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Chapter 6. GROUNDWATER OCCURRENCE IN SANA'A BASIN

EXECUTIVE SUMMARY

There are many factors affecting groundwater occurrence in Sana'a Basin:

- Climate with a high variability of rainfall from year to year,
- Topography with large differences in elevation,
- Hydrogeology with significant differences in properties of the main aquifers.

This chapter presents the groundwater occurrence in Sana'a Basin through groundwater level maps and an overview of groundwater recharge and discharge.

Groundwater levels in the Sana'a Basin have been collected intermittently since 1972. Depth to groundwater and groundwater elevation maps have been constructed from historical and from recently collected data for the alluvium, volcanic and sandstone aquifers. In the alluvium and sandstone aquifers, water levels were used from selected wells only. The selection consisted of unused wells with limits on the total depth of the wells and depth-to-water.

The elevation of the reference point was estimated using surface elevation estimates obtained through the Internet from SRTM-data.

Conclusions on groundwater flow were derived from the groundwater elevation maps.

In the alluvium aquifer:

- all surface water is absorbed except for during very wet years;
- The general decrease of the mean groundwater table since 1973 reflects the over-pumping of the alluvium aquifer;
- The groundwater flow direction is generally from the higher to the lower areas;
- The effect of the rainy season is visible by a rise in groundwater table in part of the Sana'a Basin.

In the volcanic aquifer:

- The groundwater flow is directed to the centre of the Sana'a Basin;
- The general decrease of the mean groundwater table since 1973 reflects the depletion of the volcanic aquifer;
- The lowering of the groundwater table is visible near the NWSA well fields and in South Sana'a City;
- The hydraulic gradient has decreased in the southern part of Sana'a Basin, indicating a reduction in flow from this direction.

In the sandstone aquifer:

- The groundwater flow direction from the east reflects possible recharge through the volcanic aquifer in the eastern part of the Sana'a Basin;
- The mean groundwater table has not changed significantly over the years, indicating that the depletion of this aquifer is more local in nature.

The description of the groundwater recharge and discharge summarizes the information collected in Activity 4 of the project. The annual recharge to groundwater in the Sana'a Basin is estimated at 50.7 M m^3. The annual discharge is estimated at:

- Public water supply: 24.1 M m^3 (2005, SWSLC)
- Private water supply: 31.7 M m^3 (2006, JICA)
- Rural water supply: 4.5 M m^3 (2006, JICA)
- Agricultural abstraction: 217.5 M m^3 (2002, WEC)
- Industrial water use: 4.8 M m^3 (2005, JICA)
- Tourism water use: 0.4 M m^3 (2005, JICA)

6.1 Factors influencing groundwater occurrence

The concept of the groundwater regime is based on a combination of physical factors such as climate, topography and geology. These factors and their components play a significant role in deciding the characteristics of the hydrogeological regime.

6.1.1 Climate

Rainfall, temperature, humidity and evaporation are components of climate. The annual rainfall of the region, seasonal variation and daily fluctuation of temperature and humidity are crucial for determining infiltration of rainwater and rate of evaporation respectively. Heavy to moderate rainfall favors more infiltration through soils and pervious formations. The occurrence of rainfall in many areas is uncertain. Variables of such uncertainty are changes in aggregate rainfall; dates of onset and cessation of monsoons; number of rainy days and frequency of dry spells. High temperature during the summer evaporates and depletes the water levels in surface reservoirs and also in groundwater at shallow depths. Evapotranspiration though plants further enhances the process of depletion of the water table.

In Sana'a Basin, climatic components have wide ranges of values. Table 6-1 summarizes the climatic component values.

Table 6-1 Climatic component values in Sana'a Basin

Climatic Components	Average
Average Annual Rainfall	200–400 mm/y
Average Annual Temperature	19 ºC
Average Annual Humidity	55%
Average Annual Evapotranspiration	2250 mm/y (GAF)
Average Sunshine	11 hrs
Average Wind Speed	2-3 km/h

6.1.2 Topography

Topography is another factor which contributes to the occurrence of groundwater. Mountainous topography receives heavy to moderate rainfall and the rainwater is carried away in the form of high surface runoff. As a result, such areas experience water shortages a few months after the end of monsoon. Groundwater in such areas occurs as a perched water table or emerges in the form of springs.

The elevation of Sana'a Basin ranges between 1,900 and 3,760 m asl.

6.1.3 Geology and structures

Geological features, such as folds and faults, clay beds, intrusions like dikes and pegmatite, etc., exert control over the groundwater regime. During folding and faulting, major fractures and associated joints are developed. These fractures and joints enhance the groundwater recharge. The clay beds, being impervious in nature, hinder groundwater recharge and movements. The dykes and pegmatites, depending upon presence or absence of joints, act as carriers or barriers to groundwater respectively. The disposition of these faults is thus crucial in groundwater occurrence.

Structural controls on the regional groundwater flow:

- Faults,
- Low permeability units,
- Lithological boundaries.

The study conducted by WEC and the ITC-Enschede, The Netherlands, 2001 entitled "Satellite Analysis of Cropping and Irrigation Water Use Project" stated that: In well tests carried out in the Sana'a Basin, it was indicated that high permeability or transmissivity were, in each hydro-lithologic unit, associated with fracturing. Many studies in the literature have shown that well yields can be related to proximity to lineaments. However, not all interpreted lineaments are open fractures or faults carrying groundwater. Through the main lineaments, sub-regional groundwater flow may occur, depending on overall head conditions. This could mean either a loss or gain of groundwater in a given aquifer.

6.1.4 Hydrologic significance of lineaments (WEC-ITC, 2001)

Overall permeability is increased by the presence of joints, master joints, fractures, shear zones and normal faults. Next to primary permeability, which is related to porosity of the rocks, the joints-fractures create what is termed as "secondary" permeability. Secondary permeability decreases with depth, particularly over the first tens of meters from the surface. Beyond that depth, the smaller tensional features, joints, tend to close because of pressure and the minimal effect of weathering (excluding solution in limestones). For that reason, only the lineaments larger than 1 to 1.5 km have been selected for presentation on the map. It is assumed that long lineaments extend to larger depths, i.e. they may reach beyond the groundwater table and thus influence groundwater flow. It is likely that the lineaments correspond to tensional fractures and faults, because study of available geologic data does not reveal ductile conditions (e.g. upthrusts, compressional tectonics). In the Sana'a Basin, hydrogeological investigations have shown the large differences in permeability or transmissivity values of, in decreasing order: fault zones, fracture zones and undisturbed rocks, Foppen (1996).

In 2001, the Satellite Analysis of Cropping and Irrigation Water Use study of Sana'a Basin was conducted by the "Water and Environment Centre" (University of Sana'a, Yemen) and the International Institute of Aerospace Survey and Earth Sciences (ITC-Enschede, The Netherlands).

The satellite image study conducted by WEC-ITC, indicated that the study of lineaments has not revealed important faults and fractures showing direct evidence of much loss of groundwater from the Sana'a Basin to its surroundings, mainly at lower altitudes. From a hydrogeological point of view, the only possible appreciable loss can occur through deep karst in the northern limestone country.

By using the extent of irrigated areas as an indicator of groundwater occurrence, it may be noted that the sandstone formations seem to be most productive in the Sana'a Basin proper and not outside the basin. This could indicate that drawdown extends far beyond the well fields because of relatively fast fracture flow through the many existing lineaments.

Once the propagation of the drawdown has reached the limits of the sandstone aquifer, the drop of water levels in the well fields may accelerate.

In the volcanic area west of Sana'a City, a N-S running structure is found which has some similarities to a small rift. The small rift-like structure could also feed the wells in the sandstones of Wadi Dahr. The absence of wells west of the small rift structure is noteworthy.

In the Tertiary volcanic terrain, most irrigated areas are found on lineaments, confirming the poor hydrogeologic conditions. Major faults are not associated with significant irrigation. It is therefore not likely that the southern part of the Sana'a Basin contributes much to the groundwater in the alluvial and sandstone aquifers in the northern part. A minor amount of loss across the basin boundary can occur in the south-eastern and southern boundaries.

6.1.5 Hydrogeological properties

The hydrogeological properties of rocks such as porosity and permeability influence the storativity and transmissivity of an aquifer. Some hydrogeologists have attempted to classify rocks on the basis of their process of sedimentation into hard and soft types. The rocks formed by process of sedimentation being more pervious, these are grouped into the soft category. The rocks formed by effusion of magma, being less pervious, are grouped into the hard rock category.

Secondary processes such as tectonic disturbance produce fractures and joints. .Cooling of magma generates shrinkage joints, whereas physical and chemical processes enhance weathering and opening of incipient joints. The voids, cracks and cleavage, joints and fractures thus impart secondary porosity on both soft and hard rocks making them suitable for storage and transmission of water.

6.2 Groundwater level data

6.2.1 Historical groundwater level data

In the literature, from the measured static water levels in 1972, 1985, and 1990-1993 (ref. TR-05, Vol. II, App. A4), contour lines could be drawn, which was done for the 1972 situation with the data of ltalconsult (1973) (Figure 5-4). ltalconsult did not separate the data into different aquifers: all data belonged to one aquifer complex consisting of Quaternary alluvium, Tertiary volcanics, and Cretaceous sandstone. While ltalconsult did not separate the aquifers, it is apparent that, in the northern part of the Sana'a Basin in 1993, substantial water level differences existed between the alluvium and the Tawilah sandstone: the head difference varies from l0 m in the upper Wadi As-Sirr to over 120 m in the upper Wadi Furs and near the city of Sana'a. The difference is probably caused by groundwater abstractions from the Tawilah sandstone and recharge of the Quaternary by irrigation return flow and percolation of sewage from cesspits.

For the entire Sana'a Basin, groundwater levels were measured in 22 observation wells (ref TR-05, vol. III, App. A4) located in well fields or near the local production wells of NWSA. Most data come from the files of Leas and Bamatraf (1991) and, since 1994, from the SAWAS project (TR-05, Vol. VI). The groundwater model was calibrated from this data. The highest groundwater levels (around 2,400 m amsl) have been measured in outcrops of the Tertiary volcanics in the southern part of Sana'a Basin. Excess precipitation infiltrates and probably flows through fissures and cracks and/or through sandy or gravelly deposits between the basalt layers to the north in the direction of Sana'a City. As was mentioned by Italconsult (1973), the presence of locally perched water tables in the volcanics cannot be neglected. In the cross- section, however, perched water tables seem to be absent.

The lowest groundwater levels were measured in the Arhab area, in the northern part of the cross-section. Here, groundwater flows to the east into the Wadi Kharid. Part of the water is discharged by the Wadi Kharid springs. These springs, at an altitude of 2,020 m amsl, flow continuously with a measured discharge of around 100 l/s. The water has an EC of around 1,500 µS/cm and a temperature of 32-35°C. It is believed that the presence of the springs is mainly due to the presence of dikes just a few tens of meters north of the springs.

Selkhozpromexport (1985) stated that part of the water originates from the Kohlan and Amran limestones. Figure 5-4 shows that the general trend of groundwater flow is to the north. In the mountainous areas, the direction of flow is east (on the western slopes) and west (on the eastern slopes). In the Basin itself, groundwater flows north and, north of the Jebel as Sarnma groundwater level, measurements are lacking. The same groundwater flow pattern can be seen on the maps of

Selkhozpromexport (situation 1984) and SAWAS (situation 1990), the only difference being the head decline over the years (Figures 5-5 and 5-6 respectively).

Discharge from the sewage ponds near Rawda, north of the Sana'a urban area, flows into a nearby wadi, where it infiltrates the alluvium. This causes a high groundwater level around the sewage ponds and along the Wadi bed. Subsequently, the groundwater flow is in two directions:

- Part of it flows through the alluvium to the south in the block of Tawilah sandstone. This is proved by Well E80, which is 350 m deep. The water produced by this well has an EC of 1771 µS/cm and has a geochemical classification indicative of infiltrated sewage.
- Part of the sewage flows to the north. Owners of dug wells north of the sewage ponds state that the wells were dry before the presence of the sewage ponds. After the ponds had been introduced, the wells could go into production again, which clearly shows the rise in groundwater level.

6.2.2 Field work groundwater level data

Intensive field activities were carried out during 50 days of work all over the Sana'a Basin, particularly in the selected areas (Nihm, Bani Husheish, Arhab and Bani El-Harith). During this interval, a large amount of data was collected for groundwater points representative of both alluvial and Tawilah sandstone aquifers. At the well site, part of the information was obtained by direct measurements (water level, electrical conductivity, yield, etc.). Other data, however, originate from interviewing the owners or users of the well. The reliability of such information is not always high, but can – to a certain extent – be assessed by consistency checks. The enquiry, however, mobilizes an important part of the information on wells as it is stored in the memories of the local population. Field work was carried out by two crews, each composed of a Hydrogeologist (one from HYDROSULT Inc and the other from NWRA – on-the-job-training) and a driver. Most of the tabulation and some processing work were done daily in the field. Mapping, evaluation and preparation of technical notes were carried out monthly.

