

Sustainable Groundwater Management Concepts & Tools

Case Profile Collection Number 2

Yemen: Rationalizing Groundwater Resource Utilization in the Sana'a Basin

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Sana'a Basin Water Management Program (SBWMP)

The central objective of the SBWMP (now approved for World Bank funding) is to increase the usable life of the aquifers of the Sana'a Basin – thereby postponing long-distance high-lift import of water and allowing time for a shift to a less water-based economy. In recent years groundwater abstraction has considerably exceeded aquifer recharge, and reliable answers to the questions 'what measures can best reduce the rate of aquifer depletion' and 'how long will groundwater stocks last' are critical to defining a realistic water resources strategy. As the final stage of project preparation, GW•MATE was asked to appraise the groundwater balance and the scope for management interventions in the context of an initiative which will include:

- *water-demand management through improved irrigation technology, refocused investment subsidies and irrigation expansion constraints*
- *supply-side measures to enhance groundwater recharge from surface runoff through construction of a range of field trial structures*
- *institutional action, including formalization of stakeholder participation, campaigns of public awareness and regulation of aquifer abstraction*
- *urban wastewater management to improve the treatment process and agricultural reuse of the growing volume of Sana'a sewerage effluent.*

This appraisal is based on information provided during a reconnaissance visit by Sana'a University (Water & Environment Centre), the National Water Resources Agency and the National Water Supply Agency in the Yemen and internationally through subsequent discussions with IAEA-IHS-Vienna, UN-FAO-Cairo and TNO-NITG-Utrecht / IHE-Delft in The Netherlands.

