With compliments to my colleagues in Yemen and abroad

WATER CRISIS IN YEMEN: SPECULATIONS, REALITIES AND MITIGATION ACTIONS

(INTRODUCTION TO THE UPGRADED WATER MANAGEMENT)

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Sana'a, July 2012

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1. HOW GROUNDWATER CRISIS IS DIAGNOSED IN YEMEN?

1.1 COMMONLY ADOPTED CONCEPT

It is currently accepted by most of water experts and widely discussing in mass-media that Yemen is facing a dramatic water shortage that is unprecedented in its history:

http://yemenpost.net/Detail123456789.aspx?ID=100&SubID=4356&MainCat=5
http://yemenpost.net/Detail123456789.aspx?ID=100&SubID=5086&MainCat=7
http://www.irinnews.org/Report/95907/YEMEN-Water-fights-spark-concern-over-refugee-influxhttp://www.irinnews.org/Report/88522/YEMEN-Capital-city-faces-2017-water-crunch
http://www.yobserver.com/environment/10017024
htmlhttp://www.yobserver.com/environment/10014833.html
http://www.yobserver.com/environment/10014113.html
http://www.yobserver.com/environment/10013725.html

Many other similar warnings can easily be found.

Nearly everyone believes that water shortage/depletion in the country is going on with an alarming rate. Many water institutions and donor agencies have published dramatic comparisons between the renewable resource available and the annual groundwater withdrawal. For example, the NWSSIP (2005) has stated that: *"in 2000, the annual water use has been estimated at 3.4 billion cubic meters exceeding by more than one third the annual renewable freshwater resource (estimated between 2.1 –2.4 billion cubic meters). This means that there is an annual water deficit of about one billion cubic meters… ".*

The same and even more dramatic warnings can be found in many technical reports and mass-media: (a) the city of Sana'a is predicted to be the first capital in the world to run out of economically viable water supplies by 2017; (b) groundwater resources in urban areas face depletion threats in 20 years to come; (c) water tables in the Sana'a Basin were reported to be falling by 3 to 4 m/year that will result in complete exhaustion of the Central Plains aquifer zone in as few as nine years; etc.

This pessimistic scenario is usually supported by the following evidences:

- Huge water deficit calculated between the volume of natural recharge and groundwater abstraction reported from many basin-scale water balances;
- Information on a rapid decline in groundwater level reported from some public water supply wells; and
- Interviews with the local farmers which complain that an increasing number of private wells are going dry.

1.2 SHORTCOMINGS OF AVAILABLE RECHARGE ESTIMATES

Basin-scale level. A wide range of the volumes of recharge calculated for the same basins are available from many technical studies as shown in Table 1:

Table 1. Different recharge estimates available for selected basins

Basin	Recharge, Mm^3/year	Information source
Abyan Delta	105	FAO, 1992
	109	WRAY-34, 1995
	96	Komex, 2002
	300	PTP-II, 2004
Sana'a Basin	59	Italconsult, 1973
	32	Humphreys & Sons, 1977
	56	Mosgiprovodkhoz, 1986
	42	TS-HWC, 1992
	102	Alderwish and Dottridge, 1996
	32	SAWAS, 1996
	53.4	Hydrosult, 2010
Sa'adah Basin	3	TS-HWC, 1992
	10	WRAY-3, 1985
	32	Techniplan, 2004
Amran Basin	9	BGR/GTZ, 1977
	17	DHV, 1993

Obviously, such uncertainty of recharge estimates cannot serve a basis for the adequate water resources management. In the case of the Abyan Delta, for instance, the following conflicting conclusions have been drawn: (a) groundwater recharge and abstraction are in balance (Komex,2002); (b) deficit in groundwater balance at 35 Mm^3/year (Margane, 2004); and (c) huge groundwater recharge surplus over abstraction at 200-250 Mm^3/year (PTP II, 2004).

Furthermore, in the case of a highly exploited aquifer, groundwater recharge cannot be considered as the solely natural downward phenomenon, such as rainfall/runoff infiltration. In highly disturbed hydraulic conditions, it should include also both lateral inflows from adjacent aquifer units and upward inflows from lower units whenever differences in hydraulic heads as a result of significant pumping can support upward circulations. In terms of recharging boundaries, this would mean that available recharge estimates are likely to be seriously revised because they merely ignored the increasing emphasis on the three-dimensional inflows under pumping-induced conditions.

For the above reason, none of the available water-balance estimates can be considered definitive mainly due to very speculative methods applied to estimate groundwater recharge. The theoretical approaches correctly used to estimate recharge 30-40 years ago cannot be now automatically repeated because the hydraulic environment in all critical basins has been principally changed as compared with previous nearly undisturbed conditions.

National-scale level. Because the sufficient part of Yemen (including Ramlat As Sabatayn, Al Rub Al Khali, Jawl Plateaus, Mahra Governorate, etc.) is almost completely unstudied in terms of water resources, several attempts to evaluate the entire national water potential undertaken in the past make very little sense because they used a simple aggregation of incomplete and mostly unreliable local data sets.

1.3 WATER DEPLETION REPORTED AT SOME WELLS

The simple evidence that groundwater levels are declining in time is the most easily observable phenomenon that is commonly used in Yemen to prove the basin-scale water depletion. However, a decline in groundwater level at individual well is not the sole indicator of the real aquifer's exhaustion (groundwater mining).

It is known from the well hydraulics that as pumping continues, more water must be derived from the aquifer storage at a greater distance from the well. This means that the cone of depression must expand, and the radius of influence of the well increases. Drawdown at any point *within the radius of influence* also increases as the cone deepens. The cone of depression will continue to enlarge until it intercepts enough recharge to equal the pumping rate. When the cone has stopped expanding because of the above condition, equilibrium exists, and there is no further drawdown with continuing pumping. This is true, however, if the well is pumping **at a constant rate**. Obviously, this is not a case in Yemen where a number of new wells (and, accordingly, a cumulative rate of abstraction) is growing dramatically in time. At constantly increasing pumping rate, the cone of depression will continue to deep and expand for years and decades even in conditions of significant recharge. Simultaneously, shallow wells situated within the radius of influence of the large wellfields are going dry. But - in terms of well hydraulics - this phenomenon does not mean that groundwater mining occurs when the groundwater table is not declining outside a cone of depression.