For every groundwater point, the following measurements were taken:

- Location of the groundwater point in UTM using GPS;
- Absolute level of ground surface using GPS;
- Depth-to-water from ground surface (DTW) using electric sounder;
- Electrical conductivity (µS/cm) using EC meter;
- pH using pH meter;
- The lithologic succession of the groundwater wells.

All these measurements were processed. Much care was taken to remove errors and mistakes from these data sheets before definitive maps, graphs and statistics were prepared.

6.3 Processing of the available groundwater data

Intensive processing was performed to check and verify the available groundwater records before mapping. This is presented in Table 6-2:

- Altitude correction,
- Spatial distribution correction,
- Sorting step.

6.3.1 Altitude correction

Groundwater levels in meters above mean sea level (m amsl) were determined quite accurately on the basis of measured depths to groundwater from a reference point and the altitude of this reference point. During geological field activities, the reference point altitude of every groundwater point was taken by a GPS tool. Unfortunately, for the same reference point, there are differences between the altitude readings using two different GPS systems, ranging between 5 m and 10 m. Otherwise, there is a general error between the reference point altitude reading by GPS and its altitude extracted from the Digital Elevation Model (DEM) ranging between 10 m and 90 m. This will lead to a reverse trend in the flow direction in groundwater table mapping.

Moreover, the available historical altitude records from previous studies (Italconsult 1972, Russian 1985, SAWAS 1993, NWSA 2000, 2004, WEC 2001) were based on different projection systems, mainly for determining the altitude of each water point. Some of them have applied projection of the location (X,Y,Z) from topographic maps of different scales; others applied GPS of varying accuracy. In this case, the values of absolute level of the water points were defined by different projection systems. Thus, the contouring maps extracted from these altitudes, such as water table maps, depletion maps and storage maps will not be consistent. Therefore, it was essential to transfer the available well data to a unified geographic coordinate system (X,Y,Z). It was recommended that an advanced and reliable digital geographic system be applied. The Digital Elevation Model (DEM) map system was selected as it represents a GIS delineation process and is based on a grid representation of topography. The DEM map was obtained from the Shuttle Radar Topographic Mission (SRTM). STRM consisted of a specially modified radar system that flew onboard the Space Shuttle during an 11-day mission in February 2000. The SRTM data covered the entire globe with an arc second (approximate 90 days) digital elevation model.

6.3.2 Spatial distribution correction

After altitude correction was completed for all groundwater points, the spatial distribution of these groundwater points for every aquifer studied was checked and verified by projecting them in the geo-referenced geologic map (Hydrosult 2007, modified after GAF 2005) to exclude groundwater points lying outside the boundary of the specified aquifer (Figure 6-1).

6.3.3 Sorting step

The most important step is the sorting step. In this step, the checked and verified data were sorted with respect to well type, well total depth and depth-to-water.

Firstly, the sorted well type data sets of unused dug well category took first priority for the alluvium aquifer, while the unused deep bore hole category was the first priority for the Tawilah sandstone aquifer.

Secondly, the sorted well total depth data sets less than 20 m or greater than 60 m for the alluvium aquifer, and less than 60 m for the Tawilah sandstone aquifer were excluded.

Finally, the sorted depth-to-water data sets less than 20 m and greater than 60 m for the alluvium aquifer and less than 50 m for the Tawilah sandstone aquifer were excluded (Figure 6-2).

Sorting of the wells with respect to total depth and depth-to-water was done to avoid using wells with perched groundwater or wells tapping water from another aquifer. Therefore, wells with depths to 60 m were considered to tap the alluvium aquifer, while wells deeper than 60 m were considered to tap the Tawilah sandstone aquifer. Furthermore, wells in the alluvium with water levels within 20 m of the surface were not selected, in order to avoid using wells tapping perched aquifers.

Table 6-2 Percent of excluded well data based on the three processing steps

Firm	Aquifer type	No. of monitoring wells	Date of measurements	No. of sorted well data	% of wells excluded
Italconsult	Alluvium	295	1972	205	31
Selkhozpromexport	Alluvium	135	1984	132	2
SAWAS	Alluvium	611	1993	365	40
WEC	Alluvium	2613	2001	462	82
SAWAS	Tawilah Sandstone	69	1993	42	39
WEC	Tawilah Sandstone	3507	2002	474	86

An expectedly small amount of remaining errors will not significantly affect the results. EXCEL spread sheet, ArcView 3.2, ArcMap 9.1, ERDAS IMAGIN 8.4 and SURFER software were used to produce GIS layers and data base. A set of maps was prepared in order to analyze the regional variation of the single variables. These contour maps include depth-to-water and water table maps for both alluvium and Tawilah sandstone aquifers, as mentioned in the Terms of references (TOR) and Inception report.

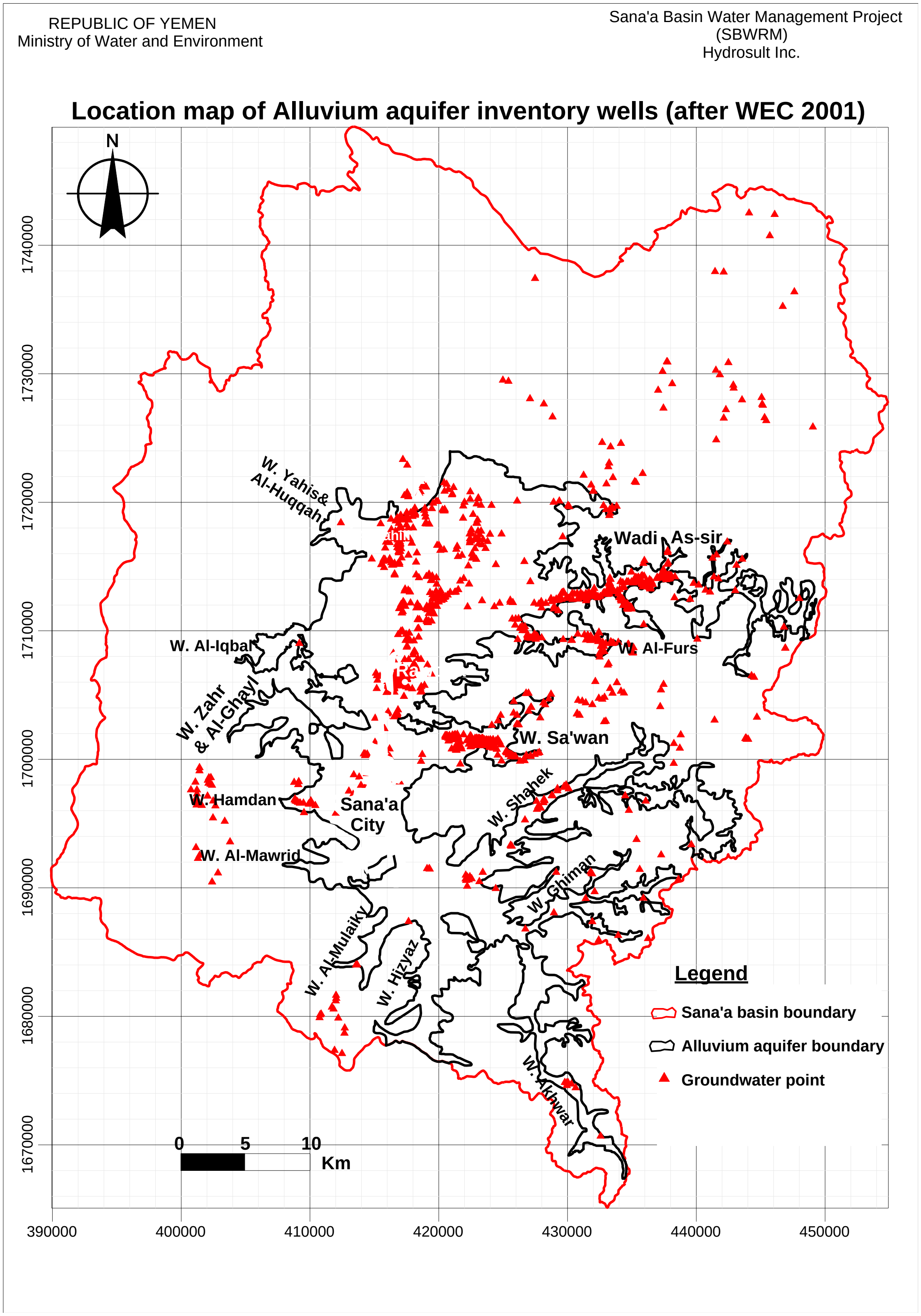

Figure 6-1 Well location map showing excluded wells lying outside the alluvium aquifer boundary before the spatial distribution correction process (data extracted from WEC 2001)

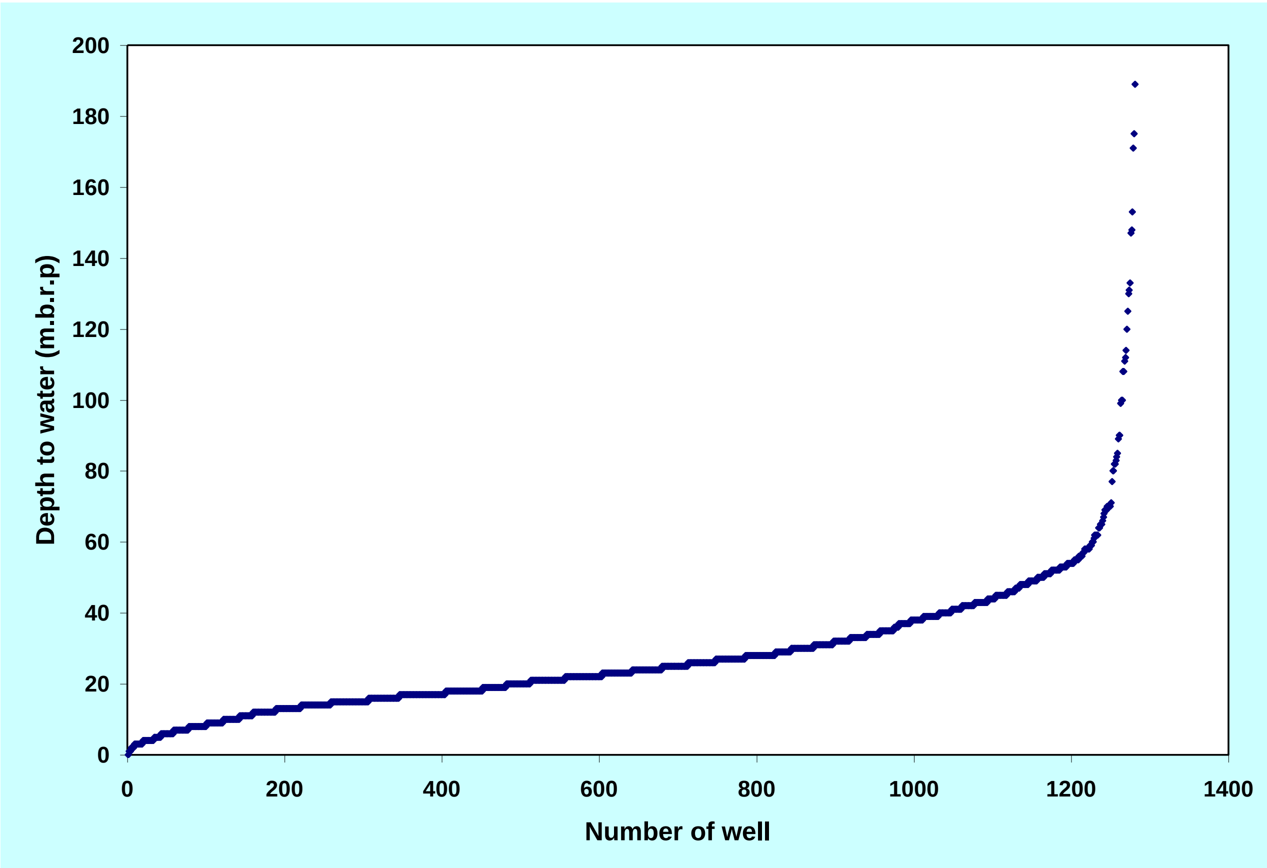

Figure 6-2 Range of depth to groundwater data sets of the alluvium aquifer before the sorting process showing the abrupt change after the depth-to-water value of 60 m (the data extracted from WEC 2001)

6.4 Groundwater flow in the alluvium aquifer

The aquifer storage investigations and assessment of any area implies the construction of a water table map which reveals the flow direction, area of recharge, area of discharge and hydraulic gradient. To execute this, a detailed water level survey was performed during the project. The number and arrangement of sites at which groundwater measurements should be made depends on the nature of the studied area and the purpose for which the measurements are made. Observation wells are often placed in a grid pattern of which the spacing is selected to coincide with the land survey system. In gently sloping areas, points of measurement can be farther apart than in areas of irregular topography. For determining the direction of the horizontal component of flow, water table readings may be made at any desired spacing.