APPRAISAL OF GROUNDWATER RESOURCE BALANCE

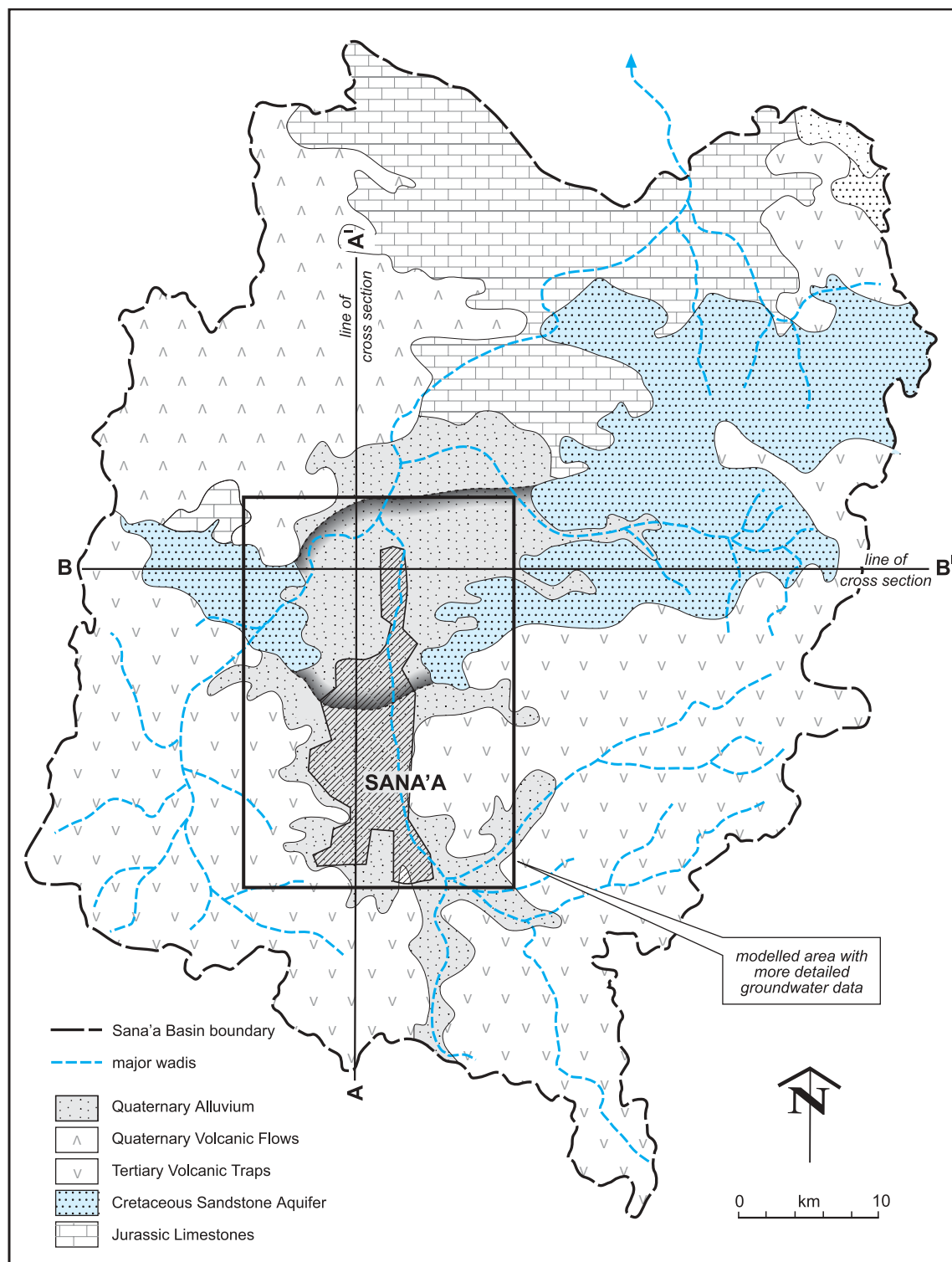
Water Resources Situation & Uncertainty

- The Sana'a Basin is a highland area of some 3,200 km², with a population of 1.8 million growing at 7% per annum. About 75% of the population depends wholly on agricultural activity, which mainly comprises qat and fruit cultivation and livestock rearing. In 2000 around 23,400 ha (7%) of the land area was dedicated to irrigated cultivation, and this area grew rapidly from less than 3,000 ha in 1985 to occupy significant areas of wadi floor and the alluvial outwash plain.

- Almost all of this irrigation is from groundwater (excepting a few very small surface water impoundments) and, in the complete absence of any regulation, around 13,000 waterwells are believed to have been constructed. This can partly be attributed to the heavy subsidy (90%) on fuel for diesel-powered pumps, although this has now been reduced to 50% and is being phased out. In such an arid climate there is a high level of social volatility over water supply with tribal rights and rural interests being strongly defended.
- The average rainfall is about 200 mm/a falling mainly as localized high-intensity episodes (during March-May and July-September) generating sheet runoff and ephemeral wadi flows, which are utilized for spate irrigation. The highest average rainfall rates (above 300 mm/a) occur across the mountainous terrain along the western boundary of the basin. Under current climatic conditions, the Sana'a Basin is an almost-closed system, since less than 1% of total catchment rainfall is estimated to flow out northwards down the Wadi Al-Kharid (Figure 1).
- There are limited data with which to appraise groundwater resources, but all past work has been recently summarized (WEC, 2001), and the most relevant for present purposes is considered to be that of Alderwish (1995) and Bazza (2001). Attempts to define the groundwater balance for the aquifers of the basin have been subject to large uncertainty due to lack of adequate data on:
 - aquifer recharge mechanisms and rates
 - current groundwater abstraction rates and their historic growth
 - aquifer properties and hydraulic connections
 - response of aquifer groundwater levels to increasing abstraction
- As an initial simplification, the approach taken was to review the present groundwater balance on the basis of consumptive use versus active replenishment, avoiding need for detailed consideration of recycling components (such as irrigation returns and wastewater recharge), although these will be critical for evaluation of the options for resource management intervention.