The introduction of motorized pumps and modern drilling techniques in Yemen has led to a rapid growth in pumped abstraction since the 1970s, and the abstraction is still increasing. An example (unfortunately, slightly outdated) of this well-known general historic trend which is common in all critical water basins is shown in Figure 1:

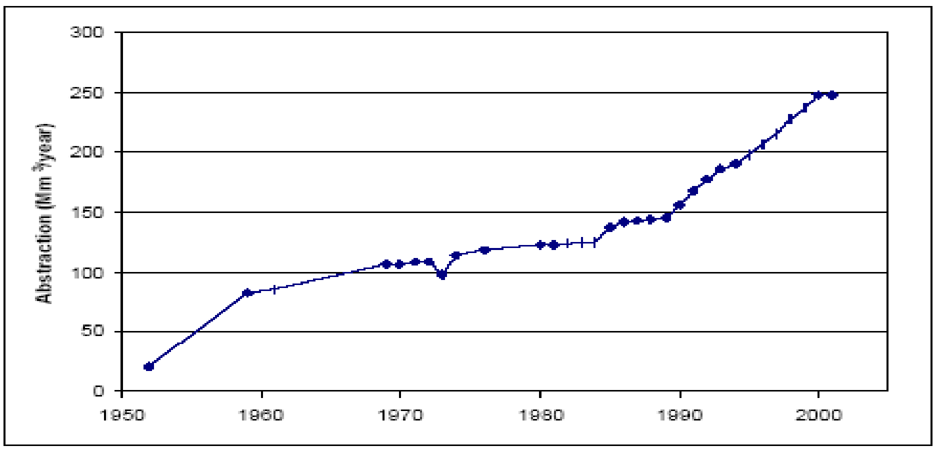


Figure 1. Typical example of the historic groundwater development (Wadi Hadhramawt)

Many public and private wells are situated in the radius of influence (cone of depression) of the large wellfields or areas of concentrated pumped irrigation. Not surprising, therefore, that these wells show a decline in water level due to continuing and increasing **cumulative** effect of groundwater abstraction from tens of closely spaced and interfering wells ("big holes").

In this context, a reasonable tool to prove an occurrence of unrecoverable aquifer's exhaustion (or a lack of exhaustion) in the vicinity of the public water sources is to precede in time the trend of so-called *"specific drawdown"* (S/Q), i.e. drawdown divided by the volume of abstraction: a lack of continuous increase of (S/Q) in time would mean optimistic scenario (no unrecoverable exhaustion) when an increase of drawdown is simply a result of continuous increase of abstraction, or, visa versa, the increase of (S/Q) in time is an indicator of an actual exhaustion of the aquifer, i.e. groundwater mining (pessimistic scenario). Long-term monitoring records are required for this simple analysis in combination with the data on groundwater abstraction which might be collected from the national archives.

Another possible reason of a dramatic depletion reported from some operating wells (both public and private) could be associated with a number of technical problems. Because a boom in introduction of the modern drilling techniques has launched in Yemen more than 40 years ago, a life-time of many operating wells is currently exceeded or close to elapse. The wells which were qualified by owners as dry should be examined and/or rehabilitated, because the installations (pumps, screens) could be improperly designed in the past or simply incrustated.

Case study 1: Examination of Hajjah public water supply well SN-2 (2009):

After completion of drilling, the drawdown-recovery pumping test has been conducted at the well with a yield of 14 l/s. The same yield was recommended by the drilling contractor for the constant well operating. After several months of operating, however, it was found by the governmental agency that a rapid drawdown occurs during the initial phase of pumping and the yield is quickly reducing in minutes. For this reason, the well is currently operating during only 1 hour after 3 hours of waiting for a water level recovery. A short pumping test conducted *in situ* by the NWRA field team confirmed a significant drawdown at the initial phase of pumping. It was recommended to remove and check the screen and pump. Obviously, no "depletion" took place in this location because a recovery of water level has been reported after termination of pumping and no change in water level was measured at the observation well located at a distance of about 10 m of the operating well.

In the case of private irrigation wells, local farmers often call some wells "dry" when they fail to produce water enough for irrigation purpose despite the water is actually available in these wells. On the other hand, many farmers prefer to complain during the interview with the officials in a hope to receive a subsidy or other governmental support rather than provide the reliable information.

Case study 2: Reconnaissance survey in Dhamar (2008):

In response to the request of the local Sheikh, NWRA HQ has carried out an urgent investigation in Al-Qazwah (Dhamar Plain) in order to understand the reason of groundwater depletion that has led to a critical situation when many of the shallow dug-wells "*were going dry*" (in terms of Sheikh). *In-situ* it was found, however, that instead of expected depletion, the local farmers complained that their dug-wells have very low yields and after couple of hours of pumping they should wait 2-3 days when the next short pumping has become possible. The collected rock samples showed that the local aquifer system is composed of the compact basalt lava which is not densely fractured. So, the really sad social environment within the local community takes place because of poor permeability of water-bearing formation rather than due to the actual exhaustion of the aquifer system.

Because of uncertainties in the recharge estimates and other evidences briefly discussed above, a threat of the coming national water crisis due to the total and unrecoverable water depletion seems to be premature overstated.

2. SUFFICIENT EVIDENCE IGNORED IN YEMENI WATER MANAGEMENT

Water resources management plans – WRMP (either established, or drafted) are formulated with the purpose to manage properly the resource of the known quality and quantity available in different basins in Yemen. However, the quantities of the resource to be adequately managed between competing water users are calculated solely based on the questionable balance estimates. These balance estimates (including modeling exercises) have not been correlated with and calibrated against the physical (hydraulic) evidence that might easily be collected and analyzed to avoid significant errors and uncertainties.

Unfortunately, none of the previous, even fundamental, technical reports (WEC, Komex, JICA, Hydrosult, etc.) – which were intended to provide a reliable basis for the WRMPs - contains a presentation and analysis of the long-term groundwater level monitoring data available from many tens of observation stations. It seems this is the big disadvantage because monitoring records provide reasonable physical evidence which reflects associated changes in the resource availability that is crucial in quantification of the water balance and, on this basis, for a wise decision-making.

In order to fill this sufficient information gap, the first countrywide analysis of the long-term monitoring records has been undertaken under the NWRA-WSSP. The outputs of this study can be found in a series of 9 technical reports (V.Rybakov et al., 2010-2011).