6.4.1 Depth to groundwater mapping in the alluvium aquifer

In the present study, water levels from reference points for every surveyed groundwater point in shallow water bearing horizons in the alluvium aquifer were detected and periodically measured during the period from Dec. 2004 until July 2006 by NWRA-Sana'a Branch team work and from Dec. 2006 until Sep. 2007 by HYDROSULT teamwork and NWRA-Sana'a Branch teamwork. Water levels were measured with electric tapes in 68 wells covering the alluvium aquifer (Photo 6-1 and Table 6-3). Among these

68 wells, 49 dug wells were chosen to develop both depth-to-water and water table maps. The data do not represent simultaneous measurements, but are distributed over a period of two months (Jan.-Feb. 2007, Table 6-4). This first record period was taken before the first rainfall season of April, while the second record period was taken after the second rainfall season of July (during Sep. 2007, Table 6-4) to study the effect of rainfall on the water table in the alluvium aquifer. However, corrections for variations in time were not applied before constructing the areal pattern depicted in Figure 6-3 and 6-4, because these variations cannot be defined accurately, whereas they are small compared to the variations in space of the depth to groundwater. Table 6-3 summarizes the depth-to-water in the different types of wells. In most dug wells, the water level did not exceed 50 m below ground level (bgl) (93%, Table 6-3), while 50% of the water level measurements in boreholes ranged between 100-200 m bgl. Applying the sorted data extracted from well inventory of WEC 2001 (713 data sets with depth-to-water ranges from 20 m to 60 m and saturated thickness greater than 4 m) and the data surveyed during this study, the depth-to-water mapping in the alluvium aquifer was developed (Figure 6-3 and 6-4).

Table 6-3 Number of wells according type and water depth in the alluvium aquifer

Well Type	Depth to groundwater (mbrp)				Total
	<50	50-100	100-200	200>	
Dug well	79	6	0	0	85
Dug/Bore	3	4	0	0	7
Bore hole	4	25	31	2	62
Total	86	35	31	2	154

mbrp : meters below reference point

Table 6-4 Depth to groundwater (mbrp) in the monitored wells in the alluvium aquifer in Sana'a Basin (Feb and Sep 2007)

S.N	WELL-ID	X-UTM	Y-UTM	Depth (mbrp) Feb 2007	Depth (mbrp) Sep 2007
1	HS43	431132	1712635	70	
2	HS44	431249	1712590	57	
3	HS45	431230	1712595	57	58.4
4	HS64	425915	1711408	214	
5	HS65	440806	1710320	41	
6	HS66	440783	1710543	27	
7	HS67	440870	1711763	81	

S.N	WELL-ID	X-UTM	Y-UTM	Depth (mbrp) Feb 2007	Depth (mbrp) Sep 2007
8	HS68	440864	1711779	11	
9	C1849(HS71)	424314	1711874		11.24
10	HS155	420783	1701771		25.5
11	HS160	424153	1701796		14.34
12	HSA1	425298	1718800	58	50
13	HSA2	422002	1719988	43	42.8
14	HSA3	421898	1719705	44	
15	HSA4	417905	1716847	26	25.97
16	HSA5	416155	1715019	22	21.4
17	HSA6	416241	1715122	25	
18	HSA7	421957	1719694	85	
19	HSA8	422438	1718813	58	78.05
20	HSA10	422788	1718243		55.09
21	HSA11	423159	1716994	87	88.9
22	HSA15	417243	1717735	32	
23	HSA19	416322	1715307	53	
24	HSA26	421938	1714069	33	
25	HSA27	422267	1715645	27	
26	HSA28	422695	1716025		16.15
27	HSA31	424283	1718407	75	
28	HSA33	427500	1721000	44	44
29	HSA36	423334	1719743	49	
30	HSA44	421000	1724000	35	35
31	HSA50	411185	1707277	78	
32	HSA52	418245	1714349		101.7

S.N	WELL-ID	X-UTM	Y-UTM	Depth (mbrp) Feb 2007	Depth (mbrp) Sep 2007
33	HSA53	416336	1717861	35	35.13
34	HSA54	416612	1717630	27	
35	HSA55	416631	1717743	28	
36	HSA56	424000	1722000	30	30
37	HSA56	416582	1717597	27	
38	HSA57	416964	1717773	30	
39	HSA58	414746	1715368	35	
40	HSA60	423000	1721100	25	
41	HSA60	415955	1714858	18	
42	HSA61	416062	1714747	21	
43	HSA62	414799	1715584	38	
44	HSA111	417906	1716588		32.92
45	HSB1	408880	1696762	17	
46	HSB2	408943	1696768	20	
47	HSB66	445000	1712000	30	30
48	HSH2	407985	1703832	21	21.1
49	HSH5	412602	1712846	180	
50	HSH6	412518	1713248	150	
51	HSS2	425190	1700940	26	25.33
52	HSS3	425231	1701003		27.33
53	HSZ1	418990	1686713		30.95
54	HSZ2	419008	1678617	104	
55	HSZ6	430466	1697997	28	
56	HSZ7	422211	1690122	30	30.54
57	HSZ9	414631	1692575	49	

S.N	WELL-ID	X-UTM	Y-UTM	Depth (mbrp) Feb 2007	Depth (mbrp) Sep 2007
58	HSZ11	417650	1687381		40.1
59	HSZ12	416473	1689675	73	

- The contours of the depth-to-water are affected by changes in depth over short distances; these may be caused by differences in elevation, but also by poorly permeable layers within the alluvium, causing shallower groundwater depths locally or by abstractions near the well observed.
- In general, the depth-to-water is largest in the northern part of the alluvium aquifer (Figures 6-3 and 6-4) which may be attributed to the same time record There is no significant difference in September 2007 after the rainy season (Figure 6-5).
- The depth-to-water generally varied from 20 m to 60 m during 2001 and from 11 m to 214 m during Feb. 2007. After the rainy season of hydrologic year 2007, it varied from 11 m to 101 m. But, in the wells measured both in Feb. and Sep. 2007, no significant change in water level can be observed.
- Seasonal fluctuations of depth-to-water, as depicted by Figures 6-4 and 6-5, have no definite trends. The correlation between the depth-to-water maps belonging to the same area of the alluvium aquifer (the northern part) in different time periods exhibits a continuous progress of the low contour values (contour line of 30 mbrp) toward the outlet of Wadi As-sir and Wadi Al furs which may reflect the recharge process through subsurface flow.
- The unsaturated thickness of the alluvium aquifer, which reflects the depletion problem in Sana'a Basin, ranged between 14 m and 60 m during hydrologic year 2001, while it ranged between 10 m and 210 m before the rainy season of hydrologic year 2007 and between 10 m and 100 m after the rainy season of the same hydrologic year. This reflects the effect of depletion during the 2001-2007 interval.

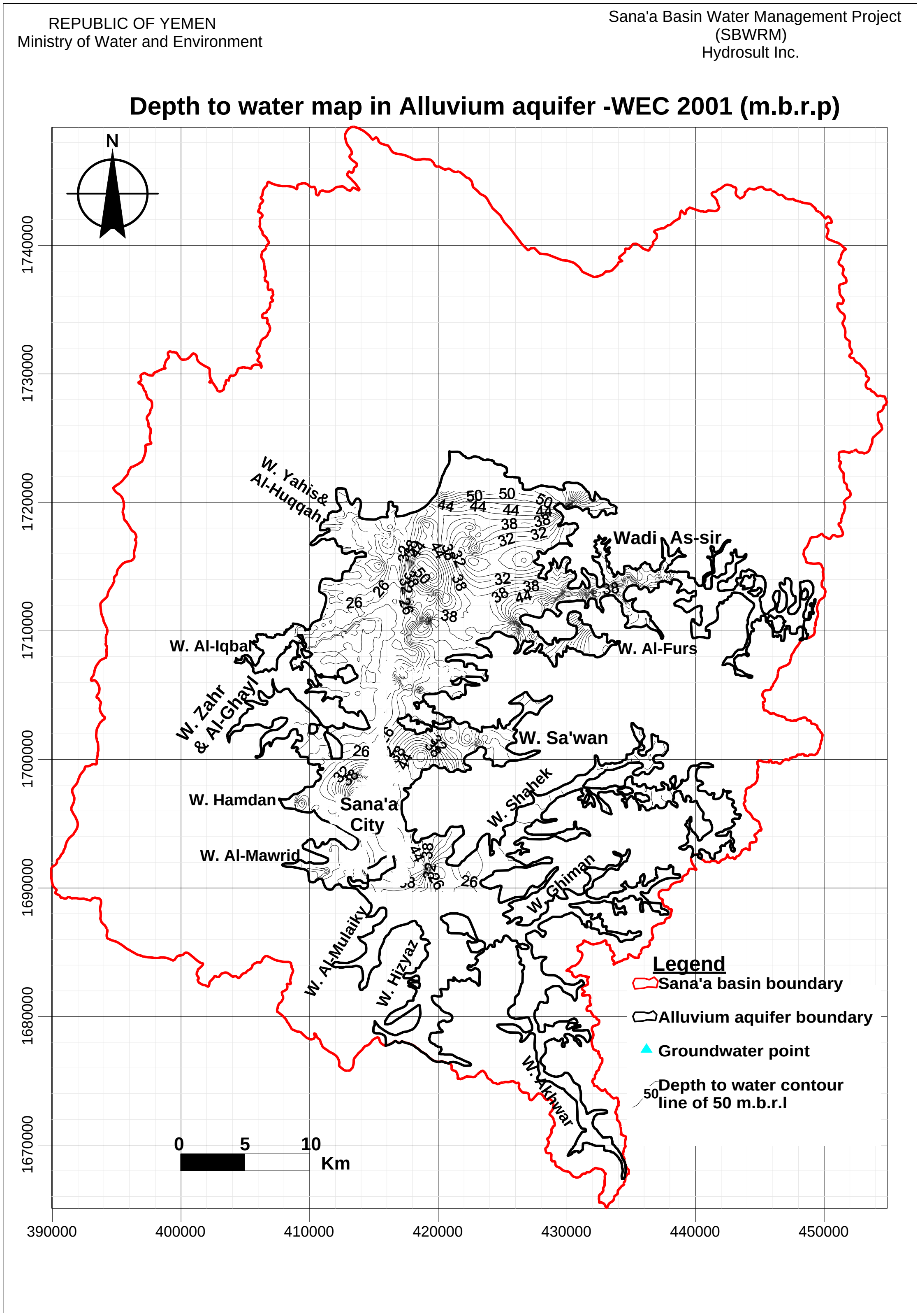

Figure 6-3 Depth-to-water contour map of the alluvium aquifer in Sana'a Basin (based on the sorted data extracted from well inventory of WEC 2001)

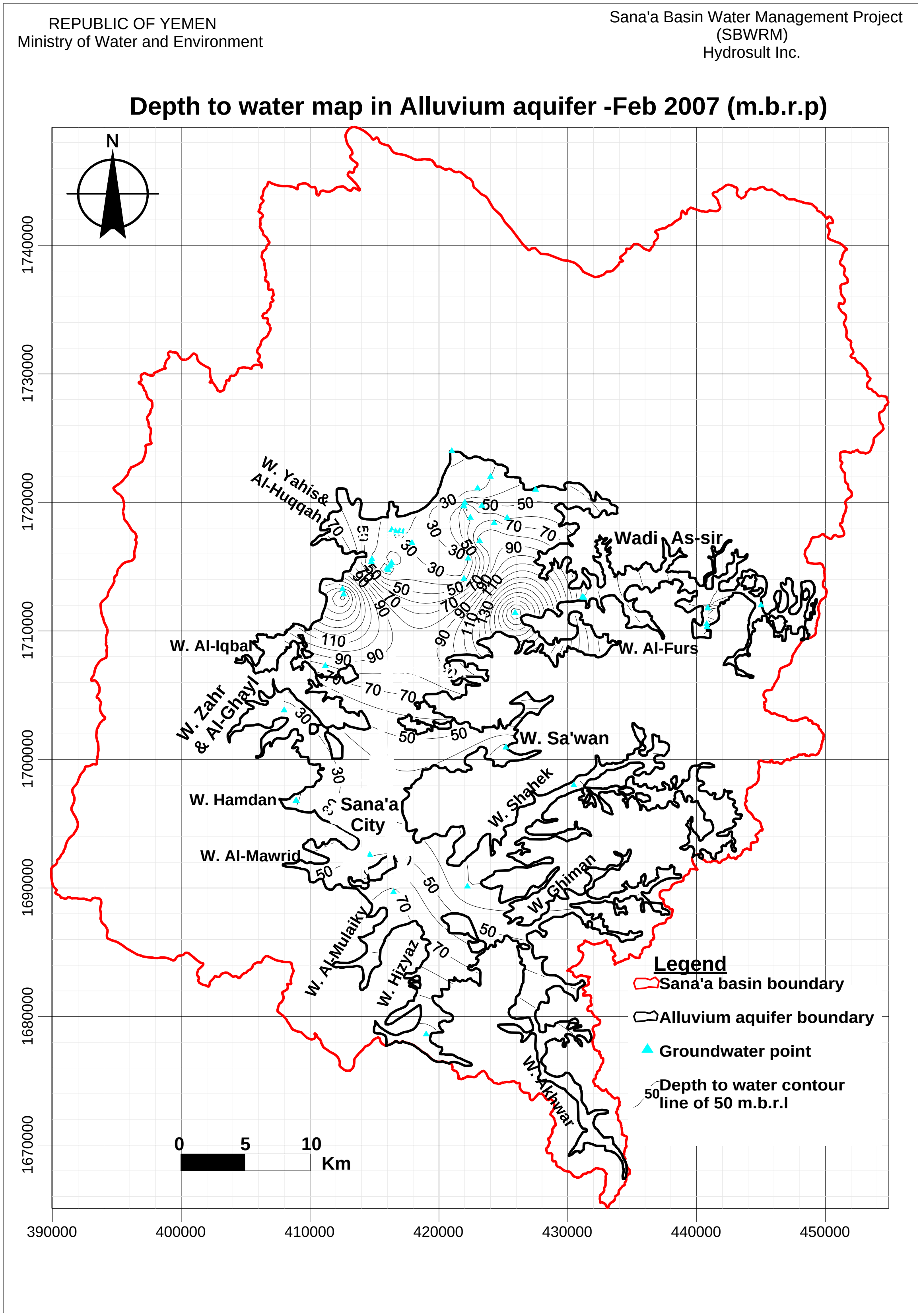

Figure 6-4 Depth-to-water contour map of the alluvium aquifer in Sana'a Basin (Feb. 2007)