Active Aquifer Replenishment

- Aquifer recharge, as always, is a difficult parameter to quantify. Moreover, considerable confusion may occur when comparing estimates, due to lack of clarity over geographical area and aquifer(s) under consideration, and whether recycling by irrigation returns and wastewater seepage are included.
- Considering new replenishment to the aquifer system only, previous estimates fall into two distinct groups:
 - a 'lower set' in the range 23-38 Mm³/a, derived from analysis of hydrometeorological data for areas occupied by the Quaternary Alluvial Deposits in the central part of the basin and the outcrop of the Cretaceous (Tawilah) Sandstone Aquifer (Figure 1)
 - a 'higher set' which include an allowance (of some 20 Mm³/a) for recharge to the Cretaceous Sandstone Aquifer through thick Tertiary and Quaternary Volcanics in the south-western/south-eastern and north-eastern parts of the basin respectively (Figure 1), calculated questionably from implied hydraulic gradients and assumed aquifer hydraulic continuity.

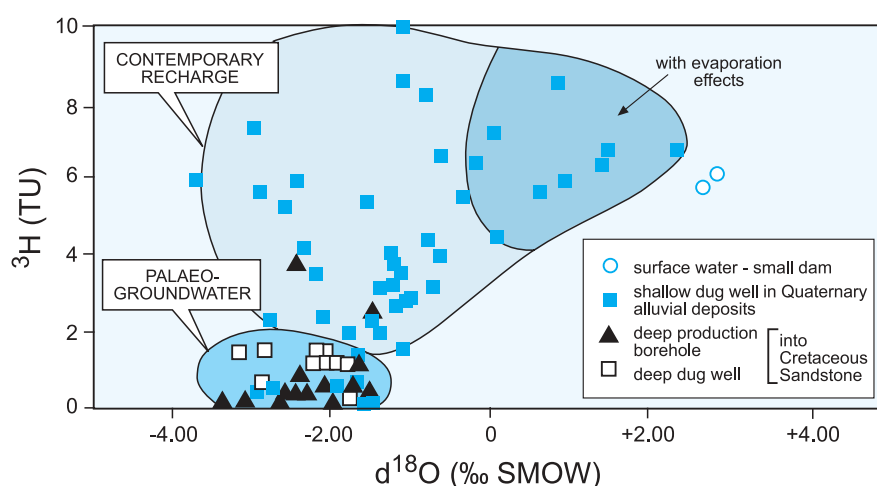
Figure 1: Hydrogeological sketch map of the Sana'a Basin


Evidence from Environmental Isotopes

- A systematic reconnaissance-level survey of the environmental isotope composition of Sana'a Basin groundwaters has been carried out at the initiative of the IAEA-IHS over the past few years. Although interpretation is constrained as a result of the sampling limitations imposed by using waterwells of uncertain and inadequate construction, the results of this work (Aggarwal, Wallin & Stichler, 2003) provide some important insights into the dynamics of aquifer recharge :
 - independent evidence of contemporary natural recharge of the Quaternary Alluvial Aquifer, whose groundwaters invariably show post-1965 tritium concentrations (Figure 2)
 - this tritiated groundwater also exhibits for the most part $d^{18}O$ values of -1.00 to -3.00 (Figure 2), which are characteristic of higher-intensity rainfall episodes (more than 20 mm/d)
 - some groundwaters in this aquifer (mainly in the wadis of sub-basins 14 and 19, immediately west and southeast of Sana'a City) exhibit a marked tendency towards evaporative effects (values of $d^{18}O$ of above 0.00 and d^2H greater than + 5.00), consistent with a recharge component from surface empoundments (Figure 2).

The effects of fractionation through irrigation use and return while discernible are less clearly marked, and more work is needed to characterise this component.

Figure 2: Characterization of Sana'a Basin groundwaters by their isotopic composition (samples from Sana'a Basin subcatchments 9,14,15,16,17 and 19)



- There is no definitive evidence in the current data of contemporary recharge having reached the Cretaceous Sandstone Aquifer, which currently yields groundwater light in stable isotopes, similar to high-intensity contemporary rainfall but with less than 1 TU and low ^{14}C (20-30% MC). Some so-called 'deep wells', however, tap both this aquifer and the overlying Quaternary Alluvial Aquifer and are the probable reason for anomalies. However, these results do not yet exclude the possibility of modern recharge to the Cretaceous Sandstone Aquifer since:
 - the isotope reconnaissance survey did not include significant areas where the aquifer is at outcrop
 - a major time lag is likely in downward leakage from the overlying alluvial aquifer (the alluvial outwash deposits being 50-200 m thick).