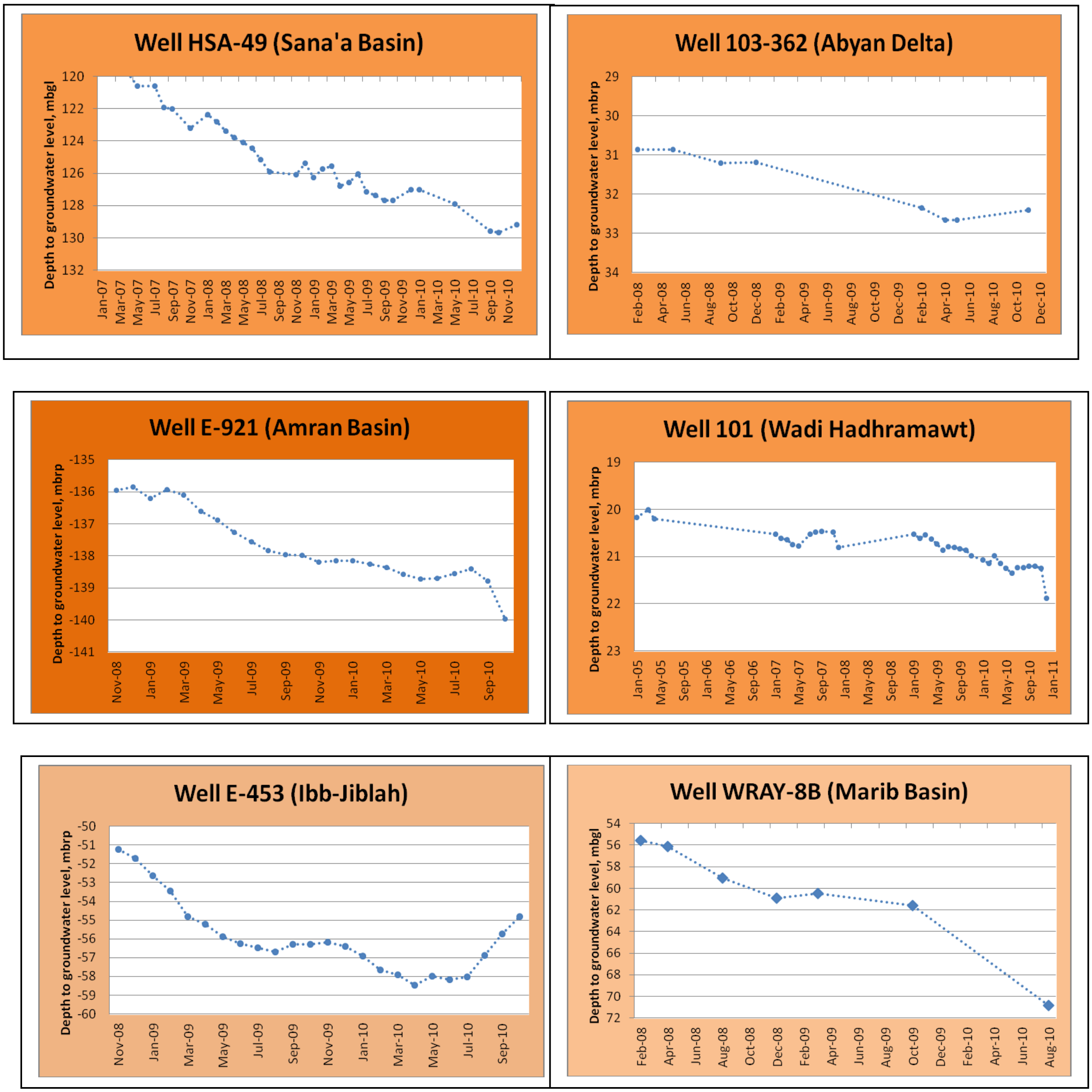
2.1 LONG-TERM RECORDS OF GROUNDWATER LEVEL

As a result of 2010-2011 technical study, the long-term monitoring records available for the last 5-7 years have been collected from the NWRA's observation stations located in the nine critical basins: (1) Sana'a; (2) Tuban; (3) Abyan; (4) Amran; (5) Wadi Hadhramawt; (6) Ibb-Jiblah; (7) Marib; (8) Wadi Surdud - Tihama; and (9) Ta'iz. Unfortunately, this study has not been completed due to a suspension of the WSSP.

It was found that many of existing monitoring stations have been established at operating which are unsuitable for collecting reliable records. A total of 180 well hydrographs (i.e. graphs showing changes in depth to water table in time) have been constructed based on the reasonable historic records and after elimination of unreliable measurements of a dynamic water level. The constructed hydrographs show several different patterns of the long-term changes in groundwater level which are presented in the following sections.

2.1.1 Decline in groundwater level in critical basins

This pattern of hydrograph indicates that the local recharge and discharge rates were out of balance in the vicinity of some monitoring stations. Despite the periods of falling water level were interrupted in some locations by irregular periods of a recharge, they were inadequate to compensate for discharges. The recovery of water levels was not complete in any of the recharge episodes (Figure2):



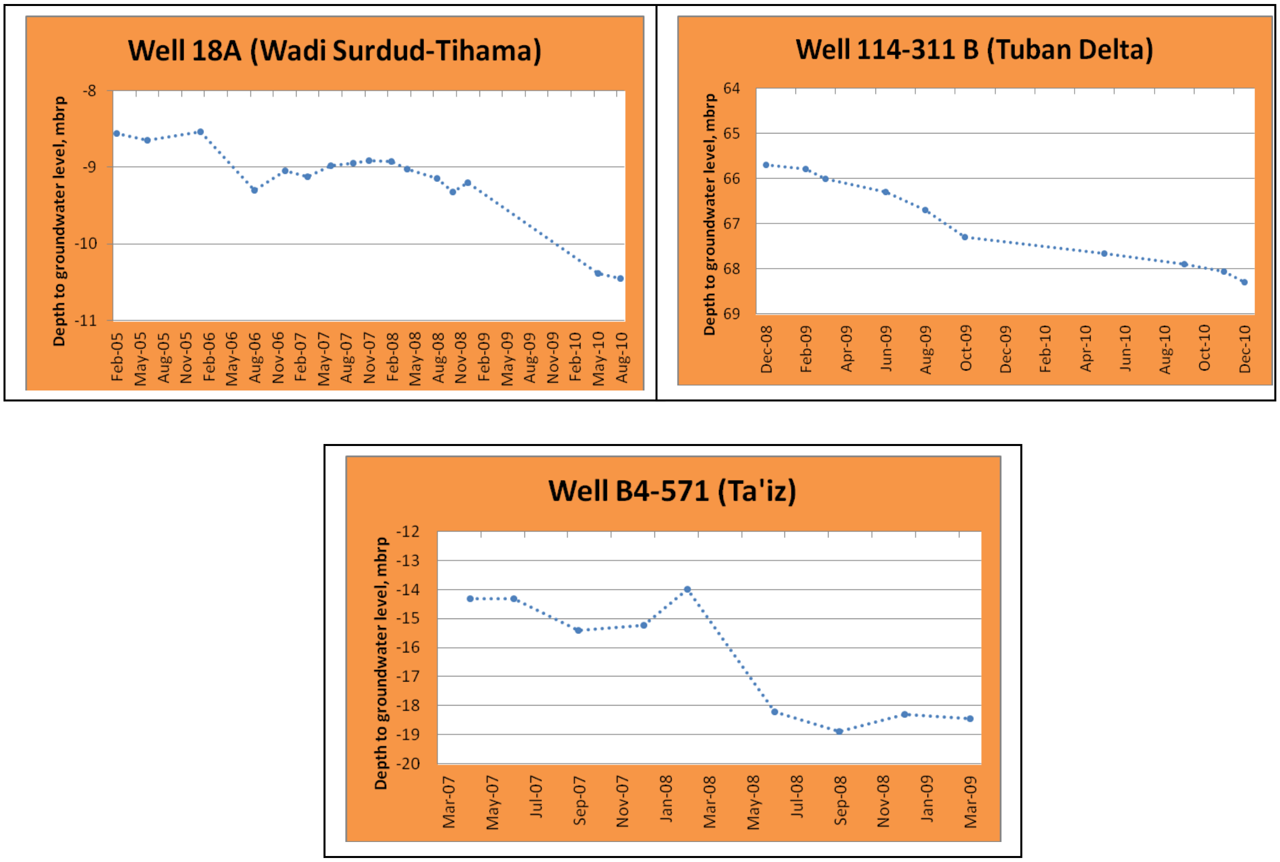
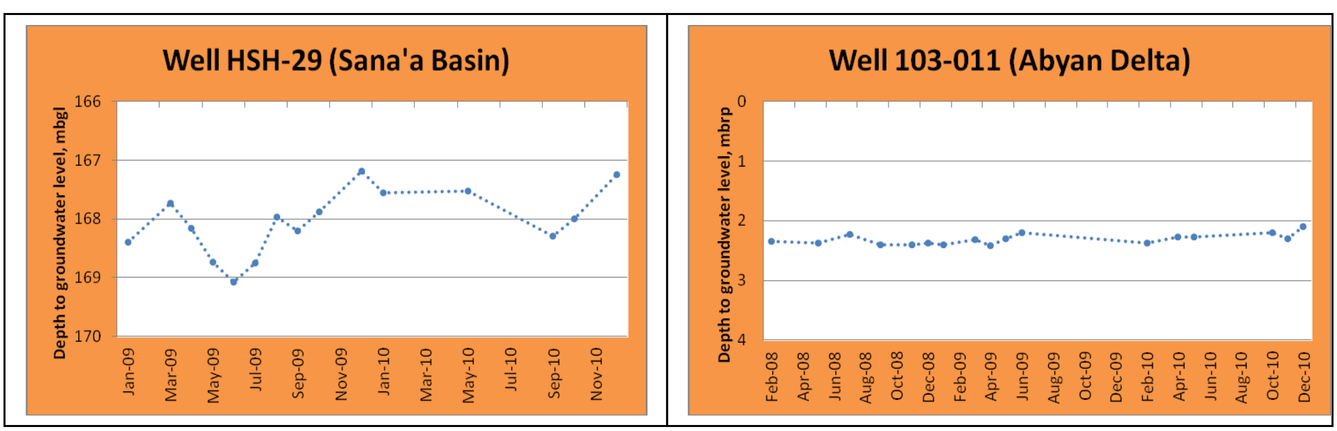


