basins into six aquifer zones (from the WEAP model);
- Grouped all demands (irrigation, domestic, and industrial) into zones by adding the quantities of water used from the sub-basins;
- Obtained initial ground water storage (2010) from the 2007-2010 WEAP model data;
- Obtained annual average recharges to each of the aquifer zones;
- Developed a base case (“do-nothing”) scenario;
- Calculated the water balance for each aquifer zone using the WEAP model;
- Calculated the unmet demand for each aquifer for the period of 2011 to 2030 and computed the life of the aquifer;
- Developed scenarios and corresponding parameters for the WEAP model and the economic analyses; and
- Examined the results from each scenario with respect to extending aquifer life and its associated benefits and costs

Hydrological and demand data for the aggregated zones were developed and used in the WEAP model. A set of assumptions consistent with these data was used for the base case and all scenarios. The time to exhaustion (years of remaining life) of the groundwater storage in the six aquifers -- most critically, in the Central Plains aquifer – was the principle physical measure from which the economic impacts of the scenarios were estimated; results are summarized in ***Exhibit ES1.*** Economic impacts were measured as present values (PV) of benfits, including increased profitability or avoided costs of imported water, and costs of implementation. A summary of key results is shown in ***Table ES1.***

Exhibit ES-1. Central Plains Aquifer Groundwater Storage under Selected Scenarios*



*The dam recharge option has the same results as the reference option for the Central Plains aquifer.

Table ES-1. Results from Scenarios

Scenario	Extended Life of Aquifer	Unit and Total Benefits (PV)	Unit Costs	Total Costs	Priority
Eliminate diesel subsidy	Very little	Small (based on little extended life)	Loss of up to $6,000/ha/yr in farm profits	Up to $33,390,000/yr in farm income; much more in overall economy	Low
Import qat	2 years	Avoided water import cost of $3.89 - $9.14 per cum; $400,000,000 to $934,000,000	Loss of about $25,000/ha in PV of farm profits; increased qat consumption	Loss of up to $134,000,000 in PV of farm income in Central Plains	Low
Improve irrigation	<1 year	Increase in farm profitability by about $4,000/ha/yr; $22,260,000	About $11,000/ha/yr	$61,215,000 paid off in less than 4 years	Medium to Low
Improve urban water supply	7 years	Avoided water import cost of $12 - $28/cum/yr; $2.2 - $5.3 billion	$188/household/yr	$2,411,500,000	High
Increase recharge	<1 year	Very small in terms of aquifer life	Varies depending on dam and site	Approximately $10,500,000	Low
Purchase wells	3 years	Avoided water import cost of $5.40 - $13.83/cum; $1.0-$2.6 billion	$0.699/cum/yr or $5.69/cum (PV)	$306,321,600	Medium
Combine Central Plains and Southeastern aquifers	9 years	Gain for Central Plains farms: $17,500 to $18,500/ha; $97,387,500 to $102,952,500	Loss of 41 years for Southeastern: $68,700 to $90,500	Net: gain of $6,000,0000 to loss of $104,000,000	Medium to high
Improve urban water supply and purchase wells	10 years	Avoided water import cost of $16.12 - $37.93/cum; $3.0-$7.1 billion	Sum of costs of both options	$2.7 billion	Medium
Import water from As-Sabata'yan	>10 years	Sana'a population is provided with water and wastewater	$68 - $160/cum	$4.7 to $11.7 billion	Will be necessary when

Scenario	Extended Life of Aquifer	Unit and Total Benefits (PV)	Unit Costs	Total Costs	Priority
aquifer or Red Sea		treatment			aquifer is exhausted

Our findings indicate that none of the options will significantly extend the life of the Central Plains aquifer. Eliminating fuel subsidies, importing qat, improving irrigation systems, or using small dams to increase groundwater recharge will each extend the life of the Central Plains aquifer for no more than 2 years. Reducing fuel subsidies would incur significant costs across the economy without producing any substantial water savings. Importing qat would result in major losses of farm income and is probably not politically feasible. Improving the efficiency of on-farm irrigation systems produces additional private profits and is a reasonable investment for farmers, if financing is available; it does not, however, produce substantial public benefits in terms of extending the life of the aquifer.

The most effective single intervention is improving the urban water distribution and wastewater collection systems to reduce physical losses, which should extend the life of the Central Plains aquifer by up to 7 years. Although the intervention is extremely costly, it should be given high priority because it will also reduce losses of even more costly water in the future, when it becomes necessary to import water for Sana'a City either from other basins or from desalination.

Reducing irrigation in the Sana'a basin by purchasing private wells and removing them from service would also add 3 years to the useful life of the Central Plains aquifer and generate a significant benefit in avoided water importation cost. This action is also a reasonable step for exercising the state's authority and facilitating the transition of farmers to other livelihoods, if it is socially and politically feasible. The action cannot be justified solely on economic grounds, however, since wells drawing from the Central Plains aquifer will go out of service in a few years in any case. Furthermore, it may not be practical to shut down private wells drawing from the Central Plains aquifer without taking similar actions on comparable terms elsewhere in the Sana'a Basin.

1. Introduction

Sana'a Basin is the most water-stressed basin in Yemen. Competing demands for the limited water resource have reached an alarming status. Prior to 1970, the balance between renewable water supply and consumption was in equilibrium. Government agricultural policy in the 1970s led to the introduction of deep well pumping for water, particularly for irrigation, but also for the exploding population of Sana'a City, currently in excess of 2 million inhabitants. The result has been severe aquifer depletion.

At present, average water withdrawals are about 4–6 times average annual recharge. Total water abstraction from Sana'a Basin is estimated at between 220 and 270 million cubic meters per year (MCM/yr), of which over 200 MCM are used for irrigation. One estimate of total renewable water supply indicated 79 MCM/yr, of which recharge of the shallow water aquifer was estimated to be between 25 and 60 MCM/yr. The imbalance between demand and renewable supply results in severe groundwater mining. Water tables in the basin are falling by 3 to 4 meters per year.[1] Moreover, the Sana'a City's Local Corporation for Water Supply and Sanitation is not able to supply water consistently or adequately to local inhabitants. Sana'a City is one of the three fastest growing cities in the world.

Despite the severe scarcity, water is managed poorly and inefficiently in the Sana'a Basin. For example, more than 80% of the water withdrawal is used in agriculture in traditional flood irrigation systems.[2] The average irrigation well depth is about 250 meters, and a limited number of farmers in Sana'a Basin have wells as deep as 600–800 meters to irrigate qat. Compounding these issues, water supply and sanitation networks are inadequately maintained, due to the fact that the network is over 30 years old and made of low-quality galvanized pipes. Leaks are commonplace and losses of up to 35% are reported.[3]

Against this background, the Government of Yemen, with support from international development partners (including the Royal Netherlands Embassy [RNE], the World Bank, and Germany) designed the five-year Water Sector Support Project (WSSP) to support implementation of the 2005-9 National Water Sector Strategy and Investment Program (NWSSIP). The WSSP aims to: (1) strengthen institutions for sustainable water resources management; (2) improve community-based water resource management; (3) increase access to water supply and sanitation services; (4) increase returns to water use in agriculture; and (5) stabilize and reduce groundwater abstraction for agricultural use in critical water basins.

Over the years, Government officials in the responsible agencies have been presented with many options for addressing water resource issues as well as many analyses of their feasibility, costs, and potential impacts. With such a plethora of reports, it has become difficult to sort through the options and evaluate the relative strength and credibility of the analyses. Some of the studies do not document their assumptions and methodology completely; others propose and evaluate interventions that are not feasible due to technical, social, or environmental constraints. In this study, the World Bank has supported a review of previous work to extract the

---

[1] Hellegers, P.J.G.J., Perry, C.J., and Al-Aulaqi, N. (2009). Incentives to reduce groundwater consumption in Yemen. *Irrigation and Drainage*. doi: 10.1002/ird.

[2] Ibid.

[3] Ministry of Water and Environment, Government of Yemen (2005). NWSSIP, 2005–2009.

most viable options and interventions and prepare a concise and credible comparative analysis of their likely costs and impacts. This study did not collect any additional, primary data.

2. Objectives of the Study

The general scheme of the assignment and the approaches is summarized in Table 1. The study included three tasks to address water availability, water demand, and comparative analysis of potential interventions, performed in a manner that promotes collaboration with technical counterparts and effective dissemination of results.

Each task was performed in progressive steps: (1) review available studies; (2) hold the first consultation with Yemeni experts and counterparts to reach agreement regarding the scenarios to be evaluated and reasonable assumptions with which to construct the analyses; (3) analyze the selected actions, scenarios, and options under a consistent set of assumptions; evaluate costs; and array the results in a manner that supports comparison; and (4) conduct a second consultation to discuss results of the analysis and take comments.

Due to the recent civil unrest in Yemen, it proved impossible to meet in person with Yemeni experts, either in Sana'a or elsewhere in the region. The first consultation was accomplished in a teleconference including World Bank staff familiar with the Yemen context and Yemeni experts. Participants agreed that this study should not simply replicate what has been done previously, but rather should produce an analysis of the various options using a consistent methodology and transparent set of assumptions. The Bank wishes to present a specific set of alternatives and scenarios and their likely effect on aquifer life to the Government of Yemen. Most important, participants agreed that the most critical issue is to ensure water supply to the urban population of Sana'a City, which currently draws its water from the Central Plains aquifer.

Participants in the call also agreed that the present study should assess the impacts of the following water management scenarios, in comparison with a "do nothing" base case:

- Using economic tools (importing qat and reducing fuel subsidies) to reduce demand for deep-aquifer pumping;
- Improving irrigation systems to avoid non-beneficial losses;
- Improving urban water delivery and waste water systems to reduce physical losses;
- Recharging aquifers from retention facilities;
- Reducing irrigation from deep aquifers by purchasing and removing private wells from service;
- Importing water from other aquifers; and
- Importing desalinated Red Sea water.

This report presents the methodology and results of the analysis. At the time of this writing, plans for the second consultation are under discussion.

Table 1. Overview of RTI's Approach

	Review Available Studies	First Consultation	Analysis	Second Consultation
Task 1. **Water Availability**	Identify and extract data and modeled estimates of water availability (rainfall, runoff, and recharge).	Gain insights for interpreting historical estimates of water availability. Agree on reasonable assumptions and scenarios for estimating future trends.	Estimate water availability trends to 2030 and 2050 under agreed assumptions and scenarios.	Discuss estimated trends in water availability. Confirm acceptance or note concerns with methods and assumptions. Gain insights for interpreting results.
Task 2. **Water Demand**	Identify and extract data and modeled estimates of water usage (amount, quality, timing, and source).	Gain insights for interpreting historical estimates of water usage. Agree on reasonable assumptions and scenarios for modeling future trends.	Estimate water demand trends and water allocation solutions to 2030 and 2050 under agreed assumptions and scenarios.	Discuss estimated trends in water demand. Confirm acceptance or note concerns with methods and assumptions. Gain insights for interpreting results.
Task 3. **Analysis of Options to Address Water Stress**	Summarize options that have been proposed for increasing water supply and reducing demand; extract estimates of costs and externalities.	Identify actions that counterparts consider technically, socially, and environmentally practical. Gather additional secondary data required for marginal cost analysis.	Evaluate cost and contribution to reduction of water stress for each management option; array options in marginal cost curves.	Discuss results of marginal cost analysis. Confirm acceptance or note concerns with methods and assumptions. Gain insights for interpreting results.
Task 4. **Consultation and Dissemination**	Review findings and plan the First Consultation with the World Bank Task Manager and the donor core group. Provide Inception Report.	Conduct the above via interviews, small group discussions, and a workshop with technical counterparts, including development partners working in this field such as GIZ (formerly GTZ) and others.	Provide updates and Progress Report; maintain transparency. Document methods, assumptions, and results in draft report.	Document comments and discussions. Prepare Final Report.

3. The Sana’a Basin WEAP Model Development

3.1 Background

The WEAP software platform (Raskin et al., 1992[4]; Yates et al., 2005[5]) crystallized from the recognition of a critical need in water resources planning and management tools – that of integrating the complex array of hydrologic, water quality, economic, and social factors that control the availability of water and influence the priorities set for its use – as water managers are increasingly called upon to do (Biswas, 1981[6]; Bouwer, 2000[7]; Zalweski, 2002[8]; Westphal et al., 2003[9]). The WEAP modeling platform allows integration of pertinent demand and supply-based information together with hydrologic simulation capabilities to facilitate analysis of a range of user-defined issues and uncertainties, including those related to climate, watershed conditions, anticipated demand, ecosystem needs, land use change, regulatory drivers, operational objectives, and infrastructure. The flexibility of the modeling platform allows a wide range of user-defined systems, sectors, and scales to be represented, from single catchments to entire basins.[10] The supply, demand, and water allocation priority designations are implemented through user friendly input tables and functions in a manner that emphasizes transparency of the process. The graphical interfaces that allow comparison of scenarios facilitate the dialogue among diverse stakeholder groups with both technical and non-technical backgrounds.

3.2 Schematic Representation

The geographical extent of the Sana’a Basin WEAP model covers the entire Sana’a Basin. The Sana’a Basin is subdivided into 22 major sub-basins, based on wadis that have been identified by the NWRA for official planning purposes (***Exhibit 1*** and ***Table*** 2). While this high resolution provides an excellent platform for local water resource planning and management, aggregation of these sub-basins into six groups, or aquifer “zones,” was adopted for the purpose of basin-wide water resource evaluation. The aggregation assumes that these sub-basins overlay loosely connected individual aquifers. This aggregation was first suggested by Mosgiprovodkhoz, 1986,[11] and has been used most recently by Heidera, et al.[12] ***Exhibit*** 2 shows the six aquifer zones.

---

[4] Raskin, P., E. Hansen, Z. Zhu and D. Stavisky. 1992. “Simulation of water supply and demand in the Aral Sea Region.” *Water International* 17(2): 55-67

[5] Yates, D., J. Sieber, D. Purkey, and A. Huber-Lee, 2005. “WEAP21 – A demand, priority, and preference driven water planning model. Part 1: Model characteristics.” *Water International*, 30 (4): 487-500.

[6] Biswas, A. 1981. “Integrated water management: Some international dimensions.” *Journal of Hydrology* 51, No. 1-4: 369.

[7] Bouwer, H. 2000. “Integrated water management: Emerging issues and challenges.” *Agricultural Water Management* 45, No. 3: 217-28.

[8] Zalewski, M. 2002. “Ecohydrology- the use of ecological and hydrological processes for sustainable management of water resources.” *Hydrological Sciences Journal* 47, No. 5:823.

[9] Westphal, K., R. Vogel, P. Kirshen, and S. Chapra. 2003. “Decision support system for adaptive water supply management.” *Journal of Water Resources Planning and Management* 129, No. 3: 165-77.

[10] Nevertheless, the WEAP model is based on water balances, and its results have not been validated using field observations.

[11] Mosgiprovodkhoz (Moscow State Designing and Surveying Institute of Water Management Project Construction). 1986. Sana’a Basin Water Resources Scheme.