Consumptive Use of Groundwater

- Estimation of present consumptive use by irrigated agriculture is subject to considerable uncertainty. Moreover, it is not helpful to compare estimates of different dates because of rapid growth of groundwater abstraction and irrigated land since 1985.
- Recent UN-FAO work (Bazza, 2001) estimated gross groundwater abstraction for an irrigated agricultural area of 23,400 ha at 208 Mm³/a, by scaling-up figures for well pumping periods/rates, irrigation frequency and unit irrigated area from a pilot study area. And although typical irrigation efficiency was put at only 40%, irrigation return was judged not to exceed 20%, suggesting a consumptive use of groundwater in agriculture of 166 Mm³/a but also implying a substantial component of non-beneficial evaporation losses.
- In the same work program satellite imagery (which gave excellent definition of land use and crop type) was also used to estimate evapotranspiration from the cultivated area. For the year 2000 this came out with an exceptionally low figure of 75 Mm³/a (bearing in mind that it represents both beneficial and non-beneficial evapotranspiration of irrigation water plus rainfall from both irrigated cultivation and rain fed crops/vegetation), although there are serious reservations about its validity as a result of extreme local variability and potential bias at the times of satellite pass.
- An earlier study (Alderwish, 1993) puts abstraction at 149 Mm³/a for an irrigated area of 21,600 ha, with an average irrigation return of 30%. Adjusting these figures to an irrigated area of 23,400 ha would imply a consumptive agricultural use of 113 Mm³/a.
- The abstraction for urban and industrial use in the Sana'a conurbation (population 1.32 million) has been estimated more precisely at 21-24 Mm³/a. This conurbation is provided by NWSA-Sana'a (mainly from two well fields to the north) and from private boreholes directly or via water trucks. Since most is returned to the ground via mains leakage and on-site sanitation, the net urban water consumption is only about 3 Mm³/a, or 7 Mm³/a if that part of sewage effluent used for (low-value) crop irrigation is included.

State of Resource Imbalance

- Certain conclusions on the resource imbalance (Table 1) can be reached despite the high level of uncertainty in groundwater recharge and discharge estimates:
 - substantial mining of groundwater storage in the Sana'a Basin, principally by resource exploitation for irrigated agriculture, is occurring
 - the level of imbalance is very uncertain—somewhere in the range 44-150 Mm³/a, having grown from zero at some time during 1978-86
 - even with widespread agricultural real water-saving measures and wadi artificial recharge measures, it is unlikely that the replenishment-consumption imbalance can be completely closed without substantial reduction in the irrigated area of the Sana'a Basin.