Figure 2. Examples of a decline in groundwater level in critical basins

2.1.2 Nearly stable groundwater level in critical basins

The nearly stable position of groundwater level over a period of years (somewhere in conditions of significant seasonal fluctuations) likely shows more favorable conditions of the local recharge and might also indicate a lack of significant increase of urban and agricultural development in the vicinity of some monitoring wells (Figure 3):



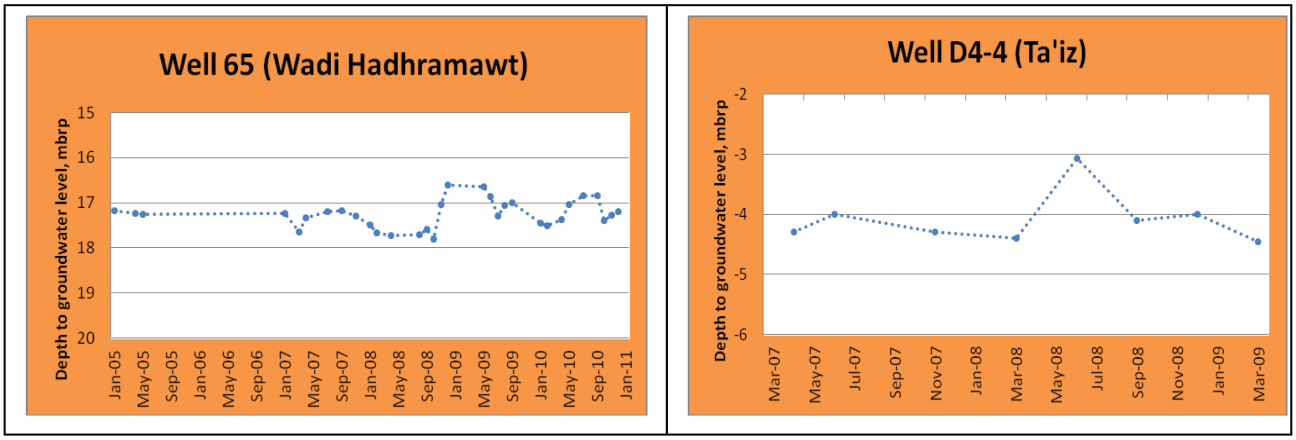
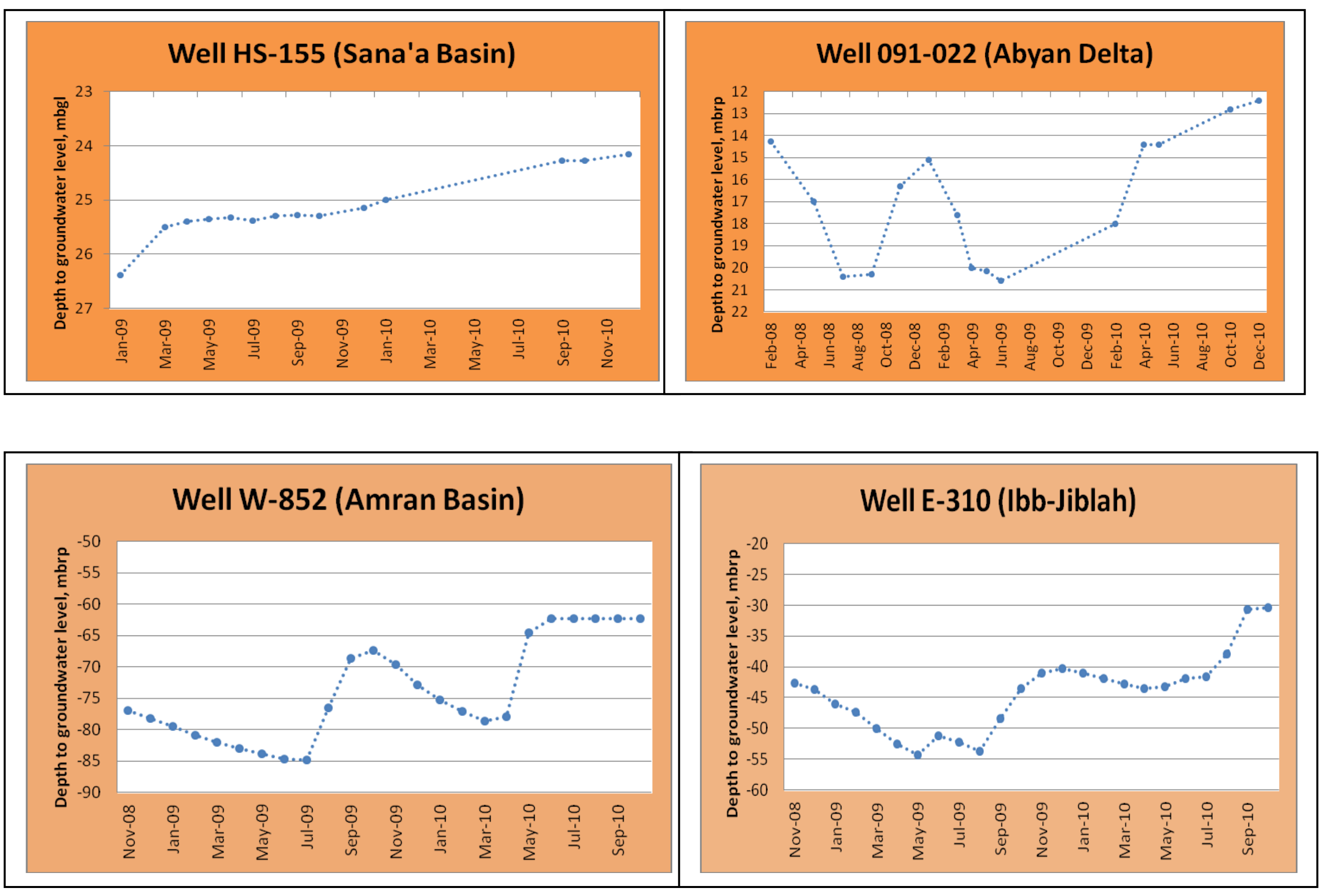