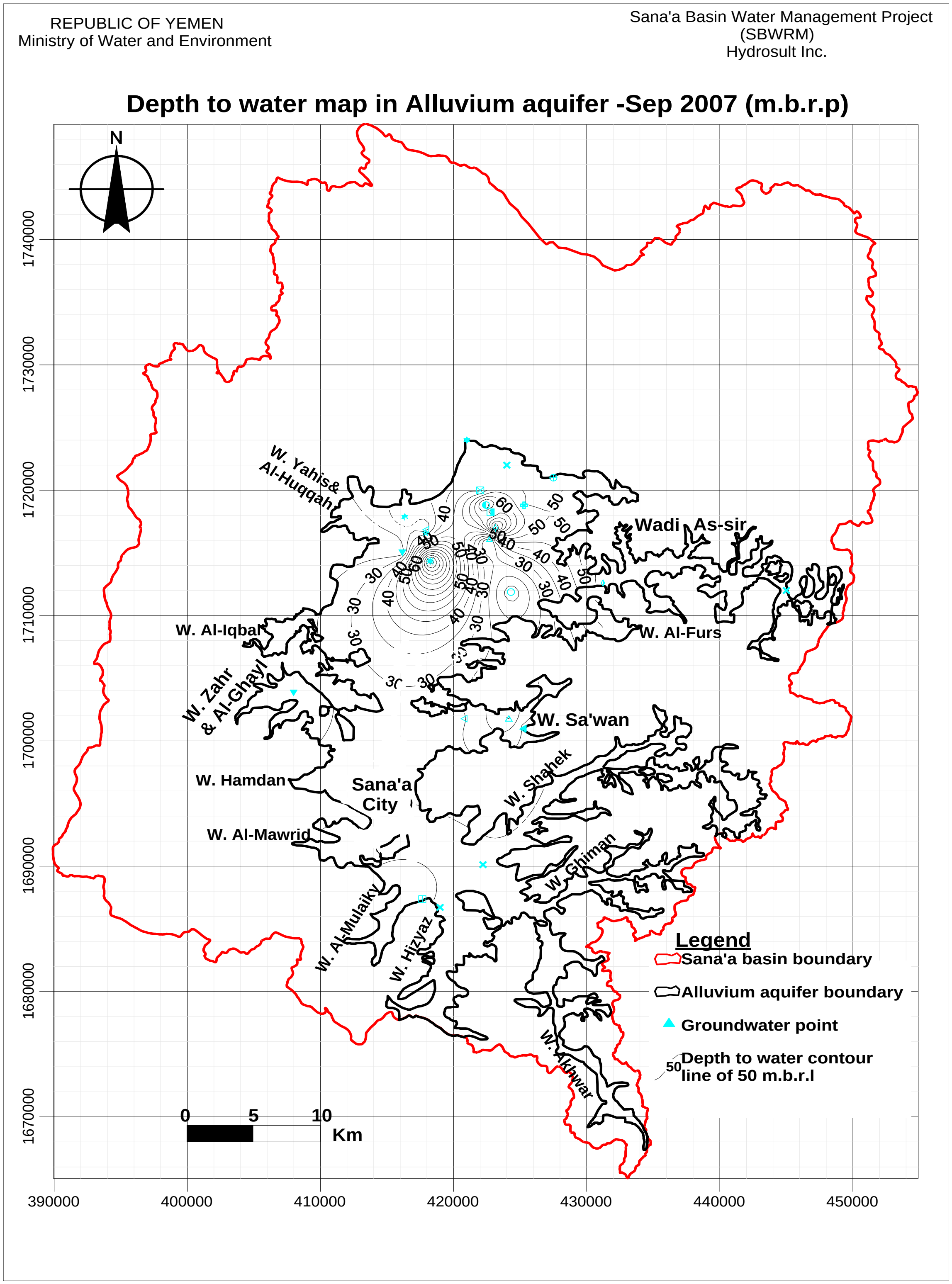

Figure 6-5 Depth-to-water contour map of the alluvium aquifer in Sana'a Basin (Sep. 2007)

6.4.2 Groundwater table mapping in the alluvium aquifer

More intensive work was carried out to construct water table maps. Initially, the processed water level records were checked against the bottom level of the alluvium aquifer to delineate the dried areas in the aquifer. The grid mathematic option in SURFER software was used to subtract the water table grid from the bottom level grid of the aquifer. The negative contour values were separated from the positive values through the zero contour line. The negative values represent the dried areas in the aquifer during the period of record (Figure 6-6). These areas were defined in the base map to blank out from the total area of the aquifer. Based on the groundwater points surveyed and procedure for delineating the dry areas, two water table maps of the alluvium aquifer were developed before and after the rainy season. Also, the water table contour maps for the years 1973, 1985, 1993 and 2001 were constructed, based on the data sets processed in the literature. These groundwater table maps represent the same period of measurements used to precisely study the groundwater flow. They shed light on the historical and seasonal changes, which form a basis for the groundwater depletion and storage study. From these six figures (Figures 6-7 to 6-12), the following may be concluded:

- Under normal conditions, the alluvium aquifer absorbs all surface water draining towards it from the surrounding mountains. Runoff, in principle, may pass over the alluvium aquifer and finally be funneled into Wadi Al-Kharid through the gorge north of the Sana'a plain. This likely occurs very seldom only, during rare periods of extremely high rainfall. The floods are normally produced by rains in hilly areas (effective catchment with an area of 1,020 km^2, SAWAS, 1995).
- Groundwater levels observed over the years:
  - in 1973, pre-development time, based on records processed, ranged between 2,115 and 2,453 m asl, with mean value of 2,250 m asl;
  - in 1985, ranged between 2,100 and 2,388 m asl with mean value of 2,190 m asl;
  - In 1993, ranged between 2,009 and 2,362 m asl with mean value of 2,233 m asl;
  - in 2001, ranged between 2,036 and 2,724 m asl with mean value of 2,210 m asl;
  - in 2007, before the rainy season, ranged between 2,010 and 2,416 m asl with mean value of 2,181 m asl;
  - in 2007, after the rainy season, ranged between 2,079 and 2,193 m asl with mean value of 2,193 m asl.
- -The general decrease in the mean value of the groundwater table since pre-development in 1973 until now may reflect the depletion problem of this aquifer as a result of over-pumping.
- Groundwater flow direction in the alluvium aquifer is generally from south to north, and from upstream of the surrounding sub-basins (red areas) to downstream (yellow areas), as depicted in the water table maps constructed. This reflects that the upstream of surrounding sub-basins act as recharge areas for the flat areas of the alluvium aquifer downstream.

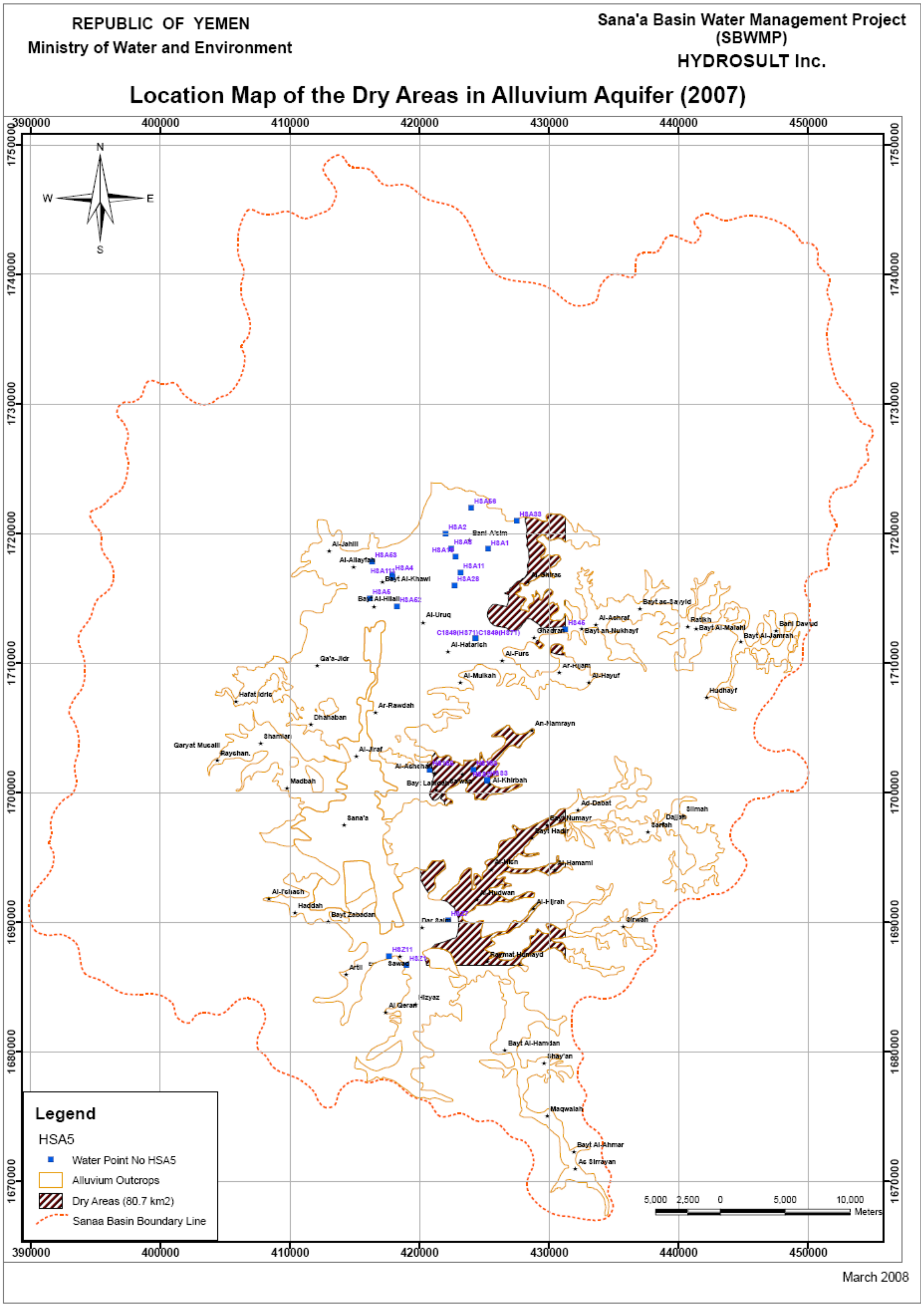

Figure 6-6 Delineation of dried area of alluvium aquifer in Sana'a Basin during 2007

- During the 1993-2001 interval, equipotential lines of the northern part of the alluvium aquifer are curved in an open trench with flow from all directions towards the low-lying areas, particularly in the area between Bayt Al Khawi and Al-Ghiras. This may be attributed to the concentration of wells in these parts with heavy, uncontrolled pumping (more than 13,500 production wells).
- The effect of the rainy season on the groundwater regime in the alluvium aquifer is clear on the water table maps for Feb. 2007 and Sep. 2007 (Figures 6-11 and 6-12). The blue-colored area with low groundwater level changed to yellow-colored, with moderate groundwater level (Rawdda and Qa'a Jidr areas). The groundwater contour line of magnitude 2,200 m asl moved towards the north for about 4 km as a result of the effect of the two rainy seasons, i.e. during April and July.
- Generally speaking, the water table maps demonstrate the existence of a predominantly directed groundwater flow, slightly divergent from the main source of recharge. The aquifer encompasses a large number of "flow domains" related to the larger and smaller wadis that recharge the aquifer from south, east and west directions towards the central part of Sana'a Basin. The larger flow systems consist of relatively permeable deposits and constitute preferential zones for groundwater flow. The equipotential contour lines show concentric shapes quite suddenly towards the central part of the aquifer (Bani El-Harith). Higher hydraulic gradients in this location may be attributed either to a higher flow density or to a lower transmissivity of the aquifer system. An abrupt decrease in the flow density is unlikely, because groundwater discharge is insignificant in the indicated transition zone (central part of Bani El-Harith) and divergence of flow lines has a gradual and limited effect only. The conclusion is that the central part of the alluvium aquifer apparently is thicker and/or is composed of other, more permeable deposits than in other places.
- The anomaly in the piezometric surface observed over the alluvium aquifer is without doubt caused by geological phenomena. In the context, a continuation of the flexure due to complete disappearance of the Tawilah sandstone aquifer in the Rawdda area might have enlarged the effective depth for groundwater flow. Another possibility is that the feature commented is associated with the transition of alluvial to predominantly aeolian sedimentation over a certain depth. Other irregularities in the water table maps may be associated with lithological variations within the Quaternary deposits.
- A continuous phreatic level is assumed to exist everywhere throughout the alluvium aquifer. The water levels in the many dug wells can be interpreted without appreciable error as the local phreatic level. In deeper, drilled wells, on the contrary, vertical flow and/or the presence of confining layers in the lithologic succession may cause discrepancies between the static water level in the well and the phreatic level. The error introduced by these conditions will not exceed a few meters, under local circumstances, and therefore has been discarded. Figure 6-11 intends to show the average position of the phreatic level in the alluvium aquifer during the beginning of 2007. It ranges from more than 4 m of depth in well no. HSS 5 (Sa'awan sub-basin) to less than 180 m in well no. HSH 5 (El Errah village in Hamadan). A general trend from deep to shallow groundwater levels can be recognized in the peripheries of the aquifer as a result of topography effects and local structures.