Table 1: Range of recent estimates for the groundwater resource balance

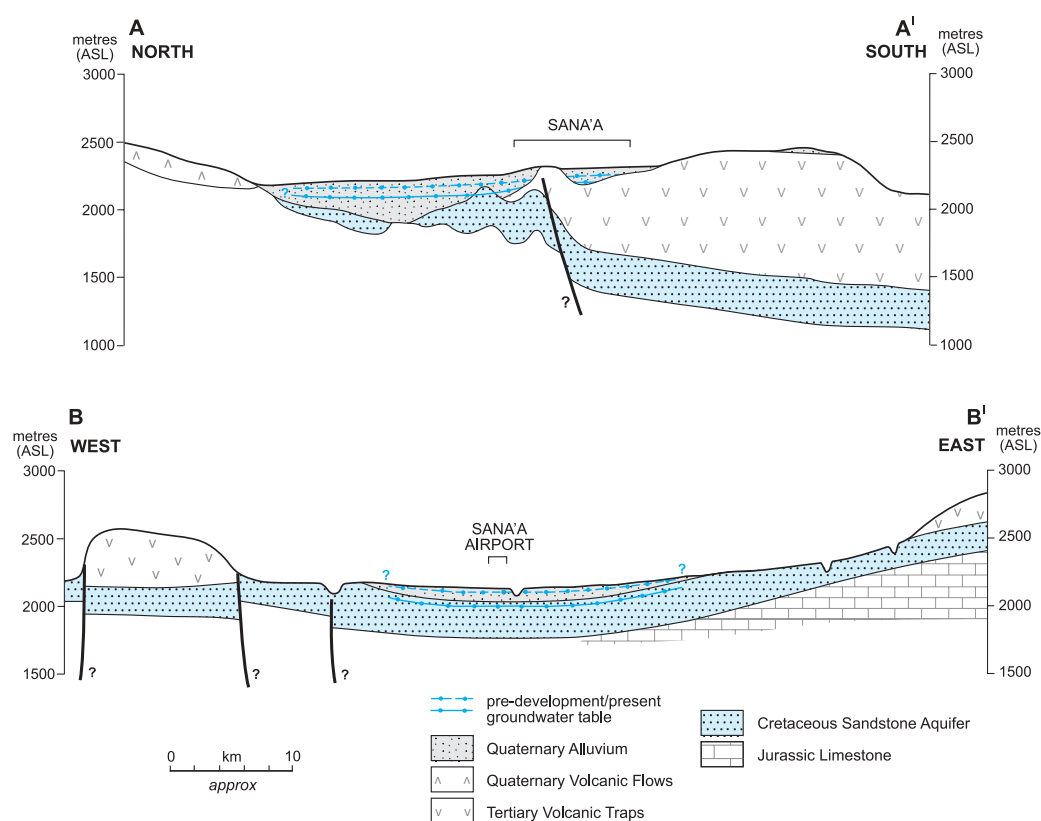
PARAMETER (2000 ESTIMATE)	RANGE OF ESTIMATES (MM ³ /A)	
	Minimum	Maximum
Active Aquifer Replenishment	+23***	+38***
Consumptive Use of Groundwater*	-173	-120
Mining of Aquifer Storage**	-150	-82***

* discounting the questionable 2000 estimate from satellite imagery of 75 Mm³/a, which should it prove valid would substantially reduce the rate of mining of aquifer storage

** net value, since in some parts of urban area groundwater levels are rising

*** if groundwater inflow from the southwest and southeast were proven then replenishment would increase and rate of mining decrease by about 20 Mm³/a

- The mining of groundwater storage reserves initially affected the Quaternary Alluvial Aquifer, which is now almost dry over significant areas despite the fact that groundwater levels are locally rising (by around 1 m/a) in the Sana'a City area (as a result of wastewater discharge to the ground). Accelerated depletion is also occurring in the Cretaceous Sandstone Aquifer (Figure 3). However, there is very little reliable measurement (and no continuous monitoring) of groundwater levels to aid the corroboration and quantification of the mining of groundwater storage. Regularly measured deep boreholes in the vicinity of the NWSA NW and NE Well fields give average rates of depletion of 3.7 and 4.2 m/a respectively during 1981-93, and hearsay from the major Wadi Al-Sirra irrigation area suggests water-levels are now falling at 3-6 m/a.

Figure 3: Hydrogeological cross-sections of the Sana'a Basin illustrating the occurrence of the Cretaceous Sandstone and Quaternary Alluvial aquifers