Exhibit 1. Sana’a Basin Location and the 22 Sub-basins

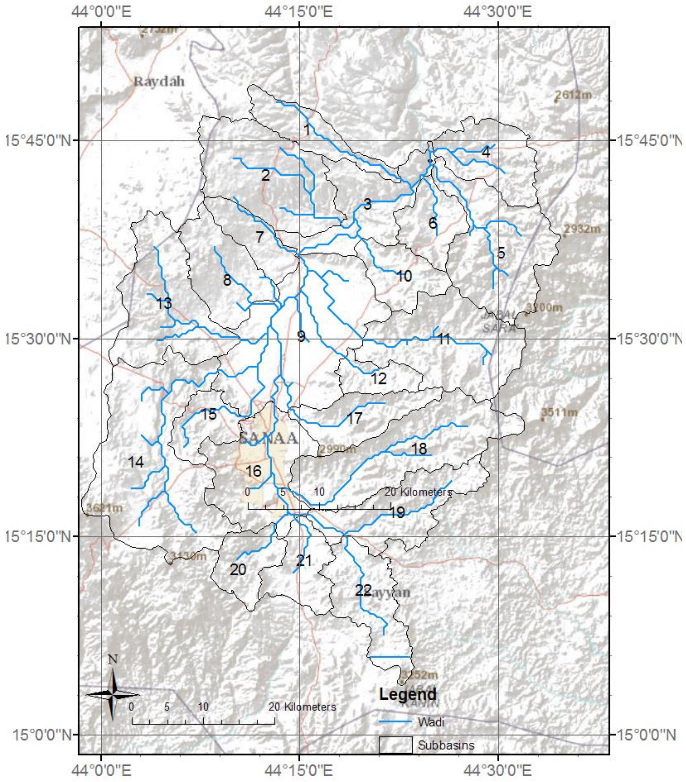


Table 2. List of Sub-basins

No	Sub Basin	Area (km^2)
1	Wadi al Mashamini	77.8
2	Wadi al Madini	213.3
3	Wadi al Kharid	138.2
4	Wadi al Ma'adi	111.3
5	Wadi A'sir	208.8
6	Wadi Khulaqah	75.7
7	Wadi Qasabah	64.5
8	Wadi al Huqqah	120.3

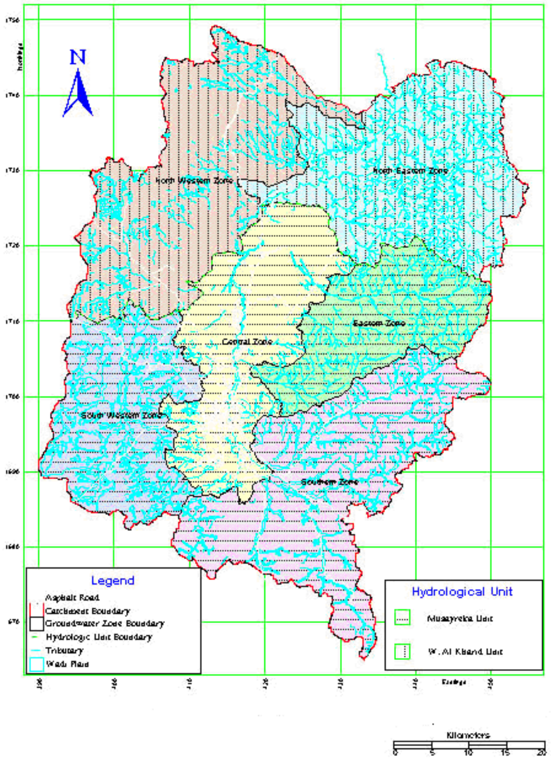
---

[12] Haidera, M. S.A. Alhakimi, A. Noaman, A. Al Kebsi, A. Noaman, A. Fencl, B. Dougherty, and C. Swartz, 2011. “Water scarcity and climate change adaptation for Yemen's vulnerable communities.” *Local Environment*, 16:5, 473-488.

9	Wadi Bani Hwat	327.0
10	Wadi Thumah	77.0
11	Wadi as Sirr	218.5
12	Wadi al Furs	45.8
13	Wadi al Iqbal	202.9
14	Wadi Zahr & al Ghayl	360.8
15	Wadi Hamdan	63.5
16	Wadi al Mawrid	179.2
17	Wadi Sa'Wan	95.9
18	Wadi Shahik	238.7
19	Wadi Ghayman	143.3
20	Wadi al Mulakhy	69.7
21	Wadi Hizyaz	81.9
22	Wadi Akhwar	125.6
Total		**3239.8**

*Sub-basin 16 includes Sana’a City

Exhibit 2. Sana’a Basin Six Aquifer Zones



KEY Sana’a Basin Six Aquifer Zones			
Northeastern Aquifer (Zone)	A	Norwestern Aquifer (Zone)	B
Central Plains Acquifer (Zone)	C	Eastern Aquifer (Zone)	D
Southwestern Aquifer (Zone)	E	Southeastern Aquifer (Zone)	F

3.3 Model Data

For each zone, two WEAP catchment nodes (greencircles, ***Exhibit 3***) were added to the schematic. One catchment node represents natural land cover and rain fed agriculture areas in that sub-basin – it is in this catchment node that the majority of rainfall runoff to the major wadi and infiltration is simulated for each sub-basin. All land cover in this catchment node that is not designated as rain fed is considered barren/rocky in character. The other catchment node represents the area of the sub-basin upon which irrigated agriculture is cultivated. (red circles ***Exhibit*** 3.)

The area of each zone was obtained by adding the areas of sub-basins within the zone available from the NWRA for input into WEAP, as were the areas of rain fed and irrigated area within each sub-basin (***Table 3***). The sum of the areas of catchments equals that of the respective sub-basin. For each irrigated catchment, the land cover was distributed among three crop types: qat, grapes, and “others,” which generally includes mixed vegetables. Fruit orchards, the fourth crop, compose only a small percentage of the irrigated land in the basin. The percentage, or share, of each crop type for each sub-basin was obtained from NWRA statistics (***Table 3***).

Domestic and industrial water demands were summed together. These demands are computed based on population for each of the zones. Annual per capita water use rates for the urban center and rural populations were estimated based on usage rates of 70 liters/capita/day (l/c/d) and 40 l/c/d, respectively. Water for use by domestic and industrial sectors, as well as irrigation, is obtained from the respective aquifer. The two catchment nodes and domestic demand node are linked via transmission links in the schematic (green arrows, ***Exhibit 3***).

Only one wastewater treatment plant (WWTP) currently operating in the basin (for Sana'a City) was included in the schematic. The WWTP node was placed downstream of Sana'a to discharge to wadi Al Kharid in the Reference scenario condition. The current operating capacity of 0.05 MCM/day was assigned to this WWTP.

Exhibit 3. Schematic Represenatation of Zones with Demand and Supply for the Sana'a Basin

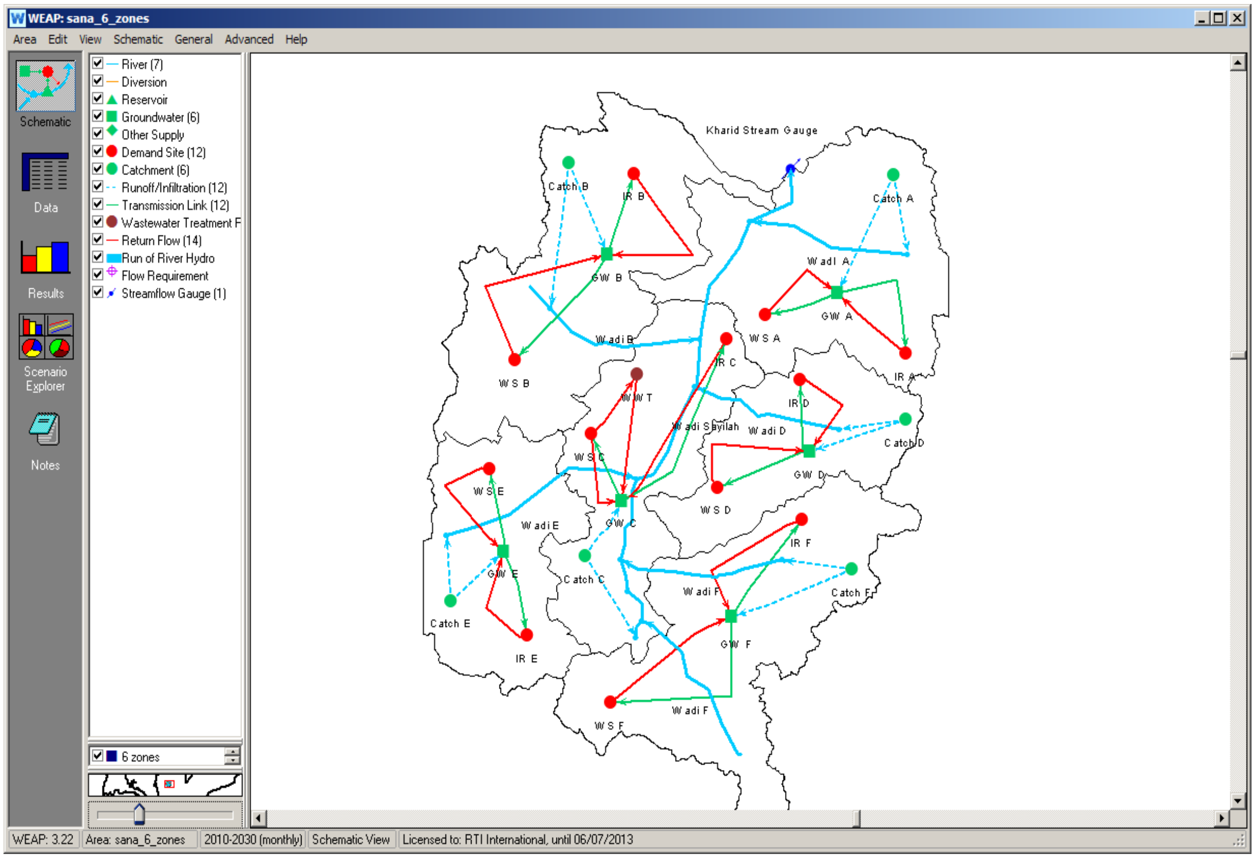


Table 3. Irrigated Agriculture in Sana'a Aquifer Zones

Aquifer /Catchment Zones	Letter Code	Total Area (ha)	Irrigated Area(ha)	Irrigated Area (%)	Percent of Irrigated Crop		
					Grape	Others	Qat
Northeastern Aquifer	A	61,100	1,237	2.02	5.40	94.10	0.50
Northwestern Aquifer	B	67,881	3,321	4.89	3.50	7.60	88.90

Central Plains Aquifer	C	50,619	5,565	10.99	40.20	41.00	18.90
Eastern Aquifer	D	36,030	4,514	12.53	58.00	41.70	0.30
Southwestern Aquifer	E	42,433	2,086	4.92	0.00	14.00	86.00
Southeastern Aquifer	F	65,914	2,231	3.38	34.80	2.60	62.80
Total		**323,976**	**18,953**	**5.85**			

Based on the 2004 census[13], we estimated the population of the Sana'a Basin for 2010 as 2.984 million: 2.43 million in the city of Sana'a with a 5.0% annual growth rate and 0.55 million in the rural area with a 3.0% annual growth rate. Our estimate for 2005 is reasonably close to the estimated figure of Sana'a University Water and Environment Center (WEC, October 2001)[14] for 2005 (1.83 million, ***Table 4***).

Table 4. Population in 2010 (based on 2004 census)

Aquifer/Catchment Zones	Letter Code	Population (thousands)
Northeastern Aquifer	A	91.06
Northwestern Aquifer	B	73.10
Central Plains Aquifer	C	2429.67
Eastern Aquifer	D	129.23
Southwestern Aquifer	E	98.68
Southeastern Aquifer	F	162.81
Total		**2984.55**

The average monthly temperature, wind speed, and humidity recorded at the NWRA-A meteorological station was used in this study. Though obtained records are very limited, general tendency in the Sana'a Basin is observed. The hottest season is from June to August, and the coldest season is around January and February. The average monthly temperature ranges between about 15 and 25 °C. However, rainfall data are sometimes collected only for short periods of time, and data are often incomplete. To address the lack of data, the Tropical Rainfall Measurement Mission (TRMM)[15] monthly rainfall was calculated from data that covered the

---

[13] Central Statistical Organization of Yemen, Statistical Year book, 2005

[14] Water and Environment Center, Socio-economic Study Report, October, 2001.

[15] Kummerow, C., W. Barnes, T. Kozu, J. Shiue, J. Simpson, 1998: The TRMM Sensor Package. *J. Atmos. Oceanic Technol.*, **15**, 809–817. doi: http://dx.doi.org/10.1175/1520-0426(1998)015<0809:TTRMMT>2.0.CO;2

period for each of the six sub-regions of the basin, as delineated by the boundaries for the groundwater aquifers. For the Sana'a area, monthly data were extracted from the TRMM satellite information.

A sequence of characteristic years was then defined for the reference scenario period (2010-2030) based on periodicity observed in the historical sequence. The base year of the model (2010) was defined as a normal year, which is equivalent to the average of the 2001-2010. For current analyses, we have used average (normal) precipitation throughout the simulation period of (2010-2030).

The average annual precipitation in the basin ranges from 200-300 mm per year across the basin. The rainwater that infiltrates to the aquifers, as well as some existing small dams, is relatively small. The water balance for the basin shows that only 17 mm per year of water is recharged to the aquifer. Most of the surface water is utilized and hence the water resource in the region depends on the use of both renewable and fossil groundwater resources.

3.4 Groundwater Resources

Groundwater resources in the basin were disaggregated into six major aquifer systems according to a characterization conducted by the WEC (2001), comprising the Central Plain, Southwestern, Southeastern, Eastern, Northeastern and Northwestern aquifers (***Table 5***). Sub-basin catchment nodes and demand nodes were linked to specific aquifers based on geographic proximity and knowledge of the basin hydrogeology (***Table 5***). The usable storage for the base year of the model (2010) has been estimated as the usable remaining storage in 2001, taking into consideration the average yearly abstraction and replenishment. Lateral groundwater recharge into the basin is currently estimated at 52 MCM/year.[16] For the base year of the model (2010), this recharge was distributed among the six aquifers proportionally by storage volume and equally among the 12 months of the year. In addition, vertical infiltration occurs from each of the catchment nodes to the aquifer to which it is linked via runoff/infiltration links (blue dashed arrows, ***Exhibit*** 3). This infiltration is simulated by the soil moisture module within WEAP.

---

[16] WEC, "Satellite Data Analysis of Cropping and Irrigation Water Use," SBMP Final Report, March 2001.

Table 5: Groundwater Aquifer Characteristics and Associated Aquifer Zones

Zone Letter Code	Aquifer	Area (km2)	Usable Storage (2001) (Mm^3)	Estimated Usable Storage (2010)
Central Plain C	Alluvium and sandstones (Q_a/K_{sst})	260	624	
	Volcanics and limestone (Q_v/J_{lst})	14	11.2	
	Volcanics and sandstones (T_v/K_{sst})	75	180	
	Alluvium, volcanics, and sandstones ($Q_a/T_v/K_{sst}$)	65	156	
	Sandstones and limestone (K_{sst}/J_{lst})	80	64	
	Limestone (J_{lst})	8	6.4	
	Total	**502**	**1041.6**	**846.63**
South-western E	Volcanics and sandstones ($Q_v/T_v/K_{sst}$)	90	229.5	
	Volcanics and sandstones (T_v/K_{sst})	283.4	722.7	
	Alluvium, volcanics, and sandstones ($Q_a/T_v/K_{sst}$)	20	51	
	Sandstones and limestone (K_{sst}/J_{lst})	35	59.5	
	Total	**428.4**	**1062.7**	**867.73**
Eastern D	Volcanics and sandstones (T_v/K_{sst})	135.3	188.7	
	Alluvium, volcanics, and sandstones ($Q_a/T_v/K_{sst}$)	25	34.9	
	Sandstones and limestone (K_{sst}/J_{lst})	200	186	
	Total	**360.3**	**409.٦**	**214.63**
South-eastern F	Volcanics and sandstones (T_v/K_{sst})	603.7	953.8	
	Alluvium, volcanics, and sandstones ($Q_a/T_v/K_{sst}$)	52.7	124.9	
	Total	**656.4**	**1078.7**	**883**
North-western B	Volcanics and limestone (Q_v/J_{lst})	517.8	274.5	
	Sandstones and limestone (K_{sst}/J_{lst})	40	42.4	
	Limestone (J_{lst})	120	63.6	

Zone Letter Code	Aquifer	Area (km2)	Usable Storage (2001) (Mm^3)	Estimated Usable Storage (2010)
	Total	**677.8**	**380.5**	**185**
North-eastern A	Volcanics and sandstones (T_v/K_{sst})	40	41.4	
	Sandstones and limestone (K_{sst}/J_{lst})	292.8	909	
	Limestone (J_{lst})	279	288.8	
	Total	**611.8**	**1239.2**	**1044**
Total		**3220**	**5212.3**	

3.5 Hydrologic Parameterization

To simulate the partitioning of rainfall between runoff, infiltration, and evapotranspiration in each of zones, the soil moisture module within WEAP was employed. This semi-distributed, lumped parameter model requires several parameters to simulate these processes. Parameters required include a crop coefficient value (Kc) to indicate the evapotranspirative demand of a given land cover relative to a reference crop, a runoff resistance factor that controls the interception of rainfall at ground surface (analogous to a Leaf Area Index), depth of the shallow soil compartment (to represent water holding capacity, analogous to a rooting depth), conductivity of the shallow soil compartment, a preferred flow direction between the shallow compartment and the aquifer that receives infiltration, represented by a fractional value with end members of fully vertical (1.0) to fully horizontal flow (0.0), and an initial value for soil moisture (as a percent) in the shallow compartment (Yates et al., 2005[17]). The runoff resistance factor, preferred flow direction, and shallow water capacity, conductivity, and initial soil moisture parameters all may vary by land cover class. Because all of the catchment nodes were designated as infiltrating to groundwater, no parameterization of a deeper soil compartment included in the soil moisture model was necessary, as the compartment is not active when infiltration directly to groundwater is chosen for the model.