Figure 3. Examples of nearly stable groundwater level in critical basins

2.1.3 Elevation of groundwater level in critical basins

The recovery of water levels was more than complete at some monitoring wells during the significant recharge episodes. The elevation of groundwater level over a period of years (somewhere in conditions of significant seasonal fluctuations) likely shows favorable conditions of the local recharge and might also indicate a lack of significant increase of urban and agricultural development in the vicinity of some monitoring wells (Figure 4):



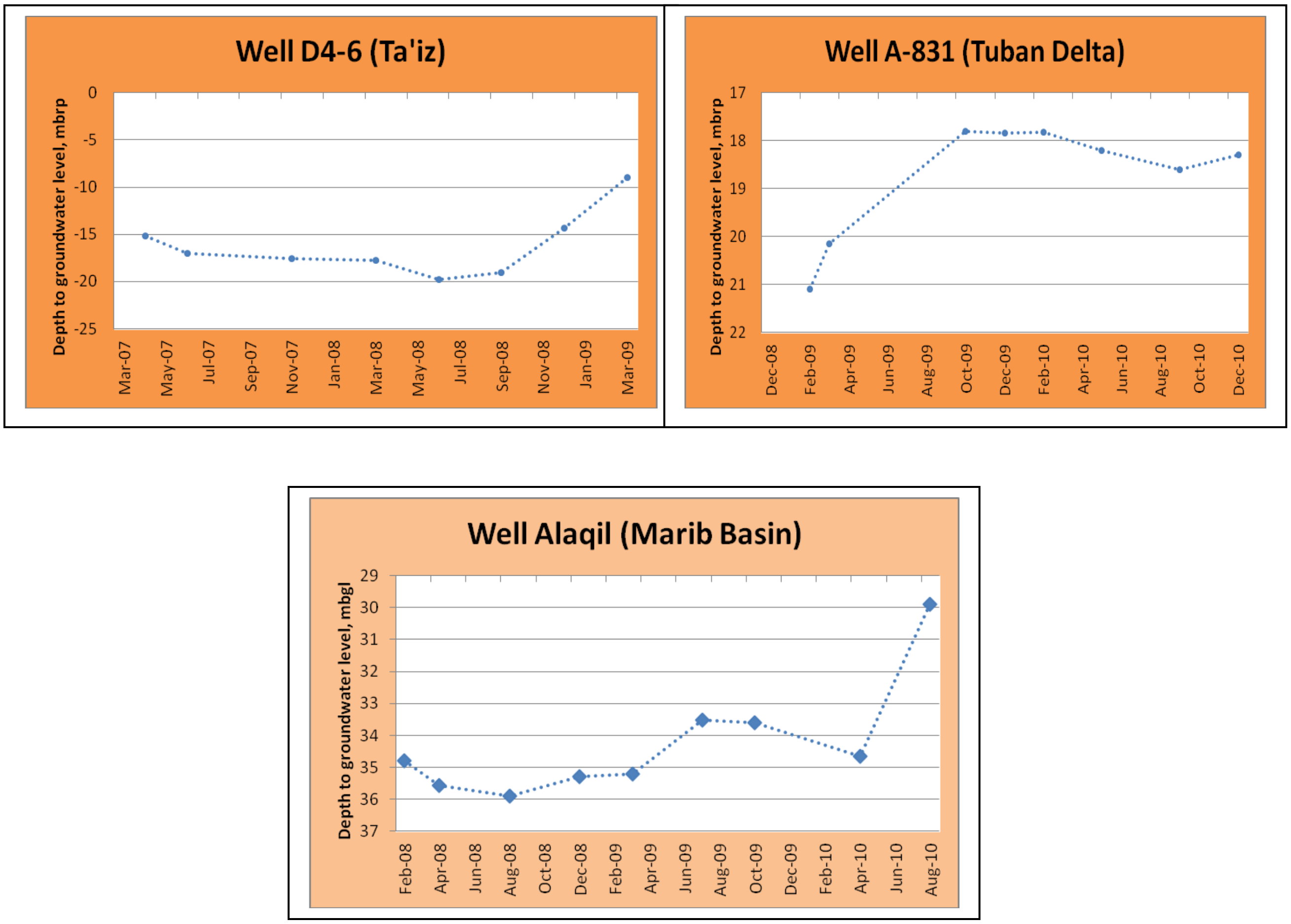


Figure 4. Examples of an elevation of groundwater level in critical basins

2.2 IMPORTANT LESSONS LEARNED FROM THE MONITORING CAMPAIGN

1. None of the existing observation wells were drilled in a proper manner and places to meet the specific monitoring purposes. The essential technical details are almost completely unknown from private wells, including screened and casing intervals, lithological sequence, etc. Somewhere it does not allow referring water levels to individual aquifers with confidence.

2. The ID numbering system currently adopted for identification of monitoring wells is not uniform and somewhere is very confusing.

3. Time intervals between manual measurements ranged irregularly because of financial constraints.

4. Only a few of the currently existing monitoring wells have measurements covering the whole period of the monitoring campaign because many of private wells previously used for observation have been closed by the owners or damaged. Most of automatic data-loggers have been damaged by the local people.

5. In general, the three different long-terms patterns of groundwater level are together reported in the critical water basins: (1) decline in water level; (2) nearly stable position; and (3) elevation of water level.

6. Decline in groundwater level indicates that the recharge and discharge rates have been out of balance in some parts of the water basins. Despite the periods of falling water level were interrupted by brief and irregular periods of elevation, the recovery of water levels was not complete in any of the recharge episodes.

7. The maximum annual rate of a decline is reported from the monitoring wells located close to the largest public wellfields. Alarming rates of a decline at these monitoring wells likely reflect a serious hydraulic influence of the nearby high-production wells supplying drinking water to the urban population. This dangerous trend may be either attributed as a normal (and inevitable) hydraulic response to the constantly increasing groundwater abstraction, or, if the abstraction has been rather stable in time, a growing drawdown at nearby monitoring wells means an unrecoverable mining of the local groundwater storage.