GROUNDWATER QUALITY CONSIDERATIONS

- Some past reports talk of a general decline of groundwater quality and serious risk of salinization. But there is little direct evidence, with most groundwaters having EC in the range 300-700 $\mu\text{S}/\text{cm}$, and it appears more likely that:
 - the entire basin was 'well flushed' during some Pleistocene episodes of much wetter climate (when outflow northwards would have been a continuous process)
 - there is no major occurrence of saline strata outcropping within the basin.
- Nevertheless, consideration of aquifer 'salt balances' and investigation of groundwater quality in the main irrigation areas would be prudent. Sampling/analysis of the shallow wells in this area is especially recommended to detect any deterioration associated with irrigation returns, although it is possible that such returns are still held as vadose zone pore-waters.
- Evidence of groundwater quality deterioration is mainly in the Sana'a urban area and immediately 'downstream' (Figure 1) (Foppen, 2002):
 - in densely-populated parts of the city shallow groundwater in the Quaternary Alluvial Deposits is said to have $\text{NO}_3\text{-N}$ and Cl concentrations in excess of 100 mg/l (and is likely also to have elevated DOC concentrations and certain types of industrial contaminants) as a result of wastewater disposal to the ground in unsewered areas
 - in the Beni Al-Harith area (close to the airport) groundwater is said to show similar tendencies as a result of past and present practices for the handling, discharge and reuse of urban sewerage effluent.
- Such groundwater pollution will become attenuated with depth, and it is not yet clear where the delicate balance lies between replenishment and pollution of the deeper aquifers. With the progressive extension of the Sana'a mains sewerage system, there will be a steady reduction in both aquifer recharge and contaminant load within Sana'a itself and an increased recharge and loading of salts and excess nutrients in the downstream area where wastewater irrigation is practiced. Careful planning will be required to minimize the negative effects.

SCOPE FOR DEMAND-SIDE AND SUPPLY-SIDE INTERVENTIONS

Agricultural Water-Demand Management

- The predominant crops are qat, grapes and mixed crops (including vegetables and animal fodder), which at present comprise around 50%, 35% and 15% of the irrigated area respectively. In the recent UN-FAO work (Bazza, 2001) estimates of crop water-use are made using independent approaches and it is instructive to consider these (Table 2).
- Only two past studies (Alderwish 1993 and Bazza 2001) have relatively detailed consideration of the soil-water balance for irrigated agriculture. However, no consistent picture emerges (for typical irrigation practices on the predominant crops) of:
 - average infiltration losses (irrigation returns to groundwater), which are variously put at from 15-20% to 30-35%

- non-beneficial evaporation (irrigation losses to the atmosphere), arising mainly from both evaporative losses in the irrigation water distribution system and from direct soil evaporation of irrigation water, which are not defined because of absence of diagnostic data.

Irrigation efficiency for most currently practiced techniques is put at about 40%, but there is implied disagreement on how this is apportioned between the above two components.

- It is also instructive to look at the detail of current irrigation practices at field level. Farmers do not irrigate qat and grapes on a continuous basis even outside of wet season – grapes are deliberately subjected to water stress during their dormant period (October-February) and qat is only irrigated in the 4-5 months before the required harvest date. Thus most groundwater irrigation is concentrated in a 5-month period when the average crop water requirement amounts to around 475 mm. Flood irrigation is practiced with some 5-6 large applications (120 -180 mm) during this period amounting to a cumulative irrigation lamina of some 825 mm. But it is uncertain what proportion of the balance of 350 mm is lost as non-beneficial evaporation and how much returns to groundwater as deep infiltration.

Table 2: Comparison of estimates of crop water use for the Sana'a Basin

CROP TYPE	CROP WATER-USE REQUIREMENT (mm/a)**		TOTAL IRRIGATION LAMINA (mm/a)*****
	by agrometeorology***	by satellite imagery ****	
Oat	1341	811	806
Grapes	1263	403	840
Vegetables *	1270	906	1238

* assuming a cropping intensity of 1.5 and with typically individual irrigation lamina of 100 mm and 12 applications per year

** will be provided not only by groundwater irrigation but also by direct rainfall and spate irrigation which probably amounts to at least 300 mm/a on average

*** using CROPWAT model which gives maximum figure assuming no soil moisture deficit

**** includes both crop beneficial /non-beneficial evapotranspiration but exhibits very wide spatial variation (more than +/- 50%) and will also vary annually (2000 figures indicated)

***** observations of typical field practices

- There is little doubt that irrigation efficiency overall could be readily improved to about 60%, even with relatively simple technology. But improving the estimates of non-beneficial irrigation water losses (as distinct from irrigation returns) is a very high priority to determine the scope for 'real water resource savings' through irrigation water management (as opposed to merely 'energy saving' by increasing irrigation water-use efficiency through reducing irrigation returns to groundwater). If the scope for field-level water saving proves in practice to be limited, the implication would be that the only way to constrain the current rate of aquifer overdraft would be to reduce the area under irrigated agriculture.