The irrigated land cover classes in each of the irrigation catchment nodes were assigned annual water abstraction based on previous study by Al-Hamdi[18] and Hellegers, et al., 2008.[19] The annual water abstracted per hectare for qat, grapes, and others is 12,500 cum; 9,500 cum; and 8,000 cum, respectively.

---

[17] Yates, et al., op cit.

[18] Mohamed I Al-Hamdi. Competition for Scarce Groundwater in the Sana'a Plain, Yemen: A Study on the Incentive Systems for Urban and Agricultural Water Use (Paperback) (ISBN: 9789054104261);; Also WEC, "Wells Inventory in the Sana'a Basin," Water and Environment Center. Final Report, 2001; and WEC, "Basin Characterization and Selection of Pilot Study Areas, Volume II, Water Resource Availability and Use." Sana'a Basin Water Resources Management Study. Final Report, 2001.

[19] Hellegers, 2008, op cit.

3.6 Sana'a Basin Agriculture by Zone

The Sana'a Basin area was divided by Mosgiprovodkhoz (1986)[20] into six natural and agricultural regions, according to spatial changes of climate, altitude, and soils. The salient features of these six agro-ecological regions are given in ***Table*** 6.

Table 6. Salient Features of Sana'a Basin's Aquifer Zones [compiled from Mosgiprovodkhoz (1986)]

	Aquifer Zones					
Features	**A**	**B**	**C**	**D**	**E**	**F**
Total area, km^2	560	689.8	690.5	437.2	351.6	479.9
Irrig. area, ha	1,237	3,321	5,565	4,514	2,086	2,231
Avrg. elevation, m	2110	2320	2270	2510	2660	2540
Mean annual P, mm	193	242	242	242	324	284
Penman's PET, mm	2150	2010	2030	1940	1850	1890
Km = P / PET	0.09	0.12	0.12	0.12	0.18	0.15

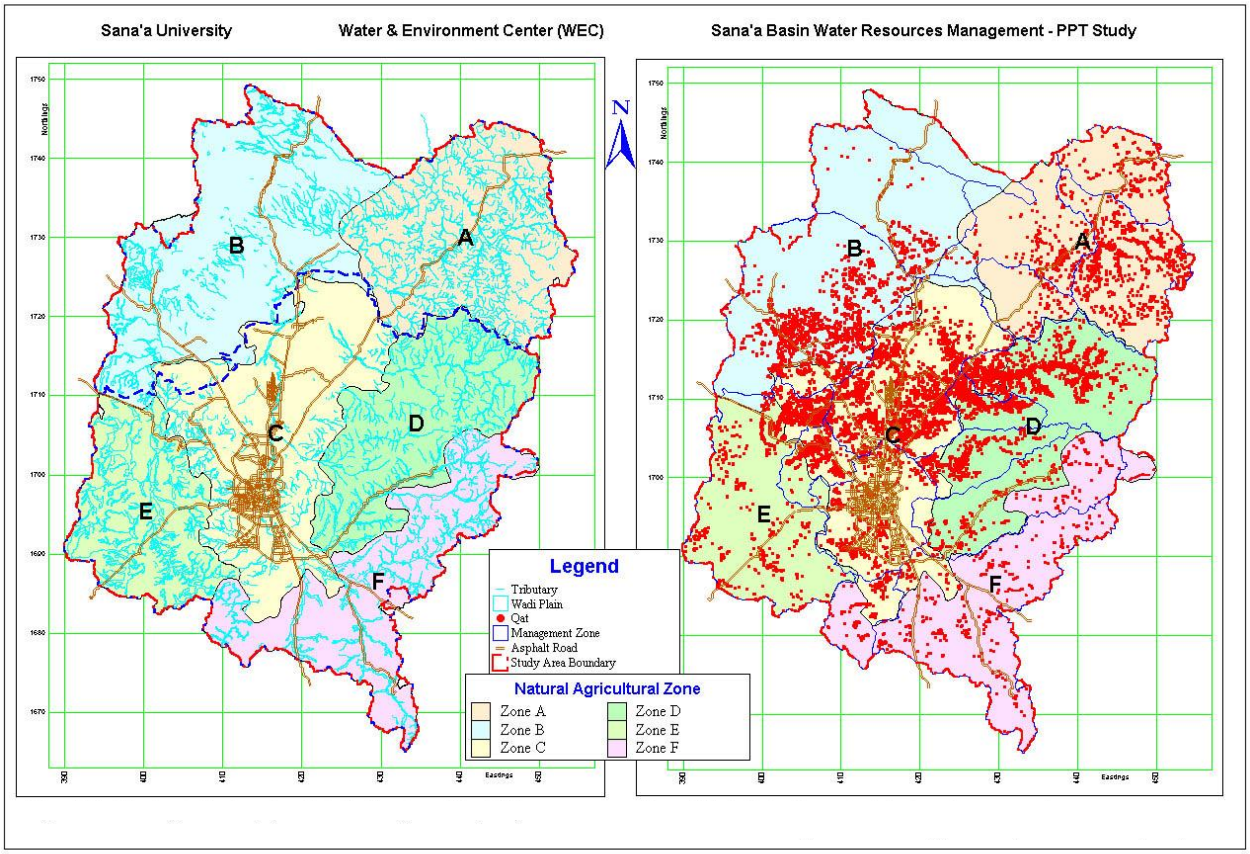
Broadly speaking, the exploitation of natural lands within the basin is determined by a number of factors related to water resources availability and land suitability. A common factor that, to a great extent, determines the availability of both water and suitable land is moisture variation, which is, in turn, related mainly to topography and altitude of a particular zone with respect to moist winds passing through the region. Using a number of indices related to these two parameters (i.e., topography and altitude), the basin has been divided into six agricultural regions. ***Exhibit*** 4A shows that these regions occur across the main hydrologic water divide within the basin. Regions A and B fall largely inside the Wadi Al-Kharid hydrologic unit while the other four (C, D, E and F) are within the Musayreka Hydrologic unit, forming the larger and more important (from the management point of view) part of the basin. For the purpose of evaluating this aggregation scheme the newly prepared cropping pattern map (WEC – ITC, 2001)[21] has been superimposed on the 1986 maps. Figure 4B indicates a reasonable good fit of the 16 WEC – ITC zone within the main boundaries of the 6 agricultural regions. The only "problematic" zone is Wadi Shahik (zone 15), which falls between regions D and F. Fortunately, a good part of the zone north of the main wadi course falling within D consists practically of barren rocks. Hence Shahik will be considered as part of region F in all calculations.

---

[20] Mosgiprovodkhoz, op cit.

[21] WEC, op cit.

Exhibit 4. Agricultural and Water Management Zones



Irrigated land is 5.8% of the total Sana's basin (as shown in Table 3), which indicates an intensive type of irrigation. This implies that land is not a limiting issue in the irrigation practice. This also implies that the practice of pumping water for irrigation will continue when wells dry in local areas so long as pumping the wells in the next available groundwater zones are not too costly.

4. Analyses and Results

We have used data from the WEAP model and formulated a simple method to quantify increases in aquifer life for the six aquifer zones. This method also allows direct computation of economic costs related to scenarios. We developed an Excel model that presents the results of our alternative scenarios in a very understandable way (see Annex 1). We implement each scenario in the WEAP and transfer the results to the Excel model. We maintain the WEAP model as a tool to look at monthly variations and effects of climate change on the aquifer lives.

Our approach then was to:

- Group the basins into six aquifer zones (from the WEAP model);

- Group all demands (irrigation, domestic, industrial) to zones by adding the quantities of water used from the sub-basins;
- Obtain initial ground water storage (2010) from the 2007-2010 WEAP model data;
- Obtain annual average recharges to each of the aquifer zone;
- Develop a do-nothing or reference scenario;
- Calculate the water balance for each aquifer zone using the WEAP model;
- Calculate the unmet water demand for each aquifer for the period 2011-2030 and compute the life of each aquifer;
- Develop scenarios and corresponding parameters[22] (changes in each scenario can be found in ***Table 7***) for the period 2010-2030 for the following:
    - Reduction of subsidies on diesel fuel;
    - Importation of qat;
    - Irrigation improvement;
    - Urban improvement;
    - Immediate reduction of irrigation
    - Combination of urban improvement and reduction of irrigation;
    -
    - Increased recharge.
- Complete, in so far as possible, an economic/financial analysis using:
    - Net value added for irrigated agriculture;
    - Avoided or delayed cost of imported desalinized water;
    - Costs of interventions; and
    - Present (discounted) value of economic/financial streams at 5% per annum.

Table 7. Changed Parameters for the Water Balance Equation by Scenario

	Parameters				
Scenarios	**Augmented recharge**	**Return Flow from Rural**	**Return Flow from Urban**	**Return Flow from Irrigation**	**Decrease in Irrigation Demand**
Do nothing					
Reduction of subsidies					

---

[22] For purposes of this analysis, we have assumed the action to be taken is accomplished immediately (in the base year). For infrastructure development, this is an unrealistic assumption. As an example, an early World Bank program for irrigation improvement projected 4,000 ha to be improved, but only a few hundred hectares were actually improved over the project life (from the World Bank WSSP Project Appraisal Document, 2009).

Scenarios	Parameters				
	Augmented recharge	Return Flow from Rural	Return Flow from Urban	Return Flow from Irrigation	Decrease in Irrigation Demand
Importation of qat					x
Irrigation improvement	x			x	x
Urban improvement			x		
Increase recharge	x				
Purchase wells					x
Combine improve urban water supply and purchase wells			x		x

4.1 Base Case

The base case assumes no change in current practices, but also includes several other assumptions, as follows.

- No new wells for irrigation water are developed after 2005. That is, the agricultural abstraction for the base year, 2010, is the irrigation pumping at the 2005 level. In fact, reports indicate that as many as 600 new wells have been dug in the Central Plains aquifer in the past five years, of which at least 2/3 were illegal.
- Sana’a City’s population increases by 5% and rural population increases 3% per year.
- Current population of Sana’a City is increased by 200,000 to account for industrial water demand and the rural population around Sana’a City. The two demands were converted to population by dividing the annual water demand (industrial and rural) by per capita water use for urban residents.

  Physical water losses from the urban water supply distribution network are assumed to be 30% of total production. However, 20% of this loss is assumed to percolate to shallow groundwater and 10% is assumed lost through evaporation. Thus, the net benefit of reduction in transmission losses is only 10%. If the aquifer is deep and water lost from distribution cannot return to the aquifer, then the net benefit of reducing losses is the full 30% of the total consumption. This assumption is an extreme case, since in reality physical losses cannot be brought to zero.
- 30% of supplied urban water goes back to the aquifer through the WWTP with a 10% system loss.
- Annual agriculture demand is estimated using applied crop water requirements of:
  - Qat= 12500 cum/ha

    - Grapes=9500 cum/ha
    - Others=8000 cum/ha
- Transmission, (agricultural conveyance) losses are included in the irrigation requirements which are based on overall irrigation "efficiencies."
- 30% of applied irrigation water will percolate back to the aquifer.
- 30% of applied irrigation water is lost in evaporation.
- 40% of applied irrigation water is actually consumed by plants.
- Irrigated agriculture (hectares) is reduced at the same rate (5%) as the population of Sana'a City grows in the Central Plains aquifer, indicating displacement of irrigation by urban development.
- Pumping continues at a constant rate until the aquifer is exhausted (that is, there is not a gradual decline in pumping over time as water becomes unavailable to some farmers). This assumption implies an equal spatial distribution of water in the aquifer, and it results in a somewhat earlier exhaustion date than might be expected otherwise.

4.1.1 Base Case Hydrologic Results

Table 8 presents this "base case" scenario. Note that, in the Central Plains aquifer, domestic (urban) use exceeds agricultural use by a substantial amount (57 MCM compared to 42 MCM) and that agricultural use declines over time. Thus, improving irrigation technology is likely not to have the same relative water saving effect in that aquifer as has been reported for the whole country. The results from the WEAP model, as found in ***Table 9***, indicate that the Central Plains aquifer, which serves Sana'a City, is predicted to be exhausted in 10 years at the assumed rates of net withdrawal. In reality, some wells will go out of production much sooner – indeed this localized exhaustion is already happening – while other wells might continue to yield water past the "exhaustion" date predicted by the WEAP model. Eventually, however, withdrawals will approximate normal recharge, estimated at 23-38 MCM per year.[23] Note that the Northwestern and Eastern aquifers have equal or slightly shorter expected lives compared to the Central Plains aquifer, whereas the Northeastern, Southeastern, and Southwestern aquifers have relatively long expected lives (past 2030). This base case provides the initial conditions to which the effects of the various options are compared. For each option, the appropriate changes in the extraction requirements and return flows were used in both the WEAP and the Excel models. These changes are listed in the text and can be observed in the associated tables in the Excel files (***Annex 1***).

Table 8. Base Case for Water Use and in 2010 (no intervention)*

Aquifer	Central Plains	North-western	North-eastern	South-western	South-eastern	Eastern
Natural recharge	7.5	7.9	12.3	7.3	12.7	5.80

---

[23] It should be noted that the analyses focus on aquifer quantity. Water quality in the aquifers could (and often does) deteriorate over time, resulting in the aquifer water being unusable before the quantity is exhausted.

Aquifer	Central Plains	North-western	North-eastern	South-western	South-eastern	Eastern
Urban (2010) pop	2,230,061	0	0	0	0	0
Rural (2010) pop	23,373	73,100	91,061	98,681	203,325	129,229
Urban use l/c/d	70	70	70	70	70	70
Rural use l/c/d	40	40	40	40	40	40
Urban use (MCM)	57.017	0	0	0	0	0
Rural use (MCM)	0.34	1.07	1.33	1.44	2.97	1.89
Industrial use (MCM in 2005)	4.76	0	0	0	0	0
Irrigated area (ha)	5,565	3,321	1,238	2,086	2,231	4,514
Irrigated abstraction (MCM – 40% efficiency)	42.47	57.17	26.38	26.46	24.37	32.35
Water balance in 2010	-72.0	-33.1	-7.4	-12.5	-7.0	-18.5
Available storage	846.6	185.5	1044.2	867.7	883.7	214.6

*See attached Excel file worksheet "Do Nothing" in Annex 1.