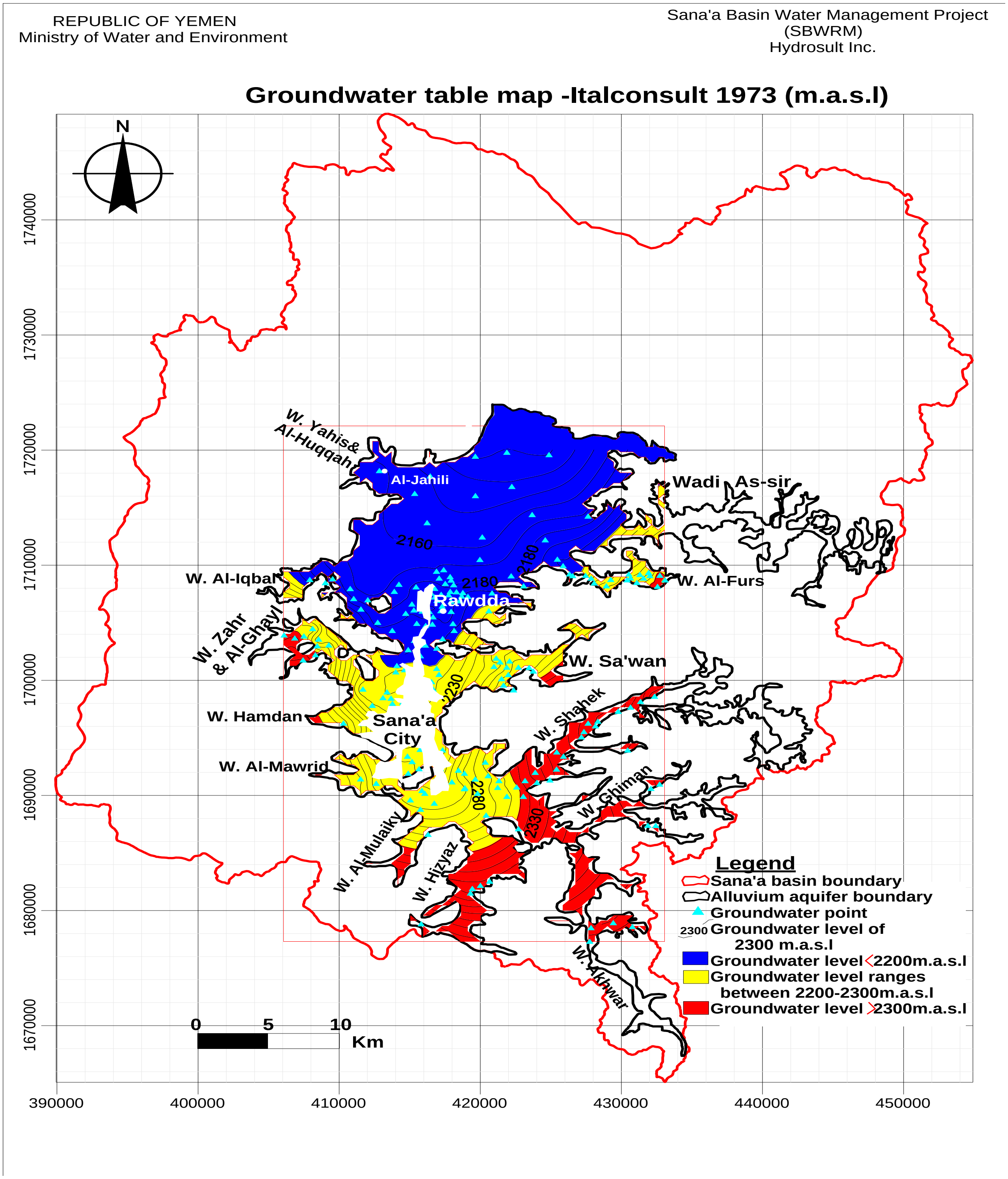

Figure 6-7 Water table contour map of the alluvium aquifer in Sana'a Basin (based on the sorted records of ITALCONSULT 1973)

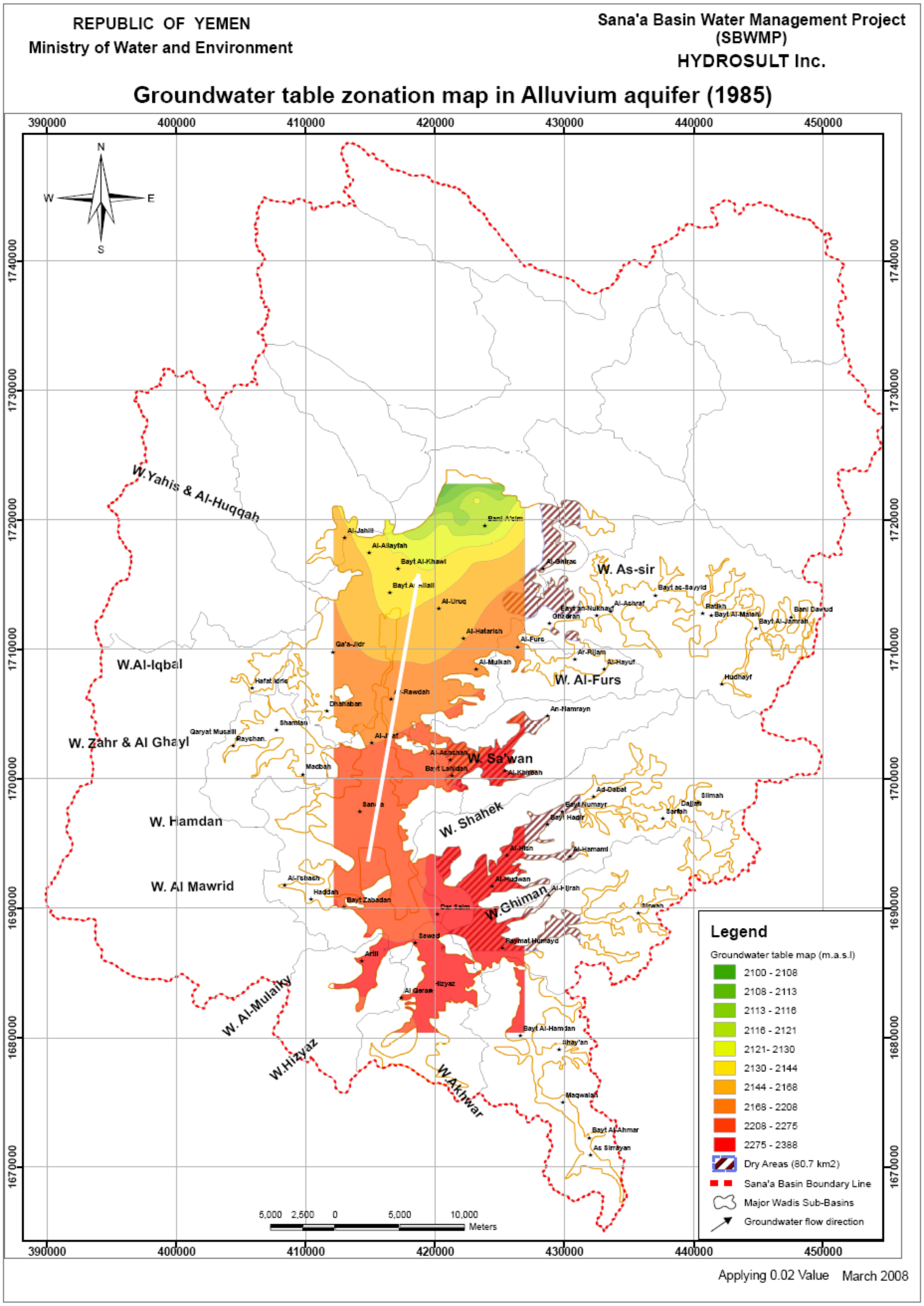

Figure 6-8 Water table contour map of the alluvium aquifer in Sana'a Basin (based on sorted records of Russian 1985)

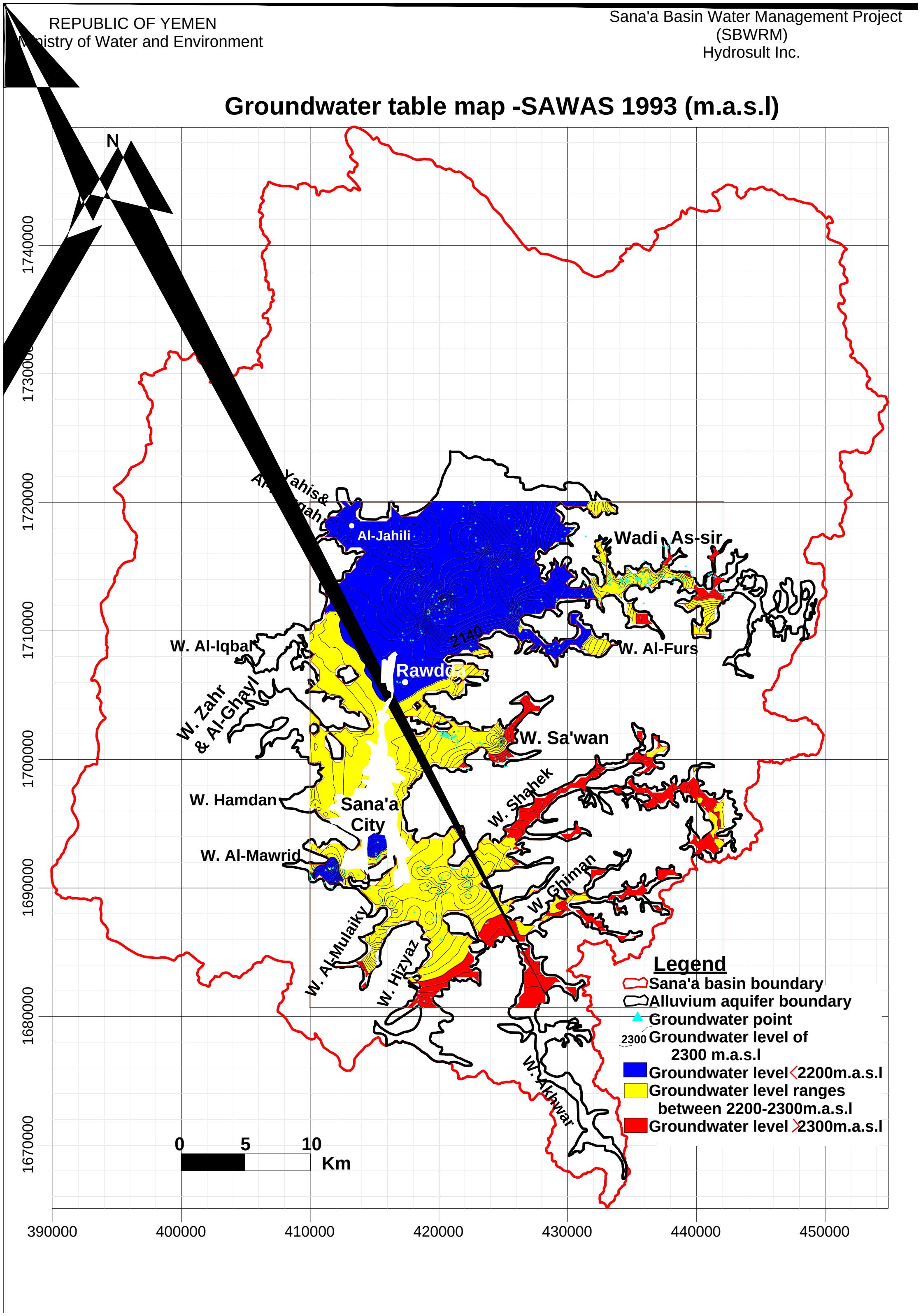

Figure 6-9 Water table contour map of alluvium aquifer in Sana'a Basin (based on sorted records of SAWAS 1993)