Aquifer Recharge Enhancement Measures

Overall Scope for Augmenting Groundwater Resources

- At basin level, the key (as yet not fully answered) questions are:
 - to what extent does existing wadi runoff and associated spate irrigation become 'lost' through non-beneficial evaporation and/or discharge to saline water bodies – if these 'losses' were small then the proposed recharge enhancement structures will only spatially re-distribute groundwater resources but not augment them
 - to what degree, and in what areas, is potential recharge to the deep Cretaceous Sandstone Aquifer temporarily intercepted and/or permanently retained in localized shallow Quaternary Alluvial Aquifers, and how important are such 'perched' aquifers for domestic and irrigation water supply.
- These questions need to be resolved to judge how much overall effort should be put into the promotion of recharge enhancement structures in the upper sections of wadis, which are underlain by Cretaceous Sandstone at depth. However, from general field observation there seems little doubt that a significant proportion of current wadi runoff is lost by non-beneficial evaporation, and the application of environmental isotope techniques, coupled with the well sampling campaigns of the last 3 years, has provided some insight into the latter question.

Appropriate Technological Options

- Four distinct types of low-cost structure for the artificial enhancement of groundwater recharge from arid zone storm runoff can be identified (Table 3). Clearly all such structures should be located at sites with potential for high rates of infiltration and absence of shallow low permeability strata which could cause groundwater perching impeding the deep infiltration process.
- A number of general observations on the Sana'a Basin can be made:
 - the deposits comprising the wadi beds themselves and adjacent valley floors (throughout their middle and upper reaches) appear to have high permeability and be widely favorable for groundwater recharge
 - the quoted runoff volumes available for recharge in the 'upper reaches' of wadis (beyond the limit of terrace cultivation) are very small (generally less than 0.2 Mm³/a) and cost effectiveness will need to be considered
 - to increase the wadi runoff available for recharge, sites further downstream will be required, but the widespread artificial terraces alongside the wadi bed (for cultivation or house construction) normally precludes construction of anything larger than small 'check dams'
 - farming communities are well aware of need to 'harvest' wadi stormflows and the area is littered with small structures (in varying states of maintenance) designed primarily to divert spate flow onto adjacent land.
- Smaller 'check dams' along the upper-middle lengths of wadis, where Alluvial Deposits overlie Cretaceous Sandstone, are likely to be more economical and effective in aquifer recharge terms, and would be an excellent vehicle to engage local communities in practical action for water resources conservation.

Table 3: Possible types of aquifer recharge enhancement structures appropriate for the Sana'a Basin

CLASS OF STRUCTURE	GENERAL FEATURES	PREFERRED APPLICATION
Spate Check Dams	structures (2-5 m high) within watercourse to detain flood runoff and augment wadi-bed infiltration; first structure tends to retain suspended solids with enhanced 'clearwater' infiltration below	low cost makes suitable where runoff frequency and volume uncertain; also where watercourse slope high and adjacent land/terraces used for productive agriculture
Recharge Basins	part of storm runoff diverted into series of artificially-excavated basins (normally 2-4 m deep) on adjacent flood plain, normally with pre-basin for reduction of suspended solids	necessary if uppermost layers of alluvial deposits are of low permeability and need to be removed to achieve high infiltration rate; only possible if suitable unused land available
Valley Dam	superficially more conventional dam across entire valley (of 10-20 m height), but with reservoir floor used for infiltration; may also be used for regular release of clearwater for wadi-bed infiltration	in middle-to-upper reaches of watercourses eroded into important aquifers with deep water-table and where runoff is sufficient to justify larger capacity structure
Subsurface Cut-Off Wall	impermeable membrane or puddle clay placed in cut-off trench (normally 1-5 m depth) across entire valley so as to impound shallow groundwater underflow within the valley, making it easier to abstract from dugwells or collector wells	only suitable for relatively wide valleys with thin alluvial deposits and weathered rockhead overlying impermeable bedrock, where soil salinity is low and if crops being grown are not sensitive to occasional waterlogging