Table 9. Projected Aquifer Life*

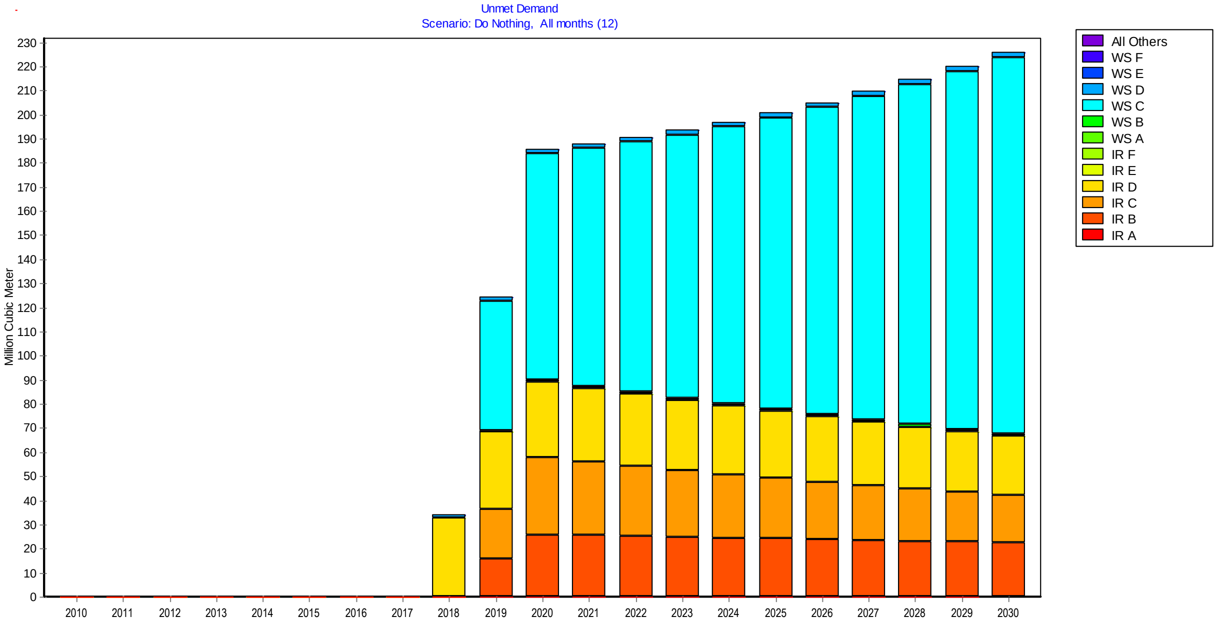
Aquifer	Central Plains Aquifer	North-western Aquifer	North-eastern Aquifer	South-western Aquifer	South-eastern Aquifer	Eastern Aquifer
Available storage	839.3	184.9	1045	867.7	883.9	213
Expected aquifer life	10	10	30+	30+	30+	8

*See attached Excel file worksheet "Do Nothing" in Annex 1.

Exhibit 5 indicates the difference between the demand for water and the supply available from the Central Plains aquifer over time. Exhaustion of the aquifer coincides with the appearance of positive bars in the graph. This figure represents a progressive decline in available supply, shown as an increasing shortfall over time. We choose not to refer to this amount as a "supply-demand gap," since it might convey the misimpression that the population of Sana'a City has enough water today when, in fact, residents currently receive only a few hours of service every third or fourth day. The "unmet demand" reflected in Exhibit 5, and in similar exhibits for each of the alternative scenarios, can only be met from water sources other than the Central Plains aquifer.

.

Exhibit 5. Unmet Demands in the Central Plains Aquifer



WS=rural or urban water supply; IR=Irrigation

4.1.2 Economic/Financial Analyses

There are two different crop budgets available in the literature: the budgets in the report by LEI (Hellegers, et al., 2008),[24] which were developed using a sample of farms in the Sana'a Basin, and the budgets that were estimated in the World Bank Implementation Completion and Results Report.[25] The former aggregated the data to obtain a per-hectare profitability by crop. The latter were based on a small farm (1/2 hectare) and in Yemeni Reals (YR), which we converted at an exchange rate of 200 YR per $1. In addition, the crops and inputs were different across the two budgets. LEI included irrigated qat, grapes, and mixed vegetables; the World Bank report included irrigated grains, fruits, "other," vegetables, and forage. We assumed that the World Bank's "other" crop is, in fact, qat, based on relative profitability. LEI included labor, water application, pumping, and "all other costs" in their budget; the World Bank reported seeds and seedling, fertilizer, pesticide, pumping, and "other inputs." We assume that fertilizer, seeds, and pesticide were included in the "all other costs" category in the LEI report, although we have no indication from that report. The LEI report had both water application (in cubic meters per hectare) and pumping costs per cubic meter, while the World Bank reported an aggregated "irrigation pumping" cost.

---

[24] Hellegers, P., C. Perry, N. Al-Aulaqi, A. R. El-Eryani, and M. Al-Hebshi, 2008. "Incentives to reduce groundwater extraction in Yemen, Chapter 5." LEI Wageningen UR, The Hague, henceforth termed LEI.

[25] World Bank Sustainable Development Section, MENA Region, 2010. "Implementation Completion and Results Report on a Credit to the Republic of Yemen for a Sana'a Basin Water Mangement Project, Annex 3."

We created comparable crop budgets using three crop categories: qat, grapes, and other, assuming that grapes (LEI) were included in the fruit category in the World Bank report, and noting that fruit orchards are a very small portion of fruit production. We used four cost categories: labor, water application, pumping, and "other." We assumed that the water application rates were the same as between the two budgets, and adjusted the per-unit pumping costs in the World Bank budget based on the cost presented in that report. The LEI report indicated $0.20 per cubic meter, while the calculated cost from the World Bank data was $0.30 per cubic meter. We used the same labor cost for both budgets.

In order to examine the economics of irrigated agriculture, it was necessary to estimate the profitability of an "enterprise" budget (per hectare). These budgets used the distribution of crops in each of the six aquifers and the data provided on revenue and costs per hectare from the two reports. ***Tables 10*** and ***11*** present the crop and enterprise budgets for each source for the Central Plains aquifer.[26]

Table 10. One Hectare Enterprise Budget Using the LEI Report*

Farm Budget				
Crop	**Qat**	**Grapes**	**Mixed Vegetable**	**Enterprise Budget**
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,823	$6,612	$5,300	$9,736
Labor cost	$326	$327	$305	$322
Other input cost (not water)	$354	$381	$356	$365
Applied water (cum)	12,500	8,500	5,585	9596.363481
Pumping cost (cum @180m)	$0.20	$0.20	$0.20	$0.20
Net returns per ha	$11,643	$4,204	$3,522	$7,129
Net returns per cum	$0.931	$0.495	$0.631	$0.699
PV of net returns per ha	$55,049			

*See attached Excel file worksheet "Do Nothing" in Annex 1.

---

[26] Crop budgets for the other five aquifer zones can be found in he attached Excel file Worksheet "Do Nothing."

Table 11. One Hectare Enterprise Budget by World Bank Report*

Crop	Qat	Grapes	Mixed Vegetable	Enterprise Budget
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,621	$7,823	$10,022	$11,024
Labor cost	$326	$327	$305	$322
Other input cost (not water)	$1,794	$1,793	$1,815	$1,798
Applied water (cum)	12,500	8,500	5,585	9,596
Pumping cost (cum @180m)	$0.30	$0.30	$0.30	$0.30
Net returns per ha	$8,751	$3,153	$6,227	$6,025
Net returns per cum	$0.700	$0.371	$1.115	$0.645
PV of net returns per ha	$46,523			

*See attached Excel file worksheet “Do Nothing” in Annex 1.

The returns per hectare and per cubic meter were slightly different between the two budgets, due in part to the conversions that were made to make the budgets compatible. Nevertheless, the calculated net returns were likely within statistical confidence limits of each other.[27]

4.2 Options Analyses

4.2.1 Macroeconomic Adjustment: Diesel Fuel Prices

Yemen provides a significant subsidy to pumping costs through reduced diesel fuel costs. In order to examine the effect of eliminating that subsidy, the “world price” of diesel fuel was determined using the data from the website http://www.globalsubsidies.org/en/subsidy-watch/commentary/removing-fuel-subsidies-clearing-road-sustainable-development provided by GTZ. From those data for November 15, 2006 (when the spot price for Brent crude was approximately $60 per barrel), the benchmark prices were as follows.

---

[27] It should be noted that the World Bank Report indicates a “value added for consumed irrigation water” of $0.26 per cum, based on their residual calculation, probably from an Integrated Water Resource Management Masters Degree study “A Case Study of Water Tariff in Sana’a City, by A. Saeed, M. Mohamed, A. Fadhel, O. Hamdan, and T. Ahmed, July 2006. This seems quite low compared to the LEI and World Bank budgets, given the net returns per hectare and the evapotranspiration requirement for the crops (in the neighborhood of 4,000 cum per hectare for the crop combination).

- Reference diesel $0.59 per liter
- Reported United States diesel price was $0.70 per liter
- Reported Yemeni diesel price was $0.28 per liter

A second website, http://chartsbin.com/view/1128 reported prices based on a GTZ study for 2010-2011 (the spot price for Brent crude price was approximately $81 per barrel) as follows.

- Reference diesel price of approximately $0.74
- Reported US price was $0.84
- Yemen price was reported to be $0.23 per liter

Thus, the Yemen price of diesel ranged from 30 to 40% of the world reference price. For our purposes, the pumping cost per cubic meter was increased by 2.5 times and by 3.33 times to determine the effects on profitability for both budgets for the Central Plains aquifer. ***Tables 12***, ***13***, ***14***, and ***15*** present the results. In only one case, the World Bank budget with the price of diesel increased by 3.33 times, was irrigation unprofitable. In all other cases, the change in diesel prices would likely not decrease irrigated area. However, under the World Bank budgets, there would likely be a shift from qat and grapes, which use substantial amounts of water, to mixed vegetables, which use relatively less water, particularly under the larger increase in diesel prices.

Table 12. LEI Budget – Central Plains Aquifer – Diesel Price 2.5 Times Higher*

Crop	Qat	Grapes	Mixed Vegetable	Enterprise Budget
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,823.00	$6,612.00	$5,300.00	$9,736.12
Labor cost	$326.00	$327.00	$305.00	$322.48
Other input cost (not water)	$354.00	$381.00	$356.00	$365.25
Applied water (cum)	12,500	8,500	5,585	9596.363481
Pumping cost (cum @180m)	$0.50	$0.50	$0.50	$0.50
Net returns per ha	$7,893.00	$1,654.00	$1,846.50	$4,250.22
Net returns per cum	$0.63	$0.19	$0.33	$0.40

*See attached Excel file worksheet “Do Nothing” in Annex 1.

Table 13. LEI Budget – Central Plains Aquifer – Diesel Price 3.33 Times Higher*

Crop	Qat	Grapes	Mixed Vegetable	Enterprise Budget
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,823.00	$6,612.00	$5,300.00	$9,736.12
Labor cost	$326.00	$327.00	$305.00	$322.48
Other input cost (not water)	$354.00	$381.00	$356.00	$365.25
Applied water (cum)	12,500	8,500	5,585	9,596.36
Pumping cost (cum @180m)	$0.67	$0.67	$0.67	$0.67
Net returns per ha	$5,768.00	$209.00	$897.05	$2,618.84
Net returns per cum	$0.46	$0.02	$0.16	$0.23

*See attached Excel file worksheet “Do Nothing” in Annex 1.

Table 14. World Bank Budget – Central Plains Aquifer – Diesel Price 2.5 Times Higher*

Crop	Qat	Grapes	Mixed Vegetable	Enterprise Budget
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,621.00	$7,823.00	$10,022.00	$11,023.80
Labor cost	$326.00	$327.00	$305.00	$322.48
Other input cost (not water)	$1,794.00	$1,793.00	$1,815.00	$1,797.52
Applied water (cum)	12,500	8,500	5,585	9596.363481
Pumping cost (cum @180m)	$0.75	$0.75	$0.75	$0.75
Net returns per ha	$3,126.00	-$672.00	$3,713.25	$1,706.53
Net returns per cum	$0.25	-$0.08	$0.66	$0.20

*See attached Excel file worksheet “Do Nothing” in Annex 1.

Table 15. World Bank Budget – Central Plains Aquifer – Diesel Price 3.33 Times Higher*

Crop	Qat	Grapes	Mixed Vegetable	Enterprise Budget
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,621.00	$7,823.00	$10,022.00	$11,023.80
Labor cost	$326.00	$327.00	$305.00	$322.48
Other input cost (not water)	$1,794.00	$1,793.00	$1,815.00	$1,797.52
Applied water (cum)	12,500	8500	5585	9596.363481
Pumping cost (cum @180m)	$1.00	$1.00	$1.00	$1.00
Net returns per ha	$1.00	-$2,797.00	$2,317.00	-$692.56
Net returns per cum	$0.00	-$0.33	$0.41	-$0.05

*See attached Excel file worksheet "Do Nothing" in Annex 1.

Profitability of vegetables is less affected by pumping costs, and remains positive even with the larger increase. We would conclude that increasing diesel prices substantially would probably not have a major impact on irrigated area, but might conceivably reduce pumping by approximately 25%, with a shift from qat and grapes to vegetables (although reduced qat production would probably cause an increase in qat price and increased profitability at the margin). Nevertheless, given results from the other scenarios (the importation of qat, for example – see below), this shift in cropping pattern would be unlikely to change the time to exhaustion significantly.

4.2.2 Macroeconomic Adjustment: Import Qat

The importation of qat has been discussed as a policy change that would reduce the profitability of qat production and therefore the amount of pumping. The LEI and World Bank budget data indicate that the farm gate gross revenues from qat are about $12,000 per hectare and that production is about 1 metric ton ($12 per kilogram). Data from England suggest a high unit price ($8.00 per "bag," which consisted of perhaps 100 - 200 grams). Kenya authorities reported that qat generated approximately $20-40 per exported kilogram.[28]

---

[28] These data come from Web pages on qat (khat): http://www.cesifo-group.de/portal/page/portal/CFP_CONF/CFP_CONF_VSI/VSI%202008/vsi08_DeGrauwe1/vsi08_it_klein.pdf; http://en.wikipedia.org/wiki/Khat; note that the Kenyan loss was due to importation restrictions by Sudan.

Ethiopia is most often suggested as the likely source for qat imported into Yemen. Farm gate price for qat in Ethiopia has been estimated at from $3.50/kg[29] to around $8.00.[30] $5.50 is a price reported for farm gate in the Ethiopian Highlands.[31] Export price (freight on board [FOB] the exporting port in Ethiopia – usually Dire, Dawa) is estimated at between $5.50[32] and $11.75.[33] All of these are more or less consistent with the 2008 United Nations Food and Agriculture Organization (FAO) report,[34] which indicates that the export price at Dire, Dawa is $9,000/T or $9.00/kg. That report suggests a transport cost of $0.10/kg from Dire, Dawa to Houdida, port fees of $0.273/kg, and transport cost from Houdida to Sana'a of about $0.90/kg (Table 16). The resulting Sana'a wholesale price would be about $17.00/kg.

Table 16. Qat Budget for Sana'a (per hectare)*

Gross Margin (Fig 5, pg 15)	Total Fixed Cost	Net Profit	Total Value Added	Irrigation Water (cum/ha)	Return to Water / cum
1,929,925YR = $9,649	1,131,231YR = $5,656	798,694 YR = $3,993	2,281,920 YR = $11,410	6,659	229 YR = $1.50

*FAO, 2008, p. 21

Table 17. Grape Budget for Sana'a (per hectare)*

Gross Revenue	Variable Costs	Gross Margin	Fixed Cost	Net Profit
927,098 YR = $4,636	286,438 YR = $1,432	640,660 YR = $3,203	396,791 YR = $1,984	374,834 YR = $1,874

*FAO, 2008, p. 22

Gross revenue is not reported in the FAO qat budget. However, if the items are consistent with those of grapes, as indicated in ***Table 17*** (and coffee, and – generally – with standard practice), gross margin is the gross revenue less the variable costs of production. The total cost for qat production (from FAO, 2008, Figure 6, page 16) is 1,380,780 YR (= $6,904). Whether that includes water cost is not indicated. In order to obtain gross revenue for qat, an estimate of variable costs must be made and then added to the gross margin. Generally, total cost equals fixed cost plus variable costs. Thus, variable cost will be 1,380,780 YR – 1,131,231 YR = 249,567 YR (or $6,903 - $5,656 = $1,247).