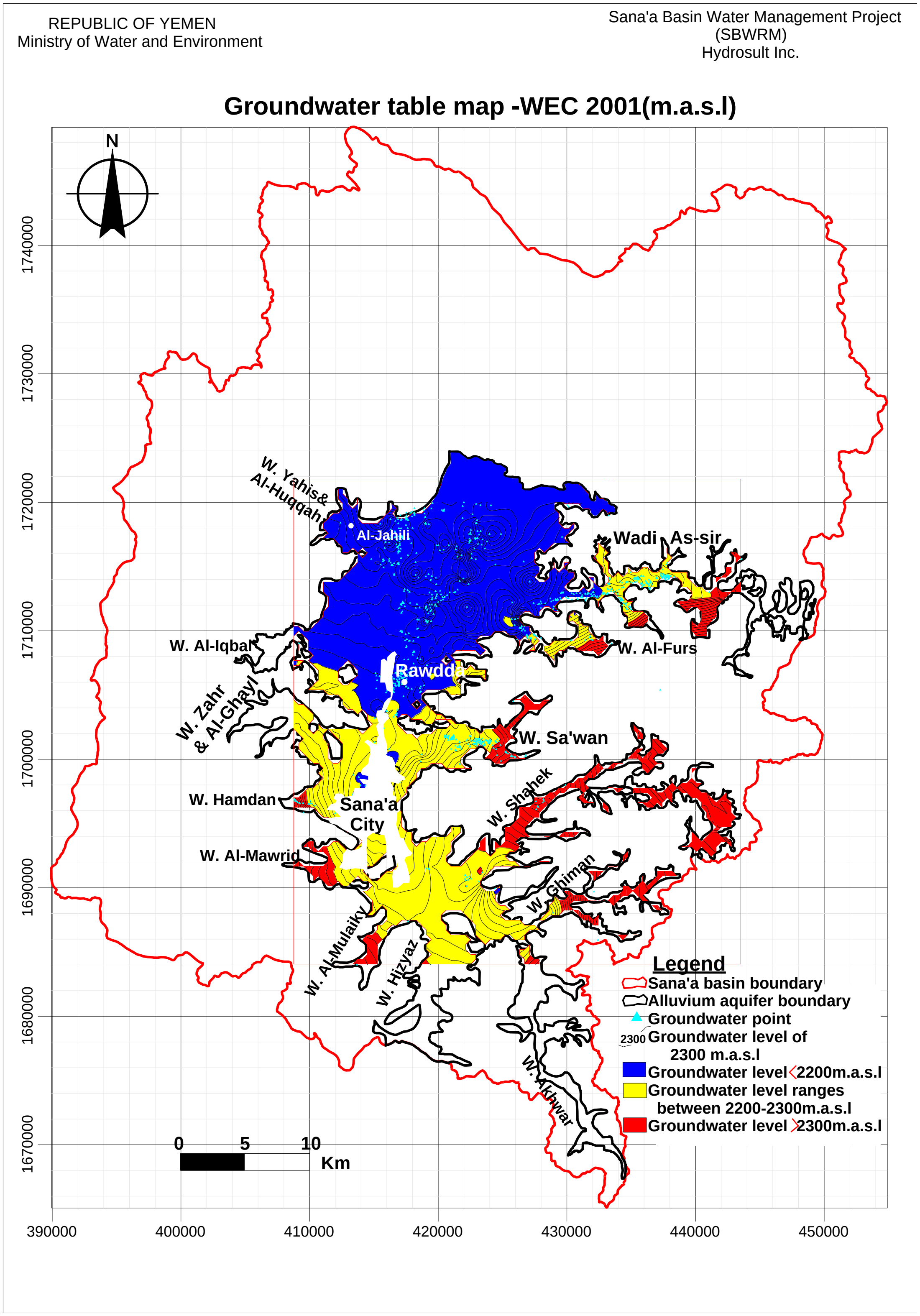

Figure 6-10 Water table contour map of alluvium aquifer in Sana'a Basin (based on sorted records of WEC 2001)

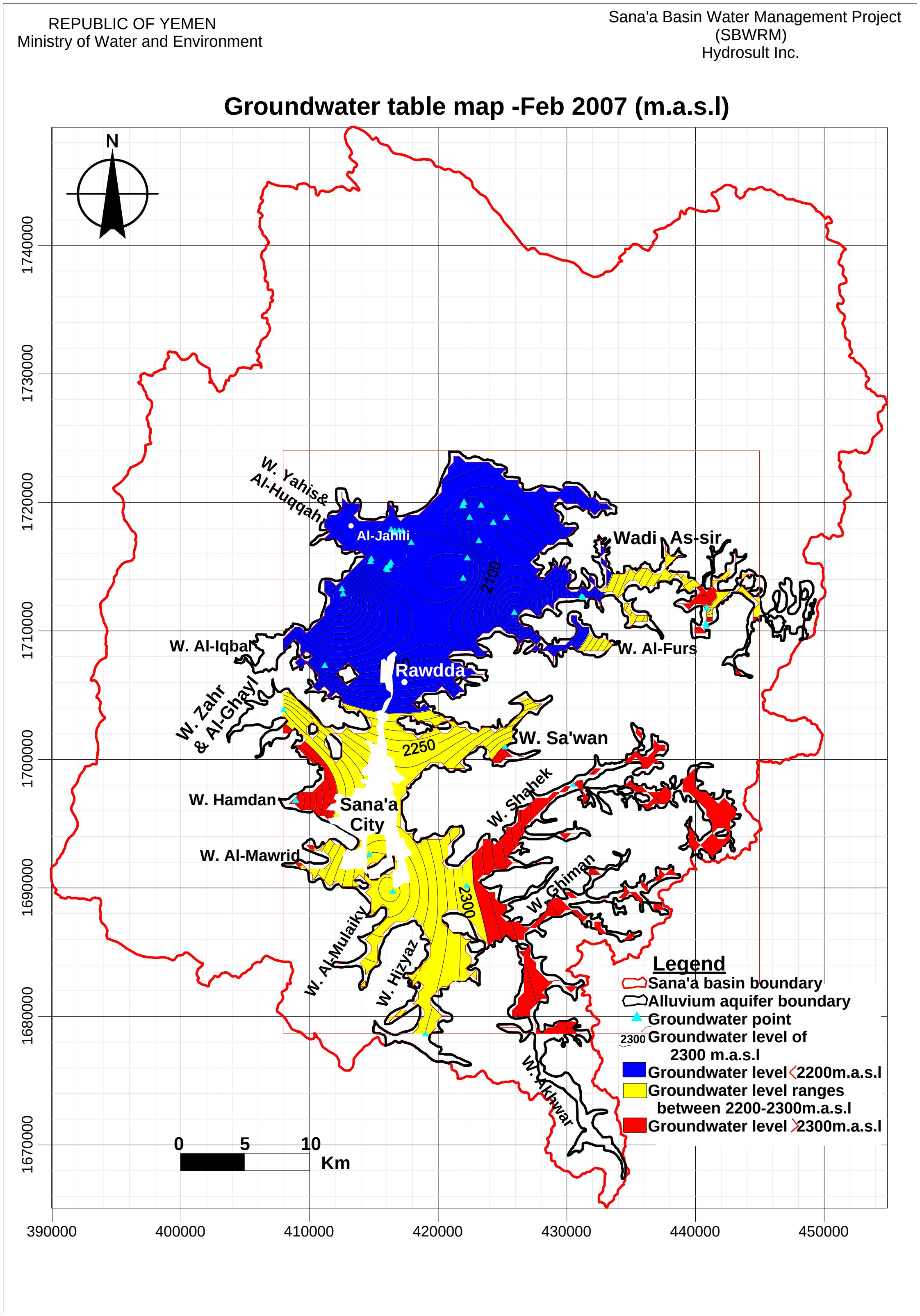

Figure 6-11 Water table contour map of alluvium aquifer in Sana'a Basin (based on sorted records of HYDROSULT Feb. 2007)

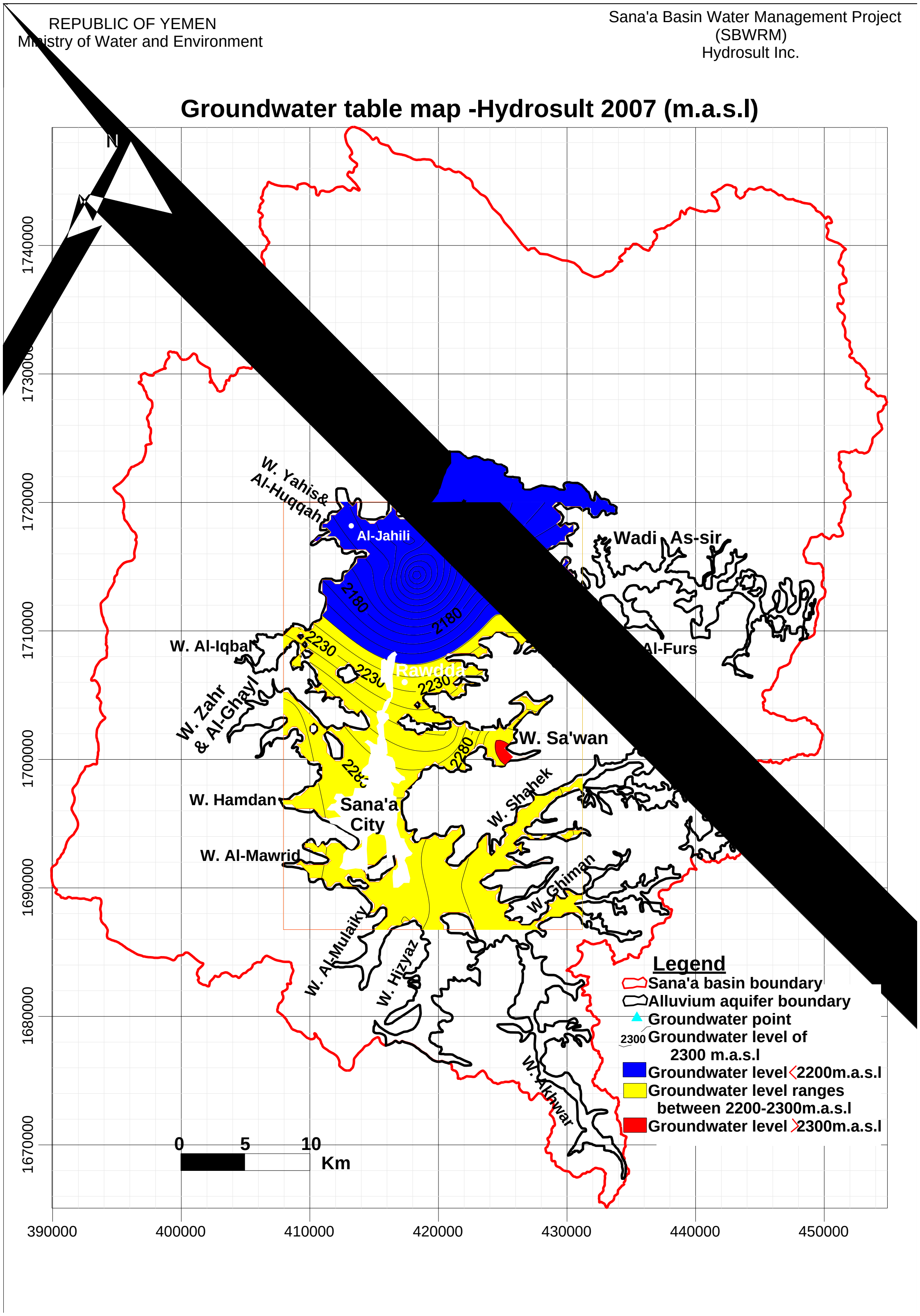

Figure 6-12 Water table contour map of alluvium aquifer in Sana'a Basin (based on sorted records of HYDROSULT Sep. 2007)

6.5 Groundwater flow in the volcanic aquifer

The lateral extent of the Tertiary volcanics is well known from the geological map (SAWAS, 1996). It outcrops over about 35% of the area of the Sana'a Basin (Foppen, 1996). The base, however, is known only at the northern edge of the outcrops, in the vicinity of Sana'a City, where boreholes fully penetrate the volcanics (Foppen, 1996). The thickness of the aquifer increases rapidly southwards to about 600 m in the southern part of Sana'a City. Towards the south, the thickness is not known. Geophysical surveys have not been successful in determining the base due to the poor contrast in resistivity between the un-weathered basalts and the Cretaceous Tawilah sandstone (SAWAS, 1991).