- An essential aspect of the maintenance of all such structures should be the periodic removal of alluvial sediment (fine sand, silt and clay) and organic material (bacterial slimes and algae) that tend to accumulate, so as to restore the infiltration capacity of the reservoir and/or wadi floor. It is important that the materials removed are recycled as a top dressing for agricultural soils.
- The rigorous technical and economic evaluation of the effectiveness of recharge enhancement structures is far from straightforward. The key requirement is to estimate the additional runoff that is recharged over-and-above that which would have occurred naturally (i.e. the difference between 'with project' and 'without project' conditions). This is difficult to fulfill because of uncertainty over rainfall-runoff relations and of limited gauging/spot measurements of flow. Nevertheless, the first structures emplaced must be regarded as 'pilots' and monitored systematically (over 5 years) to enable analysis of their cost effectiveness in terms of US\$/m³ of water harvested to be assessed

EVALUATION OF AQUIFER STORAGE RESERVES

- Current water resources strategy rests heavily upon the 'mining' of aquifer storage reserves for agricultural water-supply to 'buy time' for socio-economic transition to a less water-dependent local economy. In this sense it is critical to have more reliable estimates of the:
 - drainable storage of the aquifer system, its geometry and hydrostratigraphy
 - actual consumptive groundwater use and its spatial distribution compared to that of aquifer recharge.

- The existing MODFLOW numerical aquifer model (developed by TNO-NITG-Utrecht and subsequently refined by IHE-Delft in association with WEC-Sana'a) assumes K and Sy for the Cretaceous Sandstone Aquifer of 0.3-1.0 m/d (higher in known fracture zones) and 0.02-0.08 respectively (NWSA/TNO-NITG,1996). It was calibrated to 1995 survey data, using Sy and I (recharge) as variables, and then verified (with variable success) to 1995-2002 observation well data.
- However, there remain major uncertainties in terms of:
 - the extension and continuity of the sandstone aquifer, which determines the preferred distribution of production wells to sustain a given supply
 - the rate of recharge to the aquifer system, which determines the sustainable supply that can be withdrawn for consumptive use
 - the spatial and vertical variation in the Sy of the aquifer, which determines (in conjunction with the aquifer geometry) the rate of mining of non-renewable aquifer reserves that can be achieved
 - the reduction of transmissivity with falling water-table, which will decide the number of waterwells needed to abstract a given rate of supply.
- There is still insufficient focus on the quantification of the exploitable groundwater storage of the main aquifers. In 'more conventional' groundwater management, where physical sustainability and aquifer equilibrium are central axioms, this is not required. But where water resources strategy hinges upon the mining of aquifer storage the following are required:
 - maps of groundwater level depletion for each aquifer, using pre-development data and current recovery production well measurements
 - study of aquifer stratigraphic variations and the probable distribution of horizons with significant drainable intergranular storage
 - laboratory and field tests to determine porosity and pore-size distribution to give insight on aquifer specific yield.

Purpose-drilled boreholes will be required for the above and they could also be used to obtain closely controlled groundwater depth samples for chemical and isotopic analyses to elucidate evidence for hydraulic connection of the deep Cretaceous Sandstone with the overlying Quaternary Alluvial Aquifer.

Further Reading

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Publication Arrangements

The GW•MATE Case Profile Collection is published by the World Bank, Washington D.C., USA. It is also available in electronic form on the World Bank water resources website (www.worldbank.org/gwmate) and the Global Water Partnership website (www.gwpforum.org).

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