---

[29] Feyisa, T. H. and J. B. Aune, 2003. "Khat Expansion in the Ethiopian Highlands: Effects on the Farming System in Habro District," Mountain Research and Development, 23(2): 185-189.

[30] Beckerleg, S., D. Anderson, A. Klein and D. Hailu, 2007. The Khat Controversy: Stimulating the Debate on Drugs (Cultures of Consumption Series), Berg, London.

[31] Feyisa, op. cit.

[32] Feyisa, op. cit.

[33](Table 2 taken from the Ethiopian National Bank Export data on total value and total quantity of qat exported, in Klein, A., 2008. "Khat and the Informal Globalization of a Psychoactive Commodity)," in: Illicit Trade and Globalization, CSInfo Venice International University, Venice Summer Insitute, July, 2008.

[34] Food and Agricultural Organization, Regional Office for the Middle East, "Qat Production in Yemen: Water Use, Competitiveness and Possible Policy Options for Change," Cairo, 2008.

Value added is generally the sum of payments to hired labor (assuming unemployment is high), returns to fixed costs, and profits. Hired labor cost, then, should be equal to total value added less total fixed cost plus net profit, or 2,281,920 YR – (1,131,231 YR + 798,694 YR) = 351,995 YR ($11,409 – [$5,656 + $3,994] = $1,760). However, the variable cost was calculated above as $1,247, but the hired labor cost alone is $1,760. Unpaid family labor is probably included in that labor cost (NOT the case for the LEI or World Bank budgets). Note also that the FAO report indicates (Figure 23, page 52) that 119,300 YR ($596) is spent on pesticides and fungicides in Sana'a for qat. That cost falls between the LEI budget ("other" costs of $354) and the World Bank budget ("other" costs of $1,794).

One other problem can be found in the data from the FAO report. In that report's Table 1 (page 21), the water use for qat is 6,659 cum/ha. However, in Table 7, page 31, water consumption by irrigation is estimated as 10,913 cum/ha. Clearly (from many studies), qat uses more applied water than any other crop, so Table 1 must be using consumptive use (ET), while Table 7 is using applied water (which is what the LEI and World Bank budgets use). In addition, Table 10 (page 40) reports the water duty for irrigated qat in Sana'a as 709.4 mm (845 mm total). That would mean a water duty of 7,094 cum/ha.

The comparable Excel budgets are shown in ***Tables 18*** through ***20***.

Table 18. Economic/Financial – Central Plains – LEI Budget

Crop	Qat	Grapes	Mixed Vegetable	Enterprise Budget
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,823	$6,612	$5,300	$9736.124665
Labor cost	$326	$327	$305	$322.4759042
Other input cost (not water)	$354	$381	$356	$365.245621
Applied water (cum)	12,500	8,500	5,585	9,596.363481
Pumping cost (cum @180m)	$0.2	$0.2	$0.2	$0.2
Net returns per ha	$11,643	$4,204	$3,522	$7,129.130443
Net returns per cum	$0.93144	$0.494588	$0.630617726	$0.699289927
PV of net returns per ha	$55,049.26			

Table 19. Economic/Financial – Central Plains – World Bank ICR

Crop	Qat	Grapes	Mixed Vegetable	Enterprise Budget
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,621	$7,823	$10,022	$11,023.80331
Labor cost	$326	$327	$305	$322.4759042
Other input cost (not water)	$1,794	$1,793	$1,815	$1,797.524096
Applied water (cum)	12,500	8,500	5,585	9,596.363481
Pumping cost (cum @180m)	$0.3	$0.3	$0.3	$0.3
Net returns per ha	$8,751	$3,153	$6,226.5	$6,024.894265
Net returns per cum	$0.70008	$0.370941	$1.114861235	$0.645110237
PV of net returns per ha	$46,522.64			

Table 20. FAO Budgets

Crop	Qat	Grapes	Comments
% of crop			
Revenue/ha	$12,657	$4,646	
Labor cost			
Other input cost (not water)	$1,247	$1,432	Do these includes labor?
Applied water (cum)	10,913	8,500	No water duty available on grapes
Pumping cost (cum @180m)	$0.2	$0.2	
Net returns per ha	$9,227.4	$1,514	
Net returns per cum	$0.8445	$0.1781	

The FAO reports the following for Ethiopian qat (Table 11, pg 42).

Table 21. FAO Qat Import Costs

FOB Price Dire, Dawa, Ethiopia	$9,000/T = $9.00/kg
Insurance, Freight from Dawa to Houdida	$100/T = $0.10/kg
CIF Price Houdida	$9,100/T = $9.10/kg
Port Fees (3%)	$273/T = $0.27/kg
Price at Houdida	$9,373/T = $9.37/kg
Transport and Marketing Houdida to Sana'a (10%)	$937/T = $0.94/kg
Imported Wholesale Price in Sana'a	$10,307/T = $10.31/kg
Local Wholesale Price in Sana'a	$17,000/T = $17.00/kg
Imported as % of Local ($10.31/$17)	60.65%

The local wholesale price as reported by FAO ($17.00/kg) is about the same as the farm gate price estimated in the LEI and World Bank budgets. The FAO reported (page 57) that the marketing margin for wholesale trade was about 14.5% for Sana'a City and rural Sana'a, which means that the average farmer's share of the wholesale price was, on average, about 85.5%.[35] The local wholesale price from the FAO report would then suggest that the farm gate price of local qat was about $14.54/kg, which is not too much lower (12%) than the LEI and World Bank budgets. Alternatively, the local wholesale price based on the LEI budget would be about $19.30/kg ($16.50/0.855).[36]

The cost of transportation in the FAO report is clearly by boat. Harvest in Eastern Ethiopia and transport to the Dire, Dawa port in Ethiopia then to the Yemen port of Houdida to Sana'a would likely take at a minimum of 2 days. The over-water distance from Dire, Dawa to Houdida is about 200-250 nautical miles, and average speed for a freighter is not more that 12 nautical miles per hour (approximately 24 hours). The distance from Houdida to Sana'a is 100 miles, so offloading and transport would be another few hours at least. Given that the quality of qat is reported to decrease dramatically by 3 to 5 days after harvest (depending on the source of that information),[37] the quality of qat from Ethiopia might be fairly low relative to the "fresh" qat produced locally, and therefore not be as competitive a product. Air transport could assure "freshness" of imported qat.[38]

---

[35] The average farmer's share of retail price was reported as about 60%.

[36] This could be a function of the production levels, also. The FAO indicates an average of about 1.1 T/ha for Yemen (although there is no yield given for Sana'a itself), while the LEI report indicates 900 kg/ha.

[37] FAO, op cit.

[38] We were unable to obtain an estimate of the cost of air transport from Ethiopia to Sana'a, but "normal" costs of international air transport over short distances (found on the Web for various freight routes of similar characteristics) appears to be about $1,000/T, or $1.00/kg.

Table 2 from the Alex Klein Report,[39] taken from the National Bank of Ethiopia Quarterly Bulletin, indicates that export of qat from Ethiopia in 2003/4 was valued at 758,878,000 birr ($88,757,660 at the exchange rate of 8.55 birr/$ at that time) for a quantity of 7,825 T, or approximately $11,340/T ($11.34/kg).[40,41]

Using the marketing margins and the estimated imported wholesale price of qat from the FAO yields a farm gate price of $10.31/kg * 0.855 = $8.82/kg, or about half the current farm gate price from the LEI budget. At that price (using the LEI budget), qat remains the most profitable crop for Yemeni farmers by about 10% ($4,760/ha vs. $4,200/ha for grapes and $3,500/ha for mixed vegetables).

Using the more recent Klein data, the wholesale price of imported qat in Sana'a would be $11.34/kg + $0.10/kg + $0.34/kg + $1.17/kg = $12.95/kg. Applying the 85.5% margin yields a farm gate price of $11.00/kg. At that price, according to the LEI budget, qat is more profitable than grapes by about 50% ($6,700/ha) and 100% more profitable than mixed vegetables. If qat is air-shipped from Ethiopia to Yemen (which was reportedly the way qat was imported in the first failed attempt), the wholesale price of imported qat would likely be at least an additional $1.00 per kg, and qat grown in Yemen would be even more relatively profitable when compared to the $8.82/kg farm gate price.

Using the World Bank budget yields different results. At a price of $8.82/kg, qat remains profitable ($2,100/ha) but is the least profitable of the three crops in the enterprise budget. In fact, in the base case World Bank budget, mixed vegetables are only slightly less profitable than qat ($6,225/ha vs. $8,755/ha ,respectively). For the Klein-based analysis ($11.00/kg), qat becomes more profitable ($4,030/ha), but still lags behind mixed vegetables.

In all aquifers, there is a significant decrease (about 50 to 70% reduction) in the net income to farmers with the importation of qat, which explains the strong resistance to that importation in the past and the relatively weak government stance on importation. In the Central Plains aquifer alone, the loss in the present value of farm income is about $140,000,000 (LEI budget). In the other aquifers, the loss depends on the amount of qat in the current cropping pattern.

Nevertheless, we developed a scenario in which the supply elasticity is positive; that is, that as farm gate prices fall, farmers will grow less qat. We assume that the supply elasticity is +1, which means that a given percentage decrease in farm gate price will result in an equal percentage decrease in qat production. Such a high elasticity is probably unlikely, since qat is a perennial, very drought-resistant crop which can be produced "on demand." However, the assumption should provide a high estimate of the impact of importation. Our scenario assumes also that farmers will shift to mixed vegetables as an irrigated crop for several reasons. First, farmers already have investment in their wells, pumps, and distribution systems and are likely to be averse to stopping irrigation. Second, mixed vegetables represent crops that are profitable, but

---

[39] Klein, A., 2008. "Khat and the Informal Globalisation of a Psychoactive Commodity," In: Illicit Trade and Globalisation. CESifo Venice Summer Institute, 14-15 July 2008, Venice International University.

[40] The estimated export from Ethiopia in the FAO report was 23,000 T (pg 41; 23000 kg[sic]), which is far greater than the report from the Ethiopian Bank. However, the implied price is more or less the same ($6.00-7.00/kg) for earlier years.

[41] On page 39, the FAO report indicates that about 94,000 ha of land in Ethiopia produced 28,500 T of qat for an average yield of 3,000 kg/ha. The calculated yield is actually 300 kg (.3 T/ha). Moreover, these figures would suggest that almost all of the qat produced in Ethiopia – 80% - is exported, which appears somewhat high.

do not require extensive investment in perennial production (such as would grapes). Our scenario uses the FAO report's wholesale import price of $10.31, and, therefore, a farm gate price of $8.82/kg. That is an approximately 50% reduction in farm gate price. We apply a 50% reduction to the number of hectares producing qat, and a conversion of those hectares to mixed vegetables. The resulting cropping patterns are:

- A (Northeast): 47% qat, 47.6% "other," 5.4% grapes
- B (Northwest): 44.5% qat, 52% "other," 3.5% grapes
- C (Central Plains): 20% qat, 39.8% "other," 40.2 % grapes
- D (Eastern): 20.7% qat, 21.3% "other," 58% grapes
- E (Southwestern): 43% qat, 57% "other," 0% grapes
- F (Southeastern): 1.1% qat, 64.1% "other," 34.8% grapes

The results indicate little change in the life of the Central Plains aquifer. The only changes are an extension of aquifer life of 2 years in the Central Plains and Northwestern aquifers and 1 year in the Eastern aquifer. Results can be found in ***Table 22***. The unmet demand is indicated in ***Exhibit 6***.

Table 22. Results, Import Qat Scenario*

	Central Plains Aquifer	**North-western Aquifer**	**North-eastern Aquifer**	**South-western Aquifer**	**South-eastern Aquifer**	**Eastern Aquifer**
Available storage	846.6	185.5	1044.2	867.7	833.7	214.6
Years to exhaust	12	12	30	30	30	9
Add years to exhaust	2	2	0	0	0	1

*See attached Excel file worksheet "Import Qat" in Annex 1.

Exhibit 6. Unmet Demand, Import Qat Scenario

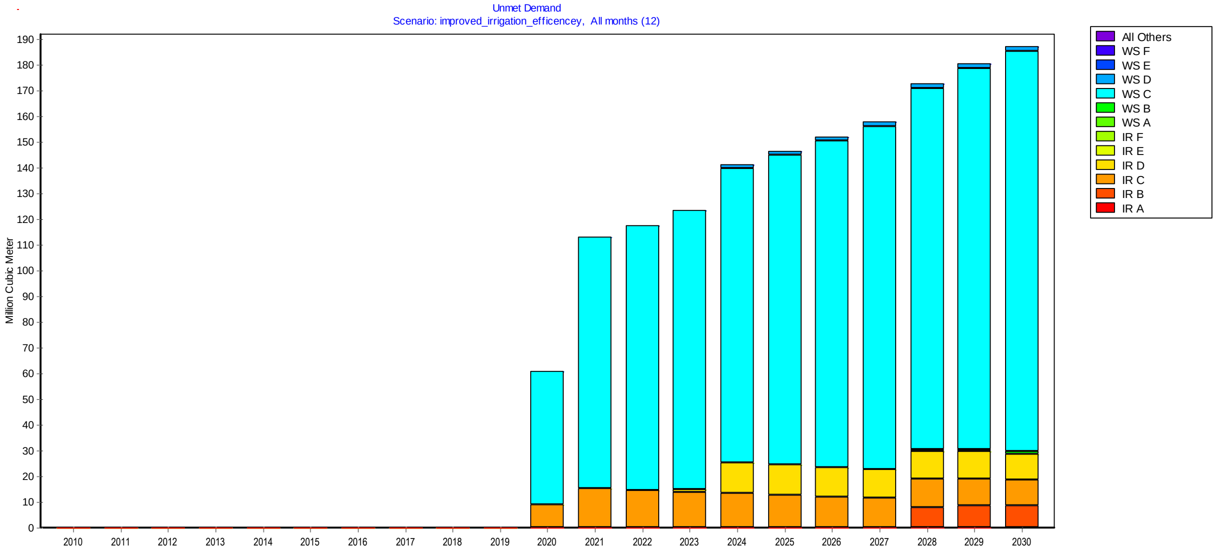


Table 23 indicates the costs to farmers and gains from delayed water importation. The benefits of qat importation are based on the delay in importing water for Sana'a City. Our importation cost was estimated at from $3.40 to $8.00 per cum, the range of estimates for the delivery of imported water from the As Sabata'an aquifer and imported desalinated water from the Red Sea to Sana'a City, respectively.[42] We used an estimated importation of 185,9 MCM as the capacity for importation, which is slightly beyond 2030 demands, and includes the effects of improvement to the urban delivery and waste water systems (see the urban improvement scenario below). The benefits in the Central Plains aquifer of the two-year delay in importing water range from about $400,000,000 to about $940,000,000, which exceeds the farmers' losses in that aquifer.

Table 23. Gains and Losses from Importing Qat*

PV of Delayed Import of Water		
PV of avoided cost of importation from As-Sabata'an aquifer - $3.4/cum		
Year 10 – on	3.4/0.05=$68/cum	PV = $41.75/cum
Year 12 on	3.4/.05=$68/cum	PV = $37.86/cum
Cost avoided		$3.89/cum
PV of avoided cost of imported desalinated water - $8/cum		
Year 10 – on	$8/.05=$160/cum	PV = $98.23/cum

---

[42] These estimates come from various sources, including the Government of Yemen, "Economic Stabilization Plan, 2010, and Ministry of Electricity and Water, Government of Yemen and Ministry of Foreign Affairs, Kingdom of the Netherlands, SAWAS Final Technical Report, "Sources for Sana'a Water Supply," December, 1995.