6.5.1 Depth to groundwater in the volcanic aquifer

In the present study, water levels from the reference point for every surveyed groundwater point in the shallow water-bearing horizons in the volcanic aquifer were measured during May 2007. Water levels were measured with electric tapes in 40 wells of the volcanic aquifer (Tables 6-5 and 6-6). From these 40 wells, 28 dug wells were chosen to develop both depth-to-water and water table maps. The data do not represent simultaneous measurements, but are distributed over a period of two months (May and June 2007). Table 6-5 summarizes the depth-to-water in the dug wells of the shallow zone. In most of the dug wells, the water level did not exceed 20 m brp (65%, Table 6-5), while 44% of the water level measurements in boreholes did not exceed 100 m brp. The recorded measurements of depth-to-water in the shallow zone range from 2.5 to 32.9 m brp with a mean value of 17.33 m brp, while in deep wells they range from 40.3 to 250 m brp with an average of 111.8 m brp.

Table 6-5 Location of hand dug wells penetrating the shallow zone of the volcanic aquifer (May 2007)

S.No	Well ID	Eastings (UTM)	Northings (UTM)	Elevation (m)	Type of Well	Depth to Water (m)
1	HS129	436266	1718787	2,627	Dug	2.5
2	HS130	436101	1718789	2,649	Dug	5
3	HS135	446616	1712360	2,416	Dug	6.1
4	HSS48	429087	1675278	2,497	Dug	8.08
5	HSS41	420470	1678554	2,439	Dug	8.6
6	HS161	424820	1703738	2,380	Dug	9.42
7	HS162	424815	1703634	2,381	Dug	11.56
8	HS143	443420	1708089	2,481	Dug	13.83
9	HSS28	439636	1697025	2,580	Dug	14
10	HSS46	431817	1673690	2,553	Dug	14.19
11	HS134	449088	1713455	2,477	Dug	16.4
12	HSS24	433021	1699479	2,482	Dug	17

S.No	Well ID	Eastings (UTM)	Northings (UTM)	Elevation (m)	Type of Well	Depth to Water (m)
13	HSS45	431223	1670070	2,598	Dug	17.13
14	HSS47	431843	1673768	2,544	Dug	17.4
15	HSS26	433599	1697699	2,491	Dug	17.67
16	HSS13	443422	1701757	2,652	Dug	18
17	HS145	437115	1710061	2,343	Dug	18.1
18	HSS16	440002	1701901	2,583	Dug	19.4
19	HSS27	435729	1697552	2,507	Dug	20.7
20	HS131	440083	1720084	2,570	Dug	21.65
21	HS164	427530	1703755	2,394	Dug	23.95
22	HSS17	439380	1701820	2,577	Dug	24
23	HSS4	426652	1699852	2,388	Dug	24.4
24	HS136	446320	1719200	2,406	Dug	25
25	HSZ5	439684	1701903	2,574	Dug	25.15
26	HSS38	416418	1676354	2,429	Dug	26.3
27	HS151	443398	1715510	2,384	Dug	27.03
28	HS150	443656	1715743	2,392	Dug	32.9

Table 6-6 Location of deep bore holes penetrating deep zone of Volcanic aquifer (May 2007)

S.No.	Well ID	Eastings (UTM)	Northings (UTM)	Elevation (m)	Depth-to-water (m)	WT
1	HS61	439084	1715863	2,336	61.27	2,274.73
2	HS62	439084	1715861	2,336	250	2,086.00
3	HSA48	409308	1709663	2,238	143.49	2,094.51
4	HS6	449395	1739725	2,193	52.9	2,140.10
5	HS13	449212	1739908	2,174	40.3	2,133.70

S.No.	Well ID	Eastings (UTM)	Northings (UTM)	Elevation (m)	Depth-to-water (m)	WT
6	HS17	434917	1729468	2,127	79.85	2,047.15
7	HS50	427222	1711226	2,244	144.18	2,0,99.82
8	HS52	429585	1716731	2,275	47.5	2,227.50
9	HS63	420466	1707697	2,245	149.7	2,095.30
10	HSH1	401668	1713477	2,298	89.55	2,208.45
11	HSA47	410059	1710070	2,235	137.79	2,097.21
12	HSA49	409754	1708942	2,234	117.4	2,116.60

6.5.2 Groundwater table mapping in the Tertiary volcanic aquifer

The processed groundwater head values surveyed by Russian 1985 and SAWAS 1993 were used in constructing the groundwater piezometric maps of the volcanic aquifer during these periods (Figures 6-13 & 6-14). These groundwater piezometric maps represent the same period of measurements used to study the groundwater flow and shed light on historical changes which are a basis for the groundwater depletion and storage study. By using the data of the depth to groundwater in the deep volcanic wells surveyed during the interval of May to June 2007 and their ground elevations extracted from the Digital Elevation Model (DEM) of Sana'a Basin (Table 6-6), the groundwater piezometric map was constructed (Figure 6-15). From these three figures (Figures 6-13 to 6-15), the following may be concluded:

- The groundwater flow direction in the volcanic aquifer is from west to east, in general, from south to north and from east to west as depicted from the constructed groundwater piezometric maps. This general trend coincides with the general trend of surface runoff. This reflects that the highly fractured Tertiary volcanic cover in the east and west may act as recharging areas to the underlying Tawilah sandstone aquifer through its fractures and joints, and laterally to the alluvium aquifer. This needs to assure from the groundwater quality inside and outside the basin due east.
- Groundwater levels observed over the years:
    - in 1973, pre-development time, based on the processed records, ranged between 2,115 and 2,453 m asl with mean value of 2,250 m asl;
    - in the year 1985, ranged between 2,151 and 2,700 m asl with mean value of 2,452.5 m asl;
    - in the year 1993, ranged between 2,158 and 2,468 m asl with mean value of 2,313 m asl;
    - in the year 2007, ranged between 2,087 and 2,504 m asl with an average value of 2,295.5 m asl.
- The general decrease in the mean value of groundwater piezometric levels during the periods studied may reflect the effect of a depletion problem of this aquifer.
- During the interval 1985-1993, the disappearance of high groundwater piezometric level areas, characterized by the closed contour line of 2,592 in the eastern part of the aquifer (Figure 6-14), reflects the recharge flow to the highly exploited areas (NE NWSA well field) and low groundwater potentiality of this area. In confirmation of this concept is the presence of this closed contour line in the map of the year 2007 with a low value of 2,441 m asl and a head difference of 151 m, which is more or less equal to the head decline in the NE NWSA well fields. The same condition is present in the area south of Sana'a City, where the decline of groundwater head reached 111 m. These

findings are in agreement with the groundwater piezometric map of the Tawilah sandstone aquifer which suggests a hydraulic connection between the two aquifers in this location. Also, the presence of local groundwater cones of depression in south Sana'a City area shows the intensive groundwater mining process at this location.

- Far from the heavily pumped locations, the configuration of the contour lines is almost without notable change. The hydraulic gradient in the western part of the volcanic aquifer was 20.4×10^{-3}, 33.7×10^{-3} and 20.4×10^{-3} and 29.6×10^{-3} during the years 1985, 1993 and 2007 respectively, whereas it reached 15.9×10^{-3}, 11.1×10^{-3} and 10.9×10^{-3} during 1985, 1993 and 2007 respectively for the southern part of the aquifer. The continuous decrease in hydraulic gradient characteristic of the southern part of the aquifer may be attributed to the continuous decrease in annual rainfall during the period 1985-2007. The hydraulic gradients, which can be directly derived from these maps, are the basis for estimating the rate of groundwater flow through cross-sections, for example through the area boundaries.

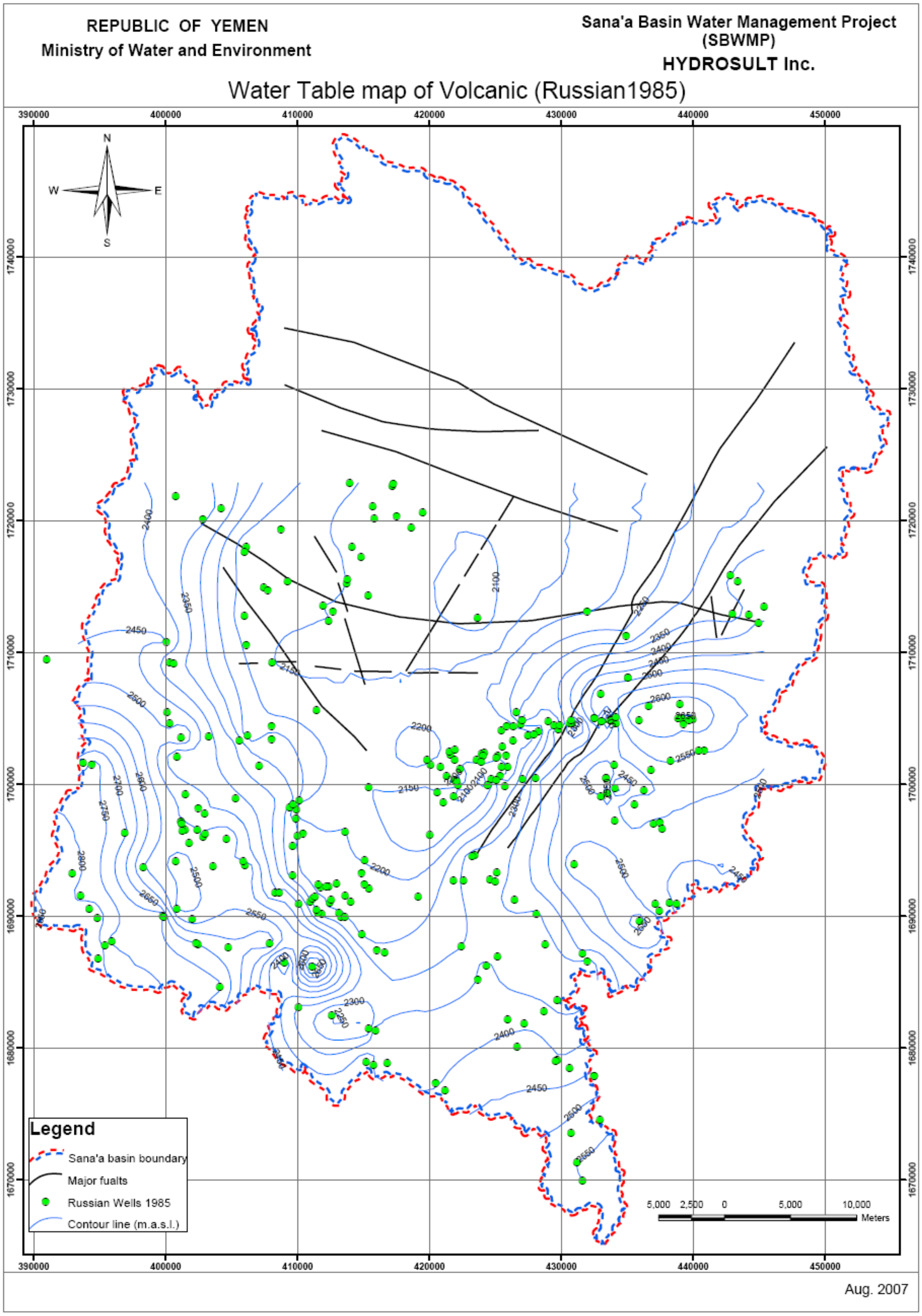

Figure 6-13 Ggroundwater piezometric map of the volcanic aquifer in Sana'a Basin during 1985 (based on the surveyed data by Russian 1985)