8. Some existing monitoring wells are surrounded by cultivated lands. The trend of a decline reported from such wells might reflect a cumulative hydraulic influence of many tens of the nearby private wells increasingly supplying water for irrigation.

9. The three basins are characterized by a significant predominance of monitoring wells which show a continuous decline in water level. These includeMarib Basin and two coastal basins (Surdud and Tuban).

10. In the **Marib Basin,** the current pattern of groundwater recharge is very complicated and it includes infiltration from wadi beds and diversion channels in combination with releases from the dam's storage reservoir. A general decline in groundwater level is the predominant trend within the entire basin with the maximum average annual rate of a decline of around 2.5 m/year. Continuous elevation of groundwater level which is reported from only a few wells is likely associated with controlled releases from the dam's storage reservoir.

11. In **Wadi Surdud** (Tihama), all monitoring wells show a long-term decline in groundwater level. The general trend of a decline was changed by rather short intervals of a recharge. These occasional recharge episodes, even sometimes being significant, were in general inadequate to compensate for discharges. The elevation of groundwater level in conditions of significant seasonal fluctuations was reported from only one monitoring well situated outside the wadi's valley. Because of the unrepresentative location, this monitoring well provides questionable groundwater-level data.

12. In **Tuban Delta**, several monitoring wells which are located close to the delta's apex (where Wadi Tuban descends from the mountain slope to the coastal plain) show a long-term stable or elevated groundwater level that means favorable conditions of a recharge contributing to the delta. Despite this fact, a continuing decline in groundwater level is reported from the monitoring wells which are located downstream in the Lower Delta and at the coastal line. Therefore, monitoring records clearly show that the total groundwater withdrawal within the Lower Delta has exceeded a nearly stable or even increasing recharge contributed to the Upper Delta. The non-renewable mining of groundwater resources in the Lower Delta has resulted in continuing groundwater table decline in the surroundings of the public wellfields supplying drinking water to the Greater Aden.

13. In **Abyan Delta**, which is adjacent to the Tuban Delta, more favorable conditions occur despite some monitoring records show a continuous decline in water level close to the public welllfields located in the Central and Southern Deltas, where the local recharge and discharge rates have been out of balance. Fortunately, other monitoring wells located downstream of the wellfields and at the coastal line show the nearly stable groundwater level. That means a lack of significant groundwater mining within the entire Abyan Delta, while a decline in groundwater level reported from the upstream monitoring wells is associated with a development of a number of local cones of depression.

14. In the **Sana'a Basin** a decline in groundwater level was reported from the most of monitoring wells penetrated the Sandstone aquifer with the maximum decline ranging between 0.8-8.3 m/year in the vicinity of the Western Wellfield. At the same time, however, an elevation or rather stable position of water levels has been reported from many monitoring wells penetrated the Alluvial, Volcanic and Limestone aquifers and from a few wells penetrated the Sandstone. This phenomenon likely shows more favorable conditions of the local recharge and might also indicate a lack of significant increase of urban and agricultural development in the vicinity of some monitoring wells. It is worth noting that two monitoring wells situated at the single outlet from the Sana'a Basin show only a minor decline (0.2 m/year) or stable position of groundwater table that could indicate a lack of basin-scale groundwater depletion despite the development of many tens of the growing local cones of depression.

15. In the **Amran Basin**, a decline in groundwater level is prevailing in the central part of the main valley and in Qa' Al-Hamidah. These important agricultural areas are a subject of intense and increasing pumping which results in significant seasonal fluctuations of groundwater level. At the same time, however, several wells - likely located outside the local cones of depression - show a nearly stable groundwater level in time.

16. The highly elevated **Ta'iz and Ibb-Jiblah regions** are situated very close to the major watershed between the Red Sea Basin and the Gulf of Aden Basin. The shallow aquifer systems are rather sensitive to changes in both direct and indirect recharge. The annual correlation coefficients are insignificant between different rainfall stations. This means that a certain year may be relatively wet in one wadi, but rather dry in adjacent wadi. The accidental pattern of recharge has a significant and irregular effect on the changes in groundwater level. There is no correlation between locations of the monitoring wells showing different changes in groundwater level (decline, stability, elevation). A decline reported from some wells might reflect a growing groundwater abstraction at some locations that inevitably would result in an increase of the local drawdown even in conditions of significant recharge.

17. In **Wadi Hadhramawt**, a minor to moderate annual decline of groundwater level ranging from 0.1 to 0.5 m/year is reported from monitoring wells located in the main valley between the towns of Al Qatn and Tarim. A decline in groundwater level might be associated here with the growing urban and agricultural development. At the same time, the nearly stable groundwater level is reported from monitoring wells located at the outlet of the main valley. This evidence could indicate a lack of basin-scale groundwater depletion.

18. In general terms, a nearly stable or elevated groundwater level which is reported from many monitoring wells might indicate a lack of groundwater depletion at the basin scale while a continuous decline in groundwater level reported from other monitoring wells might be associated with locally increasing cones of depression.

19. A continuing long-term decline in groundwater level reported in the surroundings of the highest-priority public sources supplying drinking water requires immediate technical interventions to avoid socio-economic failures in the nearest future. At the same time, any further disseminated attempts to improve groundwater environment within the entire basin (or sub-basin) through recharge dams, modern irrigation, etc. are doomed to failure because water is the moving resource and there is no reasonable means "to conserve" it underground for future generations. The principal task of the wise management is to provide an optimal pattern of the **current** resource development, ensuring sustainable water supply on the one hand, and reduction of a wasted groundwater outflow from the critical basins, on the other hand.

20. From the information listed above, it is clear that despite many troubles and shortcomings of the existing national monitoring network, the long-term and regular monitoring of groundwater level is essential for the assessment of available resources and it provides the basis for a professional data interpretation and adequate decision-making.

3. SOME OTHER CHALLENGES IN THE YEMENI WATER SECTOR

3.1 WATER QUALITY DEGRADATION

Nearly all shallow groundwater bodies within and near urban-industrial centers are now highly polluted and only a small percent of wastewater generated is properly treated and disposed.

Case study 3: Evaluation of the impact of the Amran Cement Plant on groundwater quality (2007)

The outputs of the BGR-IWRM water-quality study clearly showed a negative impact of the Amran Cement Plant on the surrounding groundwater environment despite a large thickness of covering unsaturated deposits with high adsorption capacity. This effect is more obvious in concentrations of Ca, SO_4 and TDS because these are the components of cement. Concentrations of other harmful constituents increase likely due to occasional fuel spillages and illegal waste disposal at the industrial site. Petroleum derived hydrocarbons accumulated in the excavated ponds and occasional spills are the most dangerous threats to groundwater quality in the surroundings of the ACP. The growing negative impact of the ACP on groundwater quality appears to be a dangerous phenomenon with specific reference to the several nearby public wells supplying drinking water and situated downstream of ACP.