PV of Delayed Import of Water		
Year 12 – on	$8/.05=$160/cum	PV= $89.09/cum
Cost avoided		$9.14/cum
	Minimum	Maximum
Total benefits	$399,892,000	$939,592,000

PV of Income Lost to Central Plains Farmers

Farm budget no import (LEI)				
Crop	Qat	Grapes	Mixed Vegetables	Enterprise Budget
% of crop	41.0	40.3	18.7	100
Revenue/ha	$14,823	$6,612	$5,300	$9,736
Labor cost	$326	$327	$305	$322
Other input cost (not water)	$354	$381	$356	$365
Applied water (cum)	12,500	8,500	5,585	9,596.363481
Pumping cost (cum@180m)	$0	$0	$0	$0
Net returns per ha	$11,643	$4,204	$3,522	$7,129
Net returns per cum	$0.931	$0.495	$0.631	$0.699
PV of net returns per ha	$63187			

Farm budget w/import (LEI)				
Crop	Qat	Grapes	Mixed Vegetables	Enterprise Budget
% of crop	20	40.2	39.8	100
Revenue/ha	$7,938	$6,612	$5,300	$6,355
Labor cost	$326	$327	$305	$322
Other input cost (not water)	$354	$381	$356	$365

Applied water (cum)	12,500	8,500	5,585	9596
Pumping cost (cum@180m)	0.20	0.20	0.20	0.20
Net returns per ha	$4,758	$4,204	$3,522	$4,304
Net returns per cum	$0.381	$0.495	$0.631	$0.473
PV of net returns per ha	$38,146			
	Minimum			
Change of PV of profits/ha	-$25,042			
Total lost to farmers in Central Plains	-$139,343,438			

*See attached Excel file worksheet "Import Qat" in Annex 1.

However, losses in the other five aquifers are similar to those of the Central Plains, and people in those aquifers gain no benefits from imported water and have little extension of time for their aquifers. The approximate loss to farmers in all six aquifers would be a minimum of about $560,000,000.

Moreover, there is considerable evidence that the quality of qat is highly variable and prices for qat vary accordingly. In fact, because qat must be fresh or its quality deteriorates significantly, importation would have to be by air. Economic theory suggests that only the highest quality qat would be exported to Yemen under these circumstances, and there could be relatively little price competition. In addition, should importation of qat result in lower market prices, the use of qat could increase, causing social costs to increase (in the form of lowered productivity, for example). It is also far from certain that exporters would wish to formalize and expand this market; even in Yemen, qat is seen as having a negative impact on health and society.

4.2.3 Improve Irrigation

Irrigation improvement has been suggested in many reports as a way to both reduce groundwater extraction and extend aquifer life, while at the same time improving farm incomes. The proposed irrigation improvement is composed of two interventions (treated as an aggregate change in applied water requirements in the WEAP model): reducing water losses in conveyance systems, and the implementation of advanced on-farm irrigation delivery, such as with drip or bubbler irrigation systems. We model irrigation improvements by changing the coefficients on applied irrigation water requirements and water losses as follows (other assumptions are those of the base case).

- Annual agriculture demand is estimated using applied crop water requirements of:
    - Qat=12500*0.5[43]= 6250 cum/ha
    - Grapes=9500*0.5= 4250 cum/ha
    - Others=8000*0.5= 4000 cum/ha
- Transmission losses for agricultural systems are included in the applied crop water requirements
- 10 % of applied irrigation water will percolate back to the aquifer
- 10 % of applied irrigation water is lost from evaporation
- 80 % of applied irrigation water is consumed by plants

We then adjusted irrigation revenues and costs, based on data available from our hydrologic modeling, the LEI Report, and the World Bank Report (Tables 5.10, and Table 1, Annex 3, respectively, of those reports). ***Table 24*** indicates the changes in the water balance and time to exhaustion from the hydrologic modeling and ***Exhibit 7*** indicates the unmet demand for irrigation improvement. ***Tables 25*** and ***26*** indicate the changes in the coefficients for the two budgets. ***Tables 27*** and ***28*** indicate the effects of the combined improvement on the LEI and World Bank budgets and ***Tables 29*** and ***30*** present financial analyses of irrigation improvements.

Table 24. Water Balances with Improve Irrigation Scenario*

	Central Plains Aquifer	North-western Aquifer	North-eastern Aquifer	South-western Aquifer	South-eastern Aquifer	Eastern Aquifer
Available storage	846.6	184.5	1044.2	867.7	883.9	212.5
Years to exhaust	10.0	19.0	30.0	30.0	30.0	14.0
Add years to exhaust	<1	9	30	30	30	6

*See attached Excel file worksheet “Improve Irrigation” in Annex 1.

---

[43] Assuming that irrigation efficiency increases from 40% to 80%, only half the applied water will be needed for each crop.

Exhibit 7. Unmet Demand, Improve Irrigation Scenario

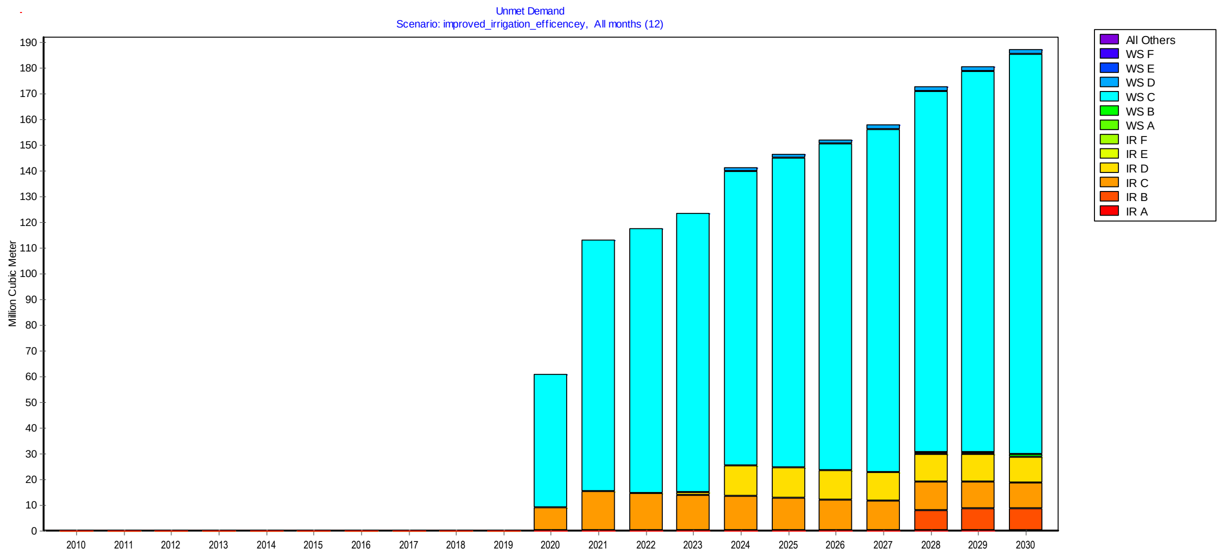


Table 25. Percentage Changes by Category – LEI Report*

Improvement	On Farm	Conveyance	Combined
Revenue	13	16	31
Labor	-32	-28	-51
Applied water	-32	-17	-44
Pumping cost	-33	-24	-49

*See attached Excel file worksheet “Improve Irrigation” in Annex 1.

Table 26. Percentage Changes by Category – World Bank Report*

Improvement	On Farm	Conveyance	Combined
Revenue	20	0	20
Other input cost	26	0	26
Applied water	-42	-31	-60
Pumping cost	-42	-31	-60

*See attched Excel file worksheet “Improve Irrigation” in Annex 1.

Table 27. Central Plains - LEI Budget with Improve Irrigation Scenario*

Crop	Qat	Grapes	Mixed Vegetables	Enterprise Budget
Revenue/ha	$19,418.13	$8,661.72	$6,943.00	$12,754.32
Labor cost	$159.74	$160.23	$149.45	$158.01
Other input cost (not water)	$354.00	$381.00	$356.00	$365.25
Applied water (cum)	7,000	4,760	3,127.6	5,373.963549
Pumping cost (cum @180m)	$0.10	$0.10	$0.10	$0.10
Net returns per ha	$18,190.39	$7,634.97	$6,118.53	$11,682.92
Net returns per cum	$2.60	$1.60	$1.96	$2.17

*See attached Excel file worksheet “Improve Irrigation” in Annex 1.

Table 28. Central Plains - World Bank Budget with Improve Irrigation Scenario*

Crop	Qat	Grapes	Mixed Vegetables	Enterprise Budget
Revenue/ha	$17,545.20	$9,387.60	$12,026.40	$13,228.56
Labor cost	$326.00	$327.00	$305.00	$322.48
Other input cost (not water)	$2,260.44	$2,259.18	$2,286.90	$2,264.88
Applied water (cum)	5,000	2,234	3,838.545392	3,669.082234
Pumping cost (cum @180m)	$0.12	$0.12	$0.12	$0.12
Net returns per ha	$14,358.76	$6,533.34	$8,973.87	$10,200.92
Net returns per cum	$2.87	$2.92	$2.34	$2.78

*See attached Excel file worksheet “Improve Irrigation” in Annex 1.

Table 29. Changes in LEI Profitability with Improve Irrigation Scenario*

Improvement	On Farm	Conveyance	Combined
Increased returns per ha	$2,413.74	$2,356.67	$4,553.79
Increased returns per cum	$0.72	$0.45	$1.43
PV of increased annual returns per ha (15 years)	$24,858.47	$24,270.70	$46,898.26
Cost per ha	$8,492.70	$2,717.98	$11,255.91
Payout period			<3 years

*See attached Excel file worksheet "Improve Irrigation" in Annex 1.

Table 30. Changes in World Bank Profitability with Improve Irrigation Scenario*

Improvement	On Farm	Conveyance	Combined
Increased returns per ha	$3,647.85	$1,508.26	$4,176.02
Increased returns per cum	$1.11	$0.51	$2.15
PV of increased annual returns per ha (15 years)	$37,568.21	$15,533.17	$43,007.74
Cost per ha	$8,492.70	$2,717.98	$11,255.91
Payout period			<3 years

*See attached Excel file worksheet "Improve Irrigation" in Annex 1.

Our results suggest that the extension of the life of the aquifers is relatively limited. In particular the life of the Central Plains aquifer is not extended a full year. That result is due to the decreasing importance of irrigation in water use over time. For the Northwestern and Eastern aquifers, the extension is more substantial, about 9 and 6 years, respectively. These results appear to be consistent with the World Bank Report (a decrease in extraction of about 14 MCM, or about 20% of current extraction). Thus, the implementation of an irrigation improvement program with the objective of extending the aquifer life (public benefits) is unwarranted in the Central Plains, and questionable in the other two aquifers. On the other hand, it is clear that the increased profitability to farmers is sufficient for farmers to pay off those investments in much less than the expected life of the aquifer.[44] Given that most improved irrigation systems last from

---

[44] Costs of irrigation improvement are taken as $3,000 investment cost per ha and $300 per ha operating and maintenance for on-farm improvements; $800 per ha and $120 per ha operation and maintenance for delivery systems based on data taken from the University of California Davis Agricultural Experiment Station Web site; other sources include http://www.epa.gov/osw/conserve/rrr/greenscapes/tools/drip.pdf;The World Bank (ICR-

10 to 15 years before having to be replaced, there would be minimal "stranded investment." Thus, public resources probably should not be used to implement this irrigation improvement; however, if impediments to private investment exist (such as lack of available credit), public efforts to reduce those impediments would likely be warranted. Note that the total cost of improved irrigation systems in the Central Plains aquifer would be approximately $11,256/ha times 5,565 ha, or $62,639,640.

However, it is important to consider the structure and nature of the "benefits" from improved irrigation technology. First, the primary benefit is a reduction in pumping costs (less water needs to be pumped to achieve the same level of crop transpiration and hence yield). This is a private benefit (that is, it accrues to the farmers) and is sufficient to justify private investment in the technology. Second, the impact of this private benefit (a reduction in fuel consumption) is precisely the reverse of the impact of increasing diesel prices, and would act to offset any progress in decreasing pumping. Third, any actual savings of water would be offset if farmers utilized the "water savings" from improved technology to expand their irrigated area, or sold "excess" water to neighbors. And finally, given that the perennial crops (qat and grapes) were, for the most part, planted many years ago, they will have developed deep rooting systems consistent with infrequent, heavy applications of water, and may not immediately adapt to frequent, shallow irrigations.[45]

4.2.4 Improve Urban Water Supply

We model urban system improvements using the following changed assumptions (from the base case).

- Physical water losses from the urban distribution network are assumed to be 30% of the production volume, two-thirds of which (20%) is assumed to percolate to shallow groundwater where it is again accessible, and one-third of which (10%) is lost to evaporation before it reaches groundwater. In such case, the net benefit of reducing transmission losses is to recover the 10% lost to evaporation. If the aquifer is deep and water that is lost from distribution lines does not return to an accessible aquifer, then the net benefit of reducing transmission losses is the full 30%.
- 70% of supplied urban water goes back to the aquifer via WWTP (with a 10% loss through the system). Note that this assumption reduces the amount of water extracted for urban uses and represents the improved efficiency of the water delivery system.[46]

SBWMP, 2010) estimate for the Sana'a Basin was a cost of $4,114 per hectare for on-farm improvement and $908 per hectare for off-farm improvements, but no distinction was made between investment and O&M. The present value of our cost assumption is consistent with the World Bank Report.

[45] Field observations (C.Perry, personal communication, 2011) report one farmer who had an old grape plantation, but had converted to a "modern" system as a demonstration plot. He was uncertain that the vines were getting enough water from the new system, and covertly added surface deliveries because he did not think the vines looked healthy under the new irrigation regime.

[46] The changes in pumped water for urban uses are:

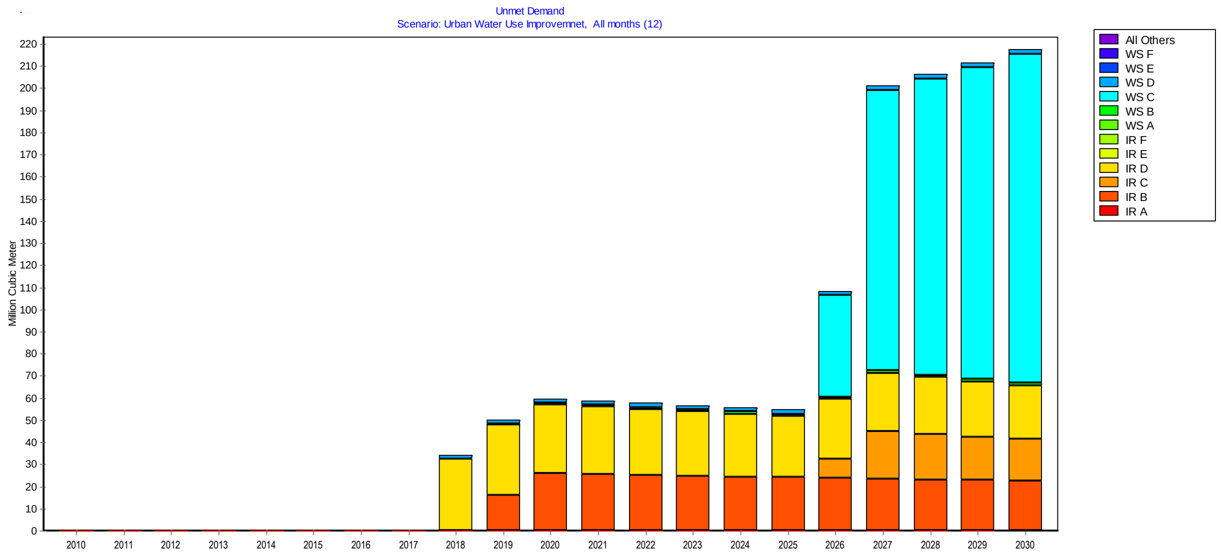
Table 31 indicates the water balance and years to exhaustion that results from urban system improvement. ***Exhibit 8*** indicates the supply-demand gap (unmet demand) for the Improve Urban Water Supplyscenario. Since there is no significant urban use in any of the aquifers in the Sana’a Basin, except for the Central Plains aquifer, the impact is nil for all but the Central Plains aquifer. Note that, because urban withdrawals from groundwater exceed irrigation withdrawals, the impact of urban system improvement in the Central Plains aquifer is larger than that of irrigation improvement, with an extension of aquifer life from 10 to 17 years (7 years).

Table 31. Water Balances with Improve Urban Water Supply Scenario*

Available storage	846.6	185.5	1044.2	867.7	883.7	214.6
Years to exhaust	17	10	30	30	30	8
Add years to exhaust	7	0				0

*See attached Excel file worksheet “Improve Urban Water Supply” in Annex 1.

Exhibit 8. Unmet Demand, Improve Urban Water Supply Scenario



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
WSC demand	62	65	69	72	76	79	83	88	92	97	101	106	112	117	123	129	136	143	150	157	165
Transmission loss 30%	89	93	98	103	108	113	119	125	131	138	145	152	160	168	176	185	194	204	214	225	236
Trasmission loss- 10%	69	73	76	80	84	88	93	97	102	107	113	118	124	130	137	144	151	158	166	175	183

For our economic analysis, we assumed that the benefits to urban improvement arise from extending the life of the aquifer, since these improvements will have a relatively long life. Thus, we calculated the benefits as the value of delaying the importation of water or urban purposes using the same approach as indicated above in the importation of qat scenario. The costs of Improve were derived from an estimated household connection cost of $163[47] plus an annual operation and maintenance cost of $1.00 per cum. We assumed that a household connection would last for 50 years, and annuitized that cost with a 5% interest rate. The total cost of improvement was based on the cost per cubic meter delivered to a household of 7 persons. ***Table 32*** presents the economic analysis.

The results appear to indicate that it is unlikely that investment in urban water systems is economically justified based on extending the aquifer life, unless the costs of imported water are very high (desalination). Moreover, the extension of the aquifer life is relatively short. Nevertheless, we would recommend that the urban water system be improved based on other benefits to local communities, such as health improvement. In addition, importation of water from the Sabata'an aquifer or from desalination plants on the Red Sea when the aquifer is exhausted will require an improved distribution and waste water treatment system.[48]

Table 32. Economic Analysis of Improve Urban Water Supply Scenario **

PV of Avoided Cost of Importation from the As-Sabata'an aquifer - $3.4/cum		
Year 10- on	3.4/.05 = $68/cum	PV = $41.75/cum
Year 17 – on	3.4/.05 = $68/cum	PV = $29.67/cum
Cost avoided		$12.08 cum
PV of Avoided Cost of Imported Desalinated water - $8/cum		
Year 10 – on	$8/.05 = $160/cum	PV = $98.23/cum
Year 17 – on	$8/.05 = $160/cum	PV = $69.81/cum
Cost avoided		$28.42 cum
Total Cost Avoided	Minimum $2.245 billion	$5.283 billion
PV of Investment and O&M for Improvement		
70 l/c/d = 25.55 cum/yr		
HH consumption cum/yr (7 persons/hh)	178.85	

---

[47] World Bank, Sana'a WSSP (1999) estimated an investment cost of $12.6 million for approximately 120,000 persons, which suggests a per-household cost of approximately $787. McKinsey (2010) estimated $163 per household connection and a $1.70 cost per cum. We used the lowest cost to be most conservative in our comparisons.

[48] The SAWAS report indicates that, due to the cost of imported water, the water treatment, delivery, and wastewater treatment system must be improved to significantly reduce losses. This has been noted in several other reports, such as the McKinsey report.

Annuitized hookup charge ($163/household)	$8.93	assumes 50-year life
O&M cost/cum	$1.00	
PV consumption cost/cum	$18.63	
PV connection and consumption	$27.56	
Total PV of system costs	$2.411billion*	

**See attached Excel file worksheet “Improve Urban Water Supply” in Annex 1.

4.2.5 Increase Recharge of the Aquifer

The Japan International Cooperation Agency (JICA) Report,[49] among others, has examined the potential for recharging the aquifers in Yemen, and in the Sana’a Basin, using strategically placed small dams. To model increased recharge, we used the following changes in assumptions, as shown in ***Table 33*** (other assumptions are those of the base case).

Table 33. Changes in Recharge Rates in the WEAP Model

Zone	Code	Recharge – Improvement (MCM)
Central Plains Aquifer	C	0
Northwestern Aquifer	B	0.4
Northeastern Aquifer	A	1.3
Southwestern Aquifer	E	2.4
Southeastern Aquifer	F	3.6
Eastern Aquifer	D	0.7

The World Bank Report indicated that for this activity “…a negative ERR was obtained.”[50] The negative ERR is primarily due to the relatively low value of water ($0.26 per cum) used as a benefit measure in that report, to the relatively limited additional recharge expected (1 MCM per year), and to the high cost of investment and operation and maintenance (O&M) of these dams (reports for specific projects suggest pay-out periods in excess of 10 years, the estimated life of the aquifer with recharge[51]). The SBWMP Environmental Impact

---

[49] JICA, 2007. “The Study for Water Resources Management and Rural Water Supply in the Republic of Yemen.

[50] World Bank, op cit, pg 27.

[51] Sana’a Basin Water Management Project, Dynamic Recharge Assessment Reports for the Al Haayathem, Al Jaef, Al Juma, Arisha, Bahman, Baninaji, and Beryan recharge dams. Note that some of these reports do not include a cost or pay-out period analysis.

Assessment (EIA) Report[52] indicated a total investment cost for the construction of five recharge dams and the rehabilitation of several others as $10,000,000.

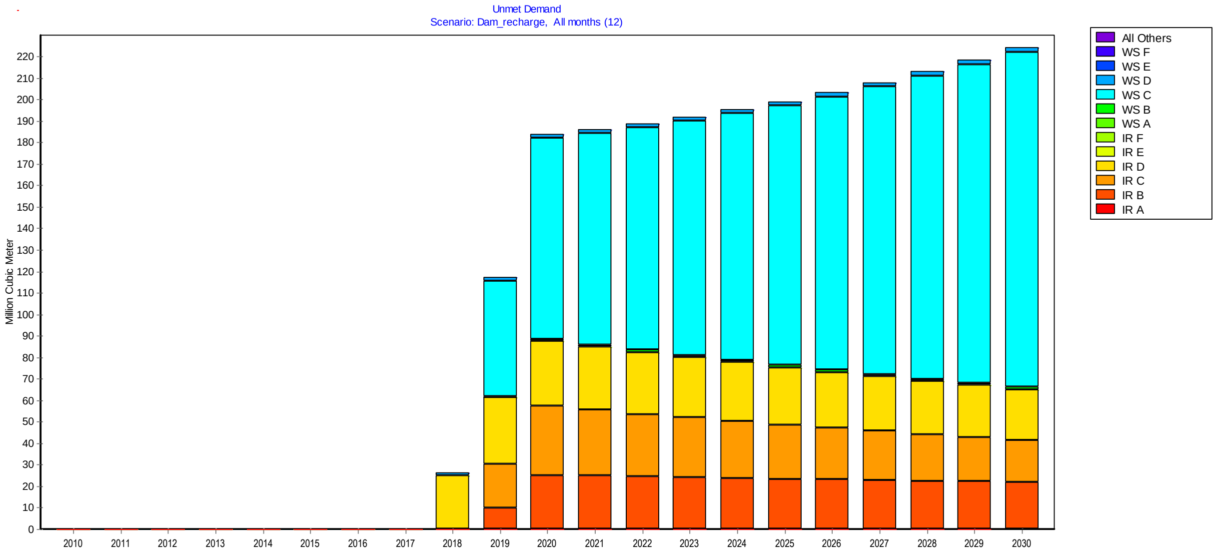
The results of our WEAP analyses can be found in ***Table 34***. The unmet demand is indicated in ***Exhibit 9***. There are no opportunities for recharging the aquifer using check dams in the Central Plains aquifer, so there is no extension of the life of that aquifer. Results indicate a slight extension of the life of the most at-risk aquifer (Eastern), but no significant extension of the life of other aquifers.

Table 34. Water Balance and Aquifer Life with Increase Recharge Scenario*

	Central Plains Aquifer	**North-western Aquifer**	**North-eastern Aquifer**	**South-western Aquifer**	**South-eastern Aquifer**	**Eastern Aquifer**
Available storage	846.6	185.5	1044.2	867.7	883.7	214.6
Years to exhaust	10	10	30	30	30	9
Add years to exhaust	0	0	0	0	0	1

*See attached Excel file worksheet “Increase Recharge” in Annex 1.

Exhibit 9. Unmet Demand, Increase Recharge Scenario



---

[52] Boydell, R.A., A. A. Al Hemyari, A. Karim, S.T. Al Suleihi, K.Y. Al Dubai, M.M. Iskandar, and P.W. Whitford, Sana’s Basin Water Management Program, Phase 1 Project, Environmental Impact Assessment Report, January, 2003.

It has been consistently suggested in previously cited studies, however, that this approach to extending aquifer life is both ineffective with respect to the amount of recharge and too expensive to be considered.

4.2.6 Reduce Irrigation by Purchasing Wells

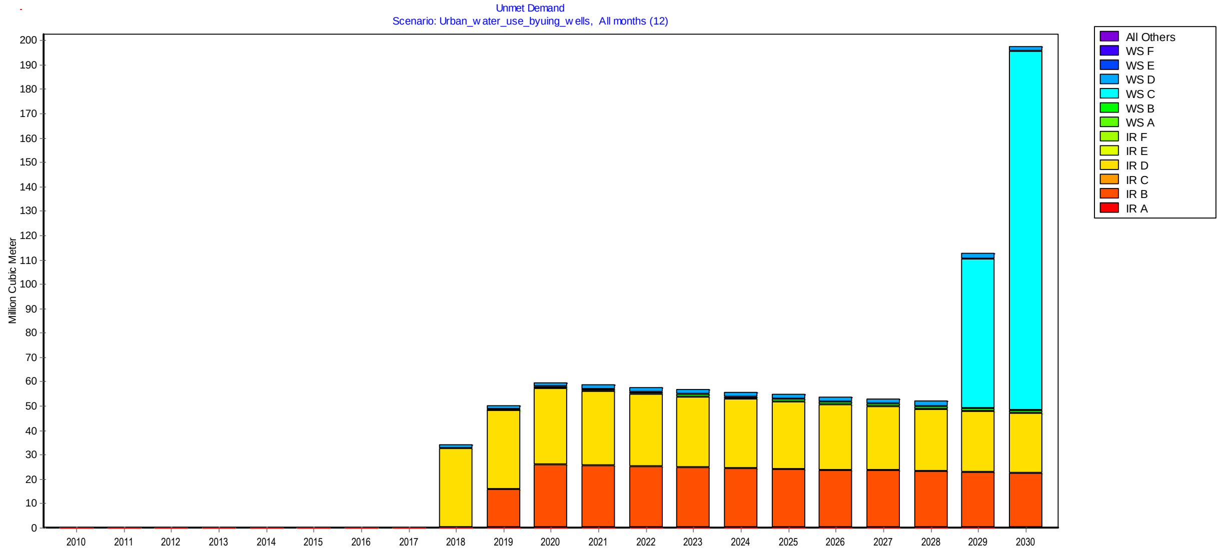
We used an approach to reducing the amount of irrigated area in the Central Plains aquifer by assuming that there would be an immediate purchase of all agricultural wells and transfer of those wells to Sana'a City to provide for urban demand. In reality, an extended period of time would likely be required over which agricultural wells would be purchased. We examined well purchase in part to provide an estimated compensation for farmers. We have modeled well purchase on the basis of reductions in hectares of irrigated agriculture in the Central Plains aquifer from 5,564 ha to 0 hectares (other assumptions remain those of the base case). ***Table 35*** presents the results from the WEAP model due to the assumed one-time purchase of all irrigated agricultural land in the Central Plains aquifer. The life of the aquifer is extended by 3 years. ***Exhibit 10*** indicates the unmet demand for this option (there is no unmet demand for irrigation in the Central Plains aquifer under this assumption, since all water is transferred to Sana'a City).

Table 35. Water Balance with Purchase Wells Scenario*

	Central Plains Aquifer	North-western Aquifer	North-eastern Aquifer	South-western Aquifer	South-eastern Aquifer	Eastern Aquifer
Available storage	846.6	185.5	1044.2	867.7	883.7	214.6
Years to exhaust	13.0	10.0	30.0	30.0	30.0	8.0
Add years to exhaust	3	0	0	0	0	0

*See attached Excel file worksheet "Purchase Wells" in Annex 1.

Exhibit 10. Unmet Demand, Purchase Wells Scenario



In order to assess the benefits of the buyout of irrigated land, the cost of importing water was used, similar to the analyses for imported qat and for improved urban efficiency. To estimate the cost of implementing the buy-out, we made an estimate of the value of the land given the length of time that irrigation will last without the buy-out (10 years) less the value of the land remaining after the buyout of water (rain fed agriculture). We use the present value of net returns per hectare and per cubic meter to make this comparison. Calculating the value of rain fed agriculture is problematic, since much of the produce is used for subsistence. Purely rain fed agricultural ground in dry areas in the United States (usually growing grains and fodder) ranges from $500 to $1,500 per acre ($1,100 to $2,250 per hectare). To be conservative in our estimate of the cost of buy-out, we use $2,000 per hectare as the value of rain fed agriculture in Yemen. The resulting present value per cum is about $0.53. Table 36 presents the economic analysis of the immediate buy-out.

Table 36. Comparison of Immediate Purchase Cost with Avoided Cost of Postponed Importation*

PV of Avoided Cost of Importation from the As-Sabata'an aquifer - $3.4/cum		
Year 10 – on	3.4/.05 = $68/cum	PV = $41.75/cum
Year 13 – on	3.4/.05 = $68/cum	PV = $36.06/cum
Cost avoided		$5.69/cum

PV of avoided cost of imported desalinated water - $8/cum		
Year 10 – on	$8/.05 = $160/cum	PV = $98.23/cum
Year 13 – on	$8/.05 - $160/cum	PV = $84.85/cum

PV of avoided cost of imported desalinated water - $8/cum		
Cost avoided		$13.83/cum
Total Avoided Cost	Minimum $1.057 billion	Maximum $2.571 billion

PV of buy out		
PV irrig/cum	$0.699	$5.40/cum
Cost of buyout/ha		$55,049/ha
Total cost of buyout	$306,321.583	

*See attached Excel file worksheet “Purchase Wells” in Annex 1.

The cost of purchasing wells per cubic meter is much less than the value of the avoided cost of imported water, suggesting that such a buy-out is economically justified. Although the benefit and cost per cubic meter is small for the case of imported As-Sabata’an aquifer water, the large difference in water demand for urban compared to irrigation results in a substantial benefit. However, the extension of the aquifer life is minimal.

4.2.7 Import Water from the Southeastern Aquifer

There has been some discussion in reports and among principles in the project that there are other aquifers from which water could be obtained. Some have suggested that the political barriers to using water from another aquifer may make this importation impossible. Moreover, there are limited detailed data with regard to the cost of importation from another aquifer, making it difficult to analyze the option. However, it has been reported by Yemeni experts[53] that Sana’a City is expanding rapidly into the Southeastern Aquifer, and that access to that aquifer for urban water supplies can probably be obtained at relatively low pumping and conveyance costs. For that reason, we examined the effects of using the Southeastern aquifer as part of the Central Plains aquifer’s water availability, using the same assumptions as in the base case, but an aggregated demand and supply for the joint aquifer (other assumptions remain the same as the base case). ***Table 37*** presents the results of combining the two aquifers. ***Exhibit 11*** indicates the unmet demand for the two aquifers.