Accurate and precise chemical analyses are the basic prerequisite for any water quality study. However, the existing national laboratories for water quality analysis suffer from poor quality control and quality assurance practices. Many national labs are hardly operable due to outdated equipment and a lack of basic supplies (chemicals, test kits, local suppliers for spare parts, standards). Only two labs (SWSLC, WEC) currently have the analytic capability to perform complete water analysis from which ionic charge balances can be calculated. Other laboratories require significant investments to modernize equipment.

Existing frameworks and networks for water quality monitoring in Yemen are highly deficient, adequate expertise on water quality management simply does not exist. National universities cannot currently provide appropriate education and training on water quality management. Accordingly, water quality problems are becoming increasingly serious and a rapid capacity building in this sector is expected to be one of the most critical challenges in the coming years.

Case study 4: Groundwater quality study in the Amran Basin (2007)

A set of water samples collected in the Amran Basin have been analyzed in the both labs of the Christian-Albrechts-University (Germany) and the LWSC, Ibb. One water sample collected from each well was sent to the lab of CAU as the reference, while the other water sample collected from the same well was forwarded to the lab of LWSC/Ibb. For comparison, the LWSC/Ibb lab's results have been evaluated by calculating the deviation from the CAU/Kiel results. Special attention was paid to the identification of any systematic errors (either positive or negative), because systematic errors are easier to eliminate than unsystematic ones. A comparison showed that the LWSC/Ibb's results are of extremely low accuracy because nearly all deviations of individual chemical parameters from the reference CAU/Kiel measurements far exceeded 10%, while systematic errors appeared to be very high or even unrealistic.

3.2 ENORMOUS INVESTMENT REQUIREMENTS

- New water projects are becoming increasingly expensive to develop.
- No accurate estimates exist to what extent would be the investment needed to improve wastewater treatment to a reasonably tolerable level. These are for point sources only.
- Investment needs for controlling non-point sources of pollution like agricultural irrigation are simply unknown at present.
- The total investment costs for modernizing and efficient management of existing and future water projects and wastewater treatment plants and to construct new ones are likely to be astronomical.
- **The lack of enough investments may lead to a real water crisis during the coming years rather than a physical depletion of available water resources.**

4. TOWARDS THE UPGRADED WATER MANAGEMENT

4.1 OPTIMIZATION OF INVESTMENTS AND TECHNICAL INTERVENTIONS

The national water strategy is currently applied in general terms to the entire water basins (or sub-basins). Numerous attempts to improve groundwater environment have been undertaken in the past aiming firstly at reduction of groundwater depletion at a basin scale. The possible physical reasons of a depletion reported from some wells (discussed in Section 1 of this report) have not been taken into account.

In our opinion, any disseminated measures to mitigate groundwater depletion at a basin scale are doomed to failure for the following reasons:

- Recharge dam reservoirs, water harvesting and introduction of the modern irrigation techniques even though being applied by a lot of projects, but in a random manner throughout the huge territory of a basin, would only result in negligible water level elevation within a basin as a whole.

- Groundwater is the moving resource and, therefore, there is no technical means to simply “conserve” it underground at place for the next generations. If the location of any water-saving project is improperly selected, the investments and technical interventions could be wasted due to increase of unbeneficial outflow from the basin.

It is not follows from the above reasons that water-saving measures are meaningless. The idea is that these important interventions should not be randomly disseminated. Instead, all the efforts should be focused on the **limited** areas supplying water to the top-priority sources. These areas are located in the upstream direction of the operating wells. Any water-saving project located outside these limited areas will not have a positive effect on the sustainability of water supply from the top-priority sources.

Therefore, it seems that the pattern of the national groundwater resource management would be shifted from traditional basin-scale managerial options to **site-related interventions** in accordance with the following hierarchy of water sectors:

1. Public drinking water supply to major towns – top priority;
2. Other public drinking supplies (provincial towns, villages, local communities) – second priority;
3. Irrigation and industrial supplies – third priority;

4. Other supplies (tourism, livestock, etc.) - fourth priority.

The upgrading the national water resources management will allow optimization of the limited investment costs and future technical interventions, and taking into account the extreme socio-economic and political importance to ensure a sustainability of the drinking water supply and agricultural incomes.

4.2 UPGRADING MONITORING NETWORK: ABSOLUTE NECESSITY

Groundwater monitoring data are crucial for the assessment of sustainable water resources and their adequate management because it provides the sound basis for a professional data interpretation and subsequent managerial actions.

Many tens of specifically designed monitoring wells should, ideally, be drilled depending on the purpose of individual station. It is evident, however, that drilling of specific monitoring wells (even of very small diameter) is unlikely possible in the nearest future because of financial constraints. In reality, a routine monitoring campaign will continue on the basis of existing holes.

Before funds required for drilling monitoring wells are available, the existing monitoring networks would incorporate only such private wells which meet the number of technical criteria.

Operating wells provided unreliable water-level records should be excluded from the existing monitoring networks. Some monitoring stations would be established within the radius of influence of the public operating wells in order to control the development of the local depression cones. In this context, all the critical water-production areas should be of particular concern at upgrading monitoring network. Groundwater and Soil Conservation Project (GSCP) which maintain its own monitoring stations should be consulted to provide a regular exchange of monitoring data between GSCP and NWRA.

Historic data on the monthly groundwater withdrawals from the public wellfields should be collected in order to proceed in time the changes of so-called *"specific drawdown"* (S/Q), i.e. drawdown divided by abstraction, and, on this basis, to diagnose a hydraulic reason of the decline in groundwater level reported from nearby monitoring wells.

Existing **water-quality** monitoring network should be seriously expanded and upgraded based on the specific technical criteria. Most monitoring stations would be established downstream of the main pollution sources, such as harmful industries, waste disposals and water treatment facilities in order to control the development of the contaminated plumes.

4.3 WATER PROTECTION ZONES: FROM DECREES TO PRACTICAL MEASURES

In 2002, three stressed basins (Sana'a, Sa'adah and Upper Wadi Rasyan) have been officially declared through the appropriate Cabinet Decrees to be entirely the Water Protection Zones. These decrees have stated, however, only the general recommendations for water quality protection.

Ideally, all water basins would be totally protected. In practice, however, this goal is absolutely unachievable because the numerous land-use restriction measures (such as ban on construction of new roads, industries and animal husbandries; total ban on using pesticides and fertilizers; etc.) being imposed within the densely populated lands will lead to a degradation of the socio-economic development.

Nevertheless, some improvement of groundwater environment **at a basin scale** would be achieved by strong licensing of drilling, deepening new wells, maximum depth of well, permissible rate of groundwater abstraction and any excavation works. In accordance with the Water Law, if the water is used for a purpose other than allowed (e.g. for qat irrigation instead of drinking), a penalty of imprisonment or a fine should be imposed on the well owner together with obliging to pay compensations against any damages of the environment. Disposal of any wastes and other activities which may adversely affect groundwater quality would be prohibited in areas of the natural groundwater recharge.

Water Law states that the contamination of water resources or deterioration of its quality is a punishable act leading to an imprisonment or the imposture of a fine. Therefore, existing hazardous industries, water treatment facilities, disposals of liquid and solid wastes should be under the permanent and strong control by responsible water and environmental institutions. Appropriate mitigation measures should be immediately undertaken at the harmful industries (cement plants, oil fields, power stations, etc.) in order to reduce or eliminate the negative impacts on groundwater quality.

Public sources supplying drinking water are the facilities of a strategic importance. Ensuring their sustainability and strongest protection should be the first-priority task in any water management plan.

Until the appropriate executive by-law is issued through the Cabinet resolution followed approval of the Council of Ministers, the general approach to the establishment of groundwater protection zones is currently regulated by the Cabinet Decree No. 343 for the year 2002. NWRA has launched an establishment of groundwater protection zones at several public wellfields, including Amran, Abyan, Tuban, Al Mokha, etc. Some water protection measures have already been implemented by the Local Governments within the delineated protection zones (e.g. Bir Ahmed in the Tuban Delta). Recommendations to establish protection zones have been also initiated by the NWRA for the public wells in Dhamar, Al Mokha, Rada'a, Hajjah. Unfortunately, this activity is not completed at the moment due to a suspension of WSSP.

It is worth stressing that except for some groundwater protection in the immediate surroundings of operating wells, no required zones (inner, outer) are in existence at the Western and Eastern wellfields supplying drinking water to the urban population in the capital Sana'a.

It is a task of the highest priority to establish new (and rehabilitate existing) water protection zones and to impose the strong land-use restrictions within these limited but critical zones in close cooperation with the Local Governments. The land-use restrictions should be imposed to be as large as necessary for safeguarding the public sources of drinking water and, on the other hand, to be as small as possible for avoiding inadequate inconveniences for local population.

4.4 UPDATING COUNTRYWIDE HYDROGEOLOGICAL MAP

Reliable countrywide map shows the synthesis of hydrogeological data providing an adequate basis for the establishing water management plans at a basin scale and expanding water-level and water-quality monitoring networks in different parts of the country. To realize these important possibilities, the available hydrogeological maps of Yemen would be seriously updated by means of modern GIS-technologies and on the basis of the relevant information collected during the last two decades.

The following countrywide hydrogeological maps are currently available:

- Robertson Group Hydrogeological Map, scales of 1:250,000 and 1: 1,000,000 (1992); and
- Geocon Ltd ("Russian") Map of Potential Exploitable Groundwater Resources, scale of 1: 500,000 (1995).

Robertson Map has been constructed in accordance with the UNESCO legend and appropriate six-fold classification of hydrogeological units. All outcrops of a certain geological formation were assigned to one of the six classes colored in specific colors, with ornaments added in order to show the individual geological formations. Piezometry is added as line symbols in some isolated locations. Despite the map is easy to review, it shows a number of serious disadvantages:

- Only uppermost rock unit (alluvium or eolian sand) is shown, even though a deeper formation forms the major aquifer system (e.g. the Wajid Sandstone in the Sa'dah Basin, the Tawilah Sandstone in the Ramlat As Sabatayn and Wadi Hadhramawt, etc.);

- Two Robertson's maps (1: 250,000 and 1: 1,000,000) are absolutely identical in terms of presented hydrogeological detail;

- Six-fold classification of hydrogeological units seems to be rather ambiguous because there is no clear definition for the "highly", "moderately" or "poorly" productive aquifers. For example, the densely fissured "highly productive" aquifer might support a significant yield but only for a short time due to a low storage capacity and limited natural recharge that is common case in Yemen;

- Water-quality information relates only to the saline groundwater and, therefore, appears to be very limited.

Geocon ("Russian") Map has been constructed in accordance with the original legend based on the tectonic classification of the different rock units which have been differentiated in accordance with: (a) stratigraphy; (b) type of permeability; (c) dominant groundwater salinity and chemical composition; and (d) estimated quantity of groundwater resource available for sustainable development per square kilometer. Despite the map is rather difficult to review, especially for non-specialists, it shows a number of important advantages:

- Two superimposed aquifer systems are shown on the map that brings the third spatial dimension in view;

- Many relevant features, such as typical water salinity and chemical composition; average depth to groundwater level; etc. are added;

- The map shows the quantity of the available resource in the terms of both recharge and usable groundwater storage that appears to be the critical issue for groundwater management plans.

A review of the available countrywide hydrogeological maps showed that none of them can be currently used without a critical attitude and serious updating. It seems, therefore, that the new mapping project would be established with the aim at upgrading the available outdated maps.

4.5 RAMLAT AS SABATAYN: A HIDDEN TREASURE

Increasing water demands of the growing population of Sana'a and other cities is becoming the great challenge. It seems that the hydrogeological investigation of the Tawilah aquifer in the Ramlat As Sabatayn will ensure a basis for a principally new countrywide water strategy and management because of the assumingly huge groundwater potential of this desert area.

The Map of the Potential Exploitable Groundwater Resources of the Southern Yemen, 1: 500,000 (Rybakov et al., 1992) has been the first attempt to delineate the regional Tawilah aquifer throughout the Ramlat As Sabatayn based on a few occasional data available from the oil drillings in late 1980s. This map shows the geological boundaries of the Tawilah aquifer (covered by eolian sands) in combination with a depth to water table and other relevant characteristics. The 1992 map (available only in a few hand-made copies) was incorporated in the Map of the PEGR of Yemen (Rybakov et al., 1995). At the same time, van der Gun and Ahmed (WRAY-35) have supported the hypothesis on the regional occurrence of the sandstone aquifer in the Ramlat As Sabatayn with enormous groundwater potential.

The sandstone is assumed to be the largest groundwater system in Yemen which contains enormous quantities of mainly fossil groundwater. Practically infinite lateral extent and significant thickness of the sandstone in combination with a favorable tectonic structure allow anticipating its significant groundwater potential. Probably, a strategy of controlled groundwater mining would be applied at the futuredevelopment of this aquifer due to a limited rate of recharge. Fortunately, a decline in groundwater level is expected to be quite low because of the high storage coefficient of the sandstone.

If assuming groundwater potential is confirmed by technical studies and surveys, it might allow establishment of a large-scale water transport to some critical basins. Despite rather long distances from major population centers (e.g. around 200 km from Sana'a and Rada, and some 350 km from Taiz), this potential source might be an attractive alternative to seawater desalination that requires an energy-consuming technology and water elevation to high altitudes (for comparison, Ramlat As Sabatayn lies at altitude of around 900 – 1000 m above sea level).

An average water level in the sandstone is thought to occur at depths of 150 to 200 meters that follows a medium depth of the required geophysical soundings and exploratory drilling. Additional advantage is that Ramlat As Sabatayn is uninhabited desert and any large-scale groundwater development would not create the conflict interests with local population.

The TOR for the pilot evaluation of the Ramlat As Sabatayn's groundwater potential is already drafted by NWRA.