---

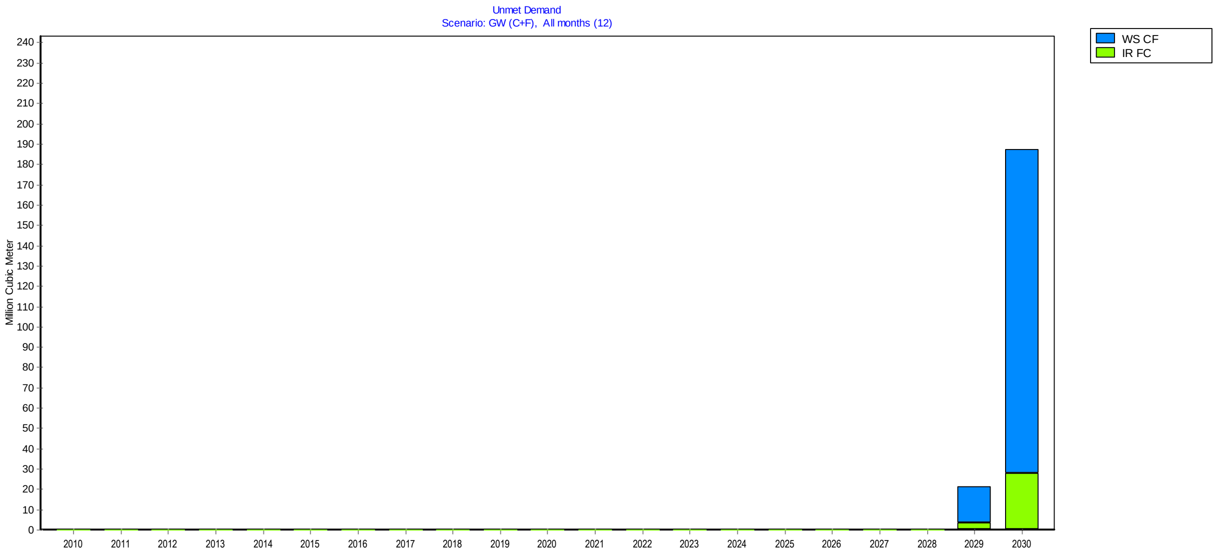
[53] A. Noaman, personal communications

Table 37. Effects on Water Balance, Combine Central Plains and Southeastern Aquifers Scenario*

	Central Plains	South-eastern	Central Plain + Southeastern
Available storage	840.4	883.9	1724.5
Years to exhaust	10	30	19
Add years to exhaust	9	-10	

*See attached Excel file worksheet “Combine CP & SE Aquifers” in Annex 1.

Exhibit 11. Unmet Demand, Combine Central Plains and Southeastern Aquifers Scenario



Note that the Southeastern aquifer when considered separately has an extended life (beyond 2030). To be conservative, we assumed that this life is about 60 years, but it is likely much longer based on the amount of water in storage in 2030 (781 MCM) and the rate at which the aquifer was predicted by the WEAP model to decline (about 5 MCM/year from 2010 to 2030). Combining these aquifers results in an extended life for the Central Plains aquifer of about 9 years (from 10 to 19 years), but a shortened life for the Southeastern aquifer of about 41 years due to the high urban demand of Sana’a City.

Table 38 presents our economic analysis of these effects. The cost of transferring water from the Southeastern to the Central Plains aquifer is estimated at about $0.67/cum.[54] We

---

[54] Based on the estimates in the SAWAS Report.

that Central Plains farmers will continue to use their aquifer at the current cost for the initial 10 years (until the aquifer is exhausted), and then will switch to the higher cost water for the remaining 9 years. Thus, the gain to Central Plains farmers (5,565 ha) will be the added profits over the 9 years of extended life with the higher water costs. The loss to the Southeastern farmers (2,231 ha) is the present value of foregone profits from the reduction of years of production (from 60 to 19 years). As can be seen from ***Table 38***, the results are either a slight gain in total present value (LEI budgets) or a relatively large loss in total present value (World Bank budgets).

Table 38. Economic Analysis of Combine Central Plains and Southeastern Aquifers Scenario– LEI Budgets*

	PV 9 year	**Discounted 10 years**
PV Gain/ha LEI Central	$18,614	$12,000
PV Gain/ha WB Central	$17,586	$10,796
	PV 41 year	**Discounted 19 years**
PV Loss/ha LEI SE 41 years	$68,789	$27,222
PV Loss/ha WB SE 41 years	$90,536	$35,828
Total change LEI	$6,047,718	
Total change WB	-$104,117,693	

*See attached Excel file worksheet “Combine CP & SE Aquifers” in Annex 1.

4.2.8 Import Water from the As Sabata’an (Marib) Aquifer or Desalinated Water from the Red Sea

The costs of importing water from the As Sabata’an aquifer or desalinated Red Sea water ($3.40/cum and $8.00/cum, respectively) have been presented in earlier analyses. It is clear that the cost per cubic meter of this water is much higher than the value of water in irrigation. Thus, the imported water could only be justified for urban water use. Moreover, if the imported water was used to supply urban demands in order to continue irrigation in the Central Plains aquifer, there would be a very large implicit subsidy being provided to irrigated agriculture. As noted above (Urban Improvement), any imported water will have to be accompanied by improvements to the urban water systems, in order to avoid large water and financial losses. We have concluded that the importation of water is a likely solution to meeting urban demand only when the aquifer is exhausted.

4.2.9 Combination of Improve Urban Water Supply and Purchase Wells Scenarios

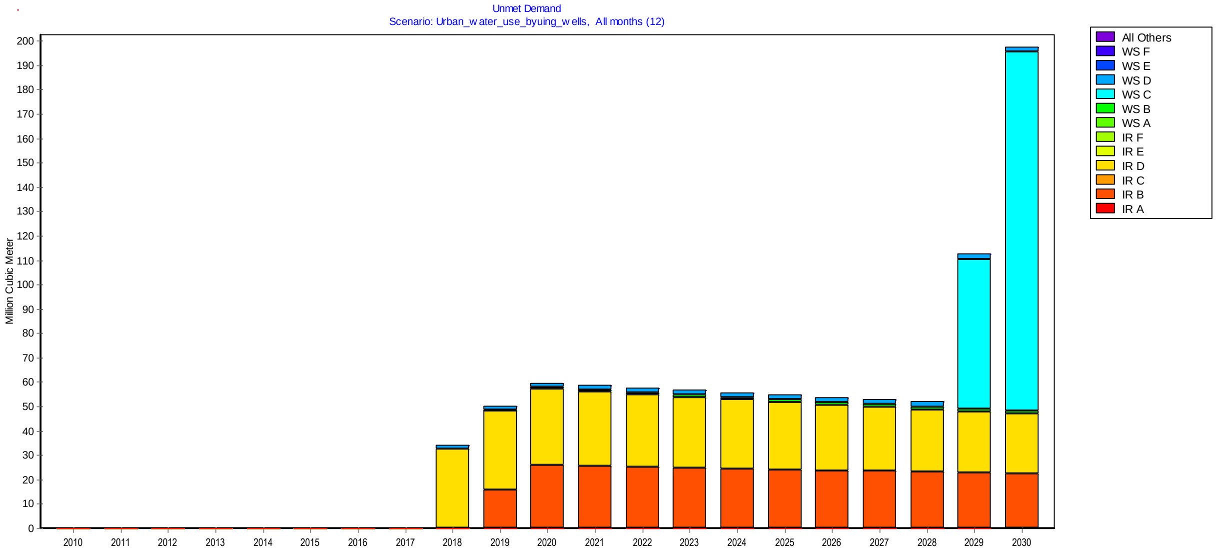
The two options which appear the most effective in prolonging the life of the Central Plains aquifer are improving the urban water systems (7 years) and buying out irrigated land (3 years). We examined a combination of the two, assuming again that these options are implemented immediately. The results can be found in ***Table 39***. These results indicate that the life of the aquifer is extended by 10 years (to 2030). ***Exhibit 12*** indicates the unmet demand for the combined option.

Table 39. Effects of Combining Improve Urban Water Supply and Purchase Wells Scenarios*

	Central Plains Aquifer	North-western Aquifer	North-eastern Aquifer	South-western Aquifer	South-eastern Aquifer	Eastern Aquifer
Available Storage	846.6	185.5	1044.2	867.7	883.7	214.6
Years to exhaust	20	10	30	30	30	8
Add Years to exhaust	10	0	0	0	0	0

*See attached Excel file worksheet “Improve Urban WS and Purchase Wells” in Annex 1.

Exhibit 12. Unmet Demand, Combined Improve Urban Water Supply and Purchase Wells Scenarios*



*See attached Excel file worksheet “Central-Southeastern” in Annex 1.

The avoided cost of importation and the cost of implementation are shown in ***Table 40***. The cost and benefits are approximately equal for the minimum benefit case, but benefits exceed costs by a considerable margin for the maximum benefit (avoided desalination) costs.

Table 40. Costs and Benefits of Combined Option *

PV of Avoided Cost of Importation from the As-Sabata'an aquifer ($3.4/cum)		
Year 10 – on	3.4/.05 = $68/cum	PV = $41.75/cum
Year 20 – on	3.4/.05 = $68/cum	PV = $25.63/cum
Cost avoided		$16.12/cum
PV of avoided cost of importing desalinated water = $8/cum		
Year 10 – on	$8/.05 = $160/cum	PV = $98.23/cum
Year 20 – on	$8/.05 = $160/cum	PV = $60.30/cum
Cost avoided		$37.93/cum
Total Benefits	Minimum	Maximum
	$2,996,708,000	$7,051,187,000
Cost of Implementation		
Total cost of buyout	$306,321,583	
Total PV of cost of urban improvement	$2,411,500,000	
Total cost	$2,717,821,583	

*See attached Excel file worksheet "Central-Southeastern" in Annex 1.

5. Summary and Conclusions

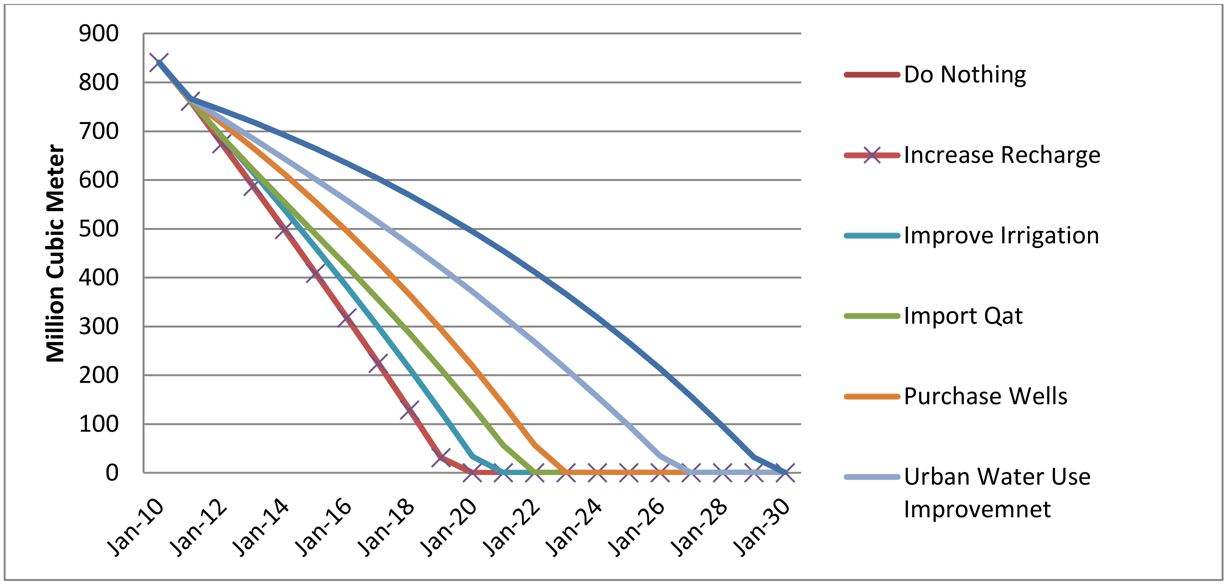
Exhibit 13 indicates the paths to aquifer exhaustion for the Central Plains aquifer for the scenarios examined. ***Table 41*** presents a synopsis of our hydrologic and economic results for the various scenarios for the Central Plains aquifer.

The following are the implications of the results of our analyses in our proposed priority of implementation.

1) Improving the urban water distribution and wastewater collection systems extends the life of the Central Plains aquifer by seven years. Even though the cost is very high and may not be economically justified solely by the extended aquifer life, it should be implemented as a priority for Yemen because it will reduce losses of more expensive water that must be imported in the future for urban use in Sana'a City.

2) Buying out irrigated agriculture may be a cost-effective way to extend the life of the aquifer for 3 years, to postpone the date by which water must be imported from the As Sabata'an aquifer or desalination plants on the Red Sea.

Exhibit 13: Central Plains Aquifer Groundwater Storage under Selected Scenarios*



*The dam recharge option has the same results as the reference option for the Central Plains aquifer.

3) Implementing improved irrigation is financially and economically justified even though it extends the life of only the Northwestern and Eastern aquifers by a few years and has no significant impact on the Central Plains aquifer. However, improving irrigation will generate *private* returns in excess of cost. If there are institutional problems that prevent private farmers from making those investments, such as credit availability, public intervention may be warranted. If not, the gain in aquifer life is not sufficient to warrant public investment. In addition, improving irrigation systems could easily lead to expansion of irrigated areas and may ultimately not produce a net reduction in withdrawals for agriculture.

4) Importing water from other nearby aquifers may be economically justified, but is very likely to have distributional and political consequences that will be barriers to that importation.

5) Importing water from distant aquifers or from the Red Sea is too expensive to maintain irrigated agriculture, but will be necessary to meet Sana'a City's urban water needs for an extended period of time, albeit at a high cost per cubic meter.

The following options do not appear to us as to be effective hydrologically, economically, or politically and should not be regarded as priority actions for water management.

6) Reducing the subsidy to diesel fuel is unlikely to reduce water extraction or extend the aquifer life significantly, and it will cause very large negative impacts on much of the Yemeni economy at least in the short term.

Table 41. Results from Scenarios

Scenario	Extended Life of Aquifer	Unit and Total Benefits (PV)	Unit Costs	Total Costs	Priority
Eliminate diesel subsidy	Very little	Small (based on little extended life)	Loss of up to $6,000/ha/yr in farm profits	Up to $33,390,000/yr in farm income; much more in overall economy	Low
Import qat	2 years	Avoided water import cost of $3.89 - $9.14 per cum; $400,000,000 to $934,000,000	Loss of about $25,000/ha in PV of farm profits; increased qat consumption	Loss of up to $134,000,000 in PV of farm income in Central Plains	Low
Improve irrigation	<1 year	Increase in farm profitability by about $4,000/ha/yr; $22,260,000	About $11,000/ha/yr	$61,215,000 paid off in less than 4 years	Medium to Low
Improve urban water supply	7 years	Avoided water import cost of $12 - $28/cum/yr; $2.2 - $5.3 billion	$188/household/yr	$2,411,500,000	High
Increase recharge	<1 year	Very small in terms of aquifer life	Varies depending on dam and site	Approximately $10,500,000	Low
Purchase wells	3 years	Avoided water import cost of $5.40 - $13.83/cum; $1.0 - $2.6 billion	$0.699/cum/yr or $5.69/cum (PV)	$306,321,600	Medium
Combine Central Plains and Southeastern aquifers	9 years	Gain for Central Plains farms: $17,500 to $18,500/ha; $97,387,500 to $102,952,500	Loss of 41 years for Southeastern: $68,700 to $90,500	Net: gain of $6,000,0000 to loss of $104,000,000	Medium to high
Improve urban water supply and purchase wells	10 years	Avoided water import cost of $16.12 - $37.93/cum; $ 3.0-$7.1 billion (PV)	Sum of costs of both options	Sum of costs of both options; $2.7 billion	Medium
Import water from Marib	>10 years	Sana'a population is provided with water	$68 - $160/cum	$4.7 to $11.7 billion	Will be necessary

Scenario	Extended Life of Aquifer	Unit and Total Benefits (PV)	Unit Costs	Total Costs	Priority
aquifer or desalination		and wastewater treatment			when aquifer is exhausted

7) Importing qat from Ethiopia or other sources is not likely to change the relative profitability of qat and other crops for Yemeni farmers, but it is likely to lower the price of qat in the wholesale and retail markets, lowering producer incomes as well as incomes of other actors in the supply chain. It may also lead to higher levels of consumption. The future of qat is an important socio-political issue, both for Yemen and potential exporters to Yemen, but it is not a critical action for water management.
8) Investing in aquifer recharge through runoff retention facilities is unlikely to extend the aquifer life significantly and the costs will likely exceed the minimal benefit of postponing water importation.