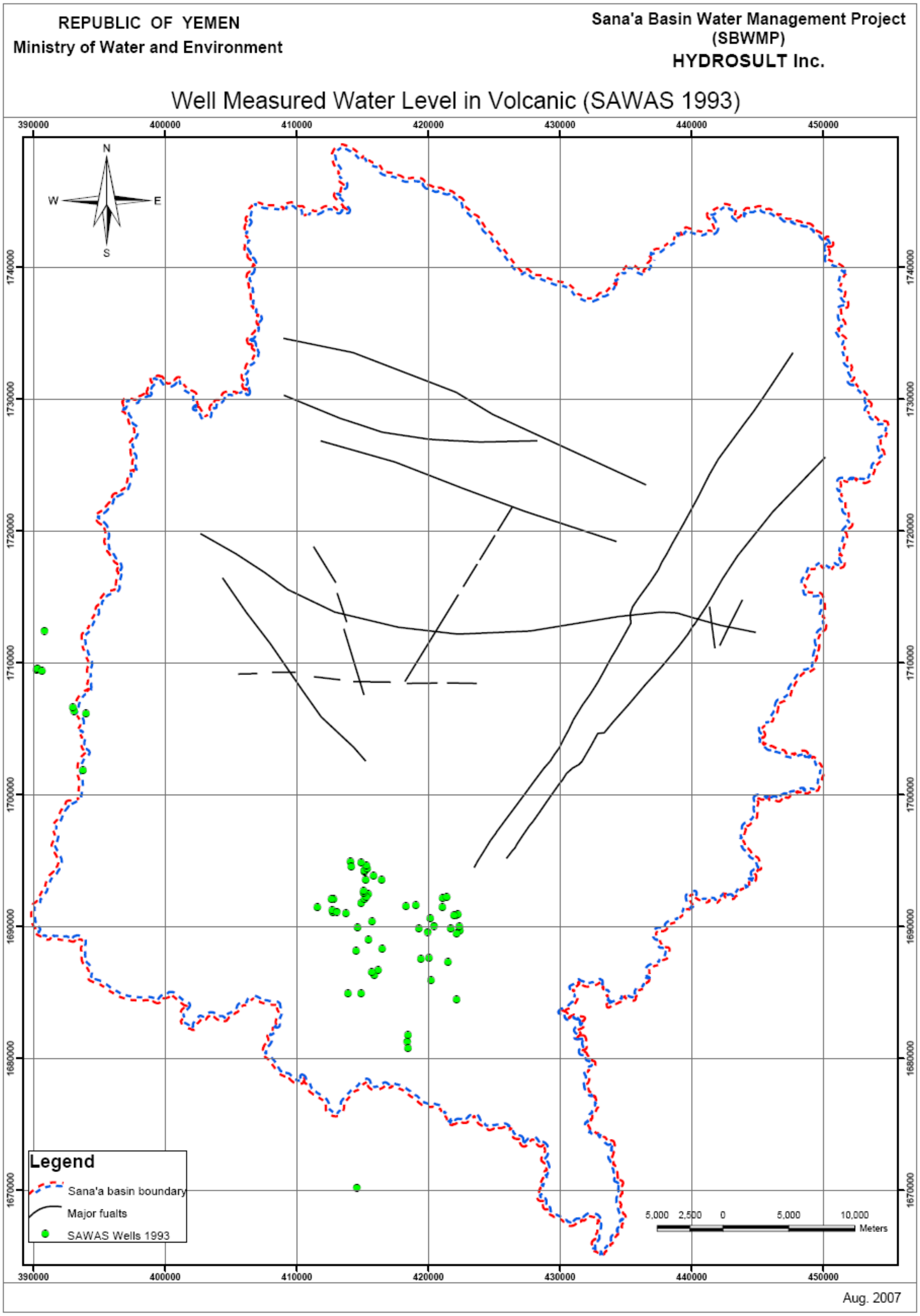

Figure 6-14 Groundwater piezometric map of the volcanic aquifer in Sana'a Basin during 1993 (based on the surveyed data by SAWAS 1985)

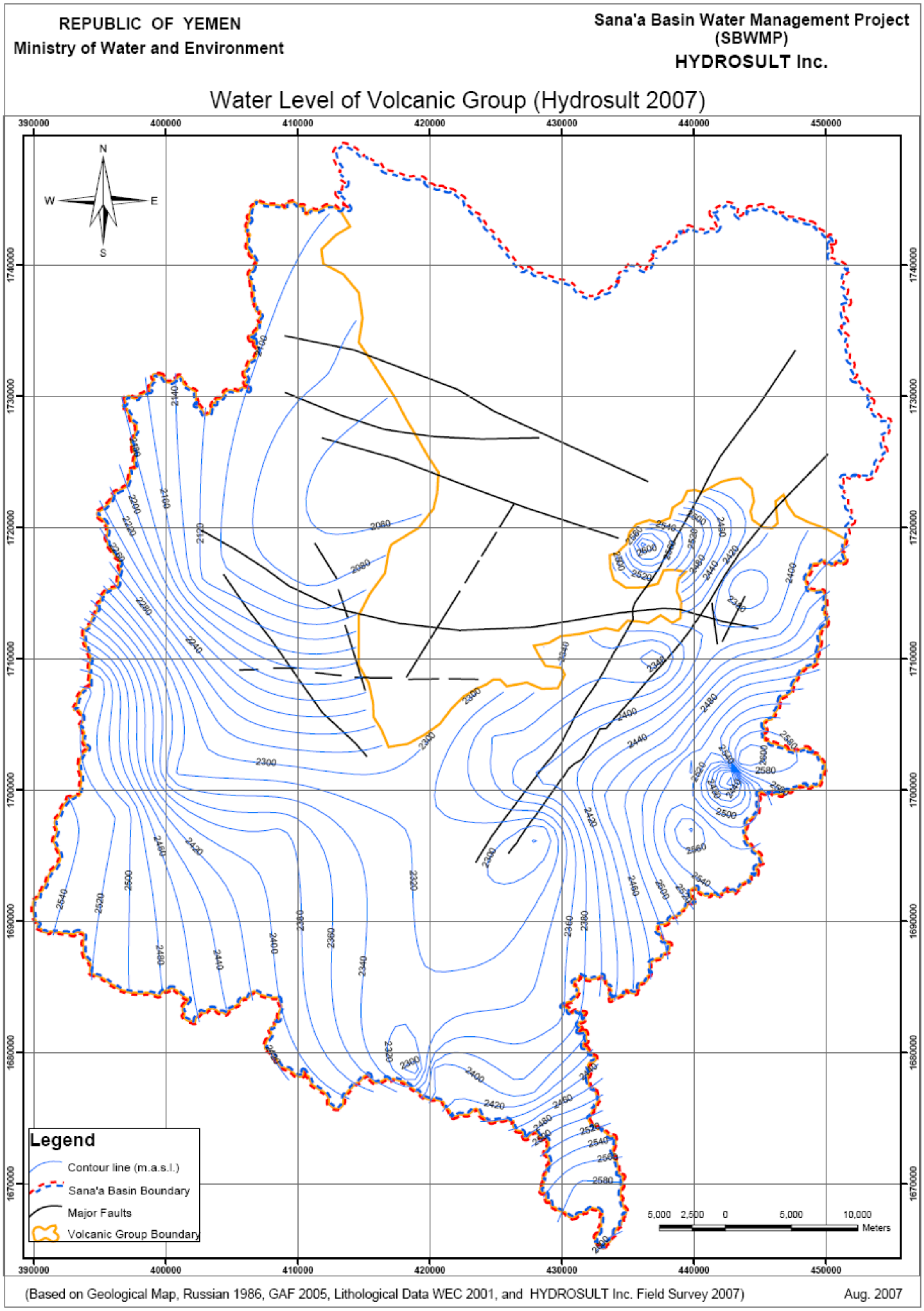

Figure 6-15 Groundwater piezometric map of the volcanic aquifer in Sana'a Basin during 2007 (based on data surveyed by Hydrosult June 2007)

6.6 Groundwater flow in the Tawilah sandstone aquifer

6.6.1 Depth to groundwater mapping in the Tawilah sandstone aquifer

The water level from reference point for every surveyed observation well in the Tawilah sandstone aquifer was detected and periodically measured during the period from Dec. 2004 until July 2006 and from Dec. 2006 until Sep. 2007. Water levels were measured with electric tapes in 43 wells over the aquifer (Table 6-7). Among these 43 wells, 10 dug wells partially penetrate the aquifer outcrops and 16 deep boreholes were chosen to develop both depth-to-water and water table maps after the rainy season (Sep. 2007). This first period was taken before the first rainfall season of April, while the second was taken after the second rainfall season of July (during Sep. 2007, Table 6-8) to study the effect of rainfall on the water table in the Tawilah sandstone aquifer. Tables 8-4 and 8-5 summarize the depth-to-water and water table in the different wells surveyed. Applying the sorted data extracted from the well inventory of WEC 2001 (Annex 1) and the data surveyed during this study, the depth-to-water mapping in the Tawilah sandstone aquifer was developed (Figures 6-16 to 6-18).

The sorted data extracted from the well inventory of WEC 2001 show a range of depth-to-water from 27 m brp (well no. C-1157) to 570 m brp (well no. C-2459). The depth-to-water contour lines in the Tawilah sandstone aquifer during the year 2001 (Figure 6-16) reflect the presence of closed contour lines in the northeastern and eastern outcrops. Figure 6-16 shows that depth-to-water values range from 10 m brp in well no. HS 74 (Nihm area) to 250 m brp in well No. HS 62 near Bani Husheish (Table 6-7). The great difference between minimum and maximum values of depth-to-water in the Tawilah sandstone aquifer may be attributed to the presence of fractures which recharge this aquifer (secondary permeability). The absence of closed contour lines in Figure 6-17 and Figure 6-18 may be attributed to the small number of data sets used in developing these two maps.

Table 6-7 Depth to groundwater (m brp) in monitored wells in Tawilah sandstone aquifer in Sana'a Basin (Feb 2007)

WELL-ID	Easting (m)	Northing (m)	Elevation (m)	DEPTH (m brp)	WT (m)
HS1	445252	1726903	2,132	16.7	2,115.3
HS2	445172	1727477	2,120	15.5	2,104.5
HS3	445199	1726998	2,133	15.1	2,117.9
HS4	448870	1739967	2,171	20	2,151.0
HS6	449395	1739725	2,191	52.9	2,138.1
HS11	450025	1739663	2,190	27.48	2,162.52
HS13	449212	1739908	2,201	40.3	2,160.7
HS14	449185	1739897	2,209	50.48	2,158.5
HS17	434917	1729468	2,124	79.85	2,044.2
HS18	434778	1729475	2,139	130	2,009.0
HS19	434946	1729320	2,126	90	2,036.0

WELL-ID	Easting (m)	Northing (m)	Elevation (m)	DEPTH (m brp)	WT (m)
HS20	434860	1729651	2,116	76.3	2,039.7
HS21	433332	1730112	2,139	80	2,059.0
HS25	432883	1724121	2,183	24.5	2,158.5
HS26	434445	1724670	2,207	23.5	2,183.5
HS31	451212	1723827	2,717	11.1	2,705.9
HS32	450519	1723451	2,545	15.3	2,529.7
HS40	423557	1706673	2,323	130	2,193.0
HS41	422351	1706550	2,271	150	2,121.0
HS42	422317	1706542	2,271	175	2,096.0
HS46	426441	1711304	2,240	188	2,052.0
HS48	428399	1711272	2,297	180	2,117.0
HS49	427218	1711223	2,254	144.65	2,109.4
HS50	427222	1711226	2,254	144.18	2,109.8
HS52	429585	1716731	2,235	47.5	2,187.5
HS53	429648	1716682	2,264	50.53	2,213.5
HS54	429528	1716740	2,235	90	2,145.0
HS55	429466	1716736	2,239	40.2	2,198.8
HS56	431087	1715023	2,280	115.96	2,164.0
HS57	431026	1714902	2,273	120	2,153.0
HS58	431500	1714850	2,274	160	2,114.0
HS59	437694	1713870	2,326	117.3	2,208.7
HS60	437670	1713866	2,326	200	2,126.0
HS61	439084	1715863	2,391	61.27	2,329.7
HS62	439084	1715861	2,391	250	2,141.0
HS63	420466	1707697	2,234	149.7	2,084.3

WELL-ID	Easting (m)	Northing (m)	Elevation (m)	DEPTH (m brp)	WT (m)
HS71	424314	1711874	2,218	11.71	2,206.3
HS72	428441	1716025	2,240	25.8	2,214.2
HS73	433256	1726202	2,209	11.1	2,197.9
HS74	433366	1725618	2,200	10.33	2,189.7
HSA47	410059	1710070	2,219	137.79	2,081.2
HSA48	409308	1709663	2,246	143.49	2,102.5
HSA49	409754	1708942	2,217	117.4	2,099.6

Table 6-8 Depth to groundwater (m) in monitored wells in Tawilah sandstone aquifer in Sana'a Basin (Sep 2007)

Well ID	X-UTM	Y-UTM	TD	Elevation (m)	DEPTH (m)	WT (m)
HS10	453170	1742503	31	2,132	28.35	2,104
HS11	450025	1739663	35	2,187	27.48	2,160
HS14	449185	1739897	114	2,206	50.48	2,156
HS126	440909	1723588	25	2,322	20	2,302
HS128	436064	1722730	--	2,228	52.6	2,175
HS2	445172	1727477	16	2,122	15.5	2,107
HS13	449212	1739908	113	2,203	40.68	2,162
HS17	434917	1729468	150	2,119	79	2,040
HS31	451212	1723827	15	2,723	10.78	2,712
HS50	427222	1711226	270	2,249	145	2,104
HS52	429585	1716731	65	2,237	46.71	2,190
HS56	431087	1715023	160	2,281	116.77	2,164
HS61	439084	1715863	240	2,385	47.85	2,337
HS63	420466	1707697	300	2,234	154.37	2,080

Well ID	X-UTM	Y-UTM	TD	Elevation (m)	DEPTH (m)	WT (m)
HSH1	401668	1713477	180	2,295	90	2,205
HS71	424314	1711874	15	2,218	11.24	2,207
HS72	428441	1716025	30	2,240	25.71	2,214
HSA47	410059	1710070	400	2,219	152.43	2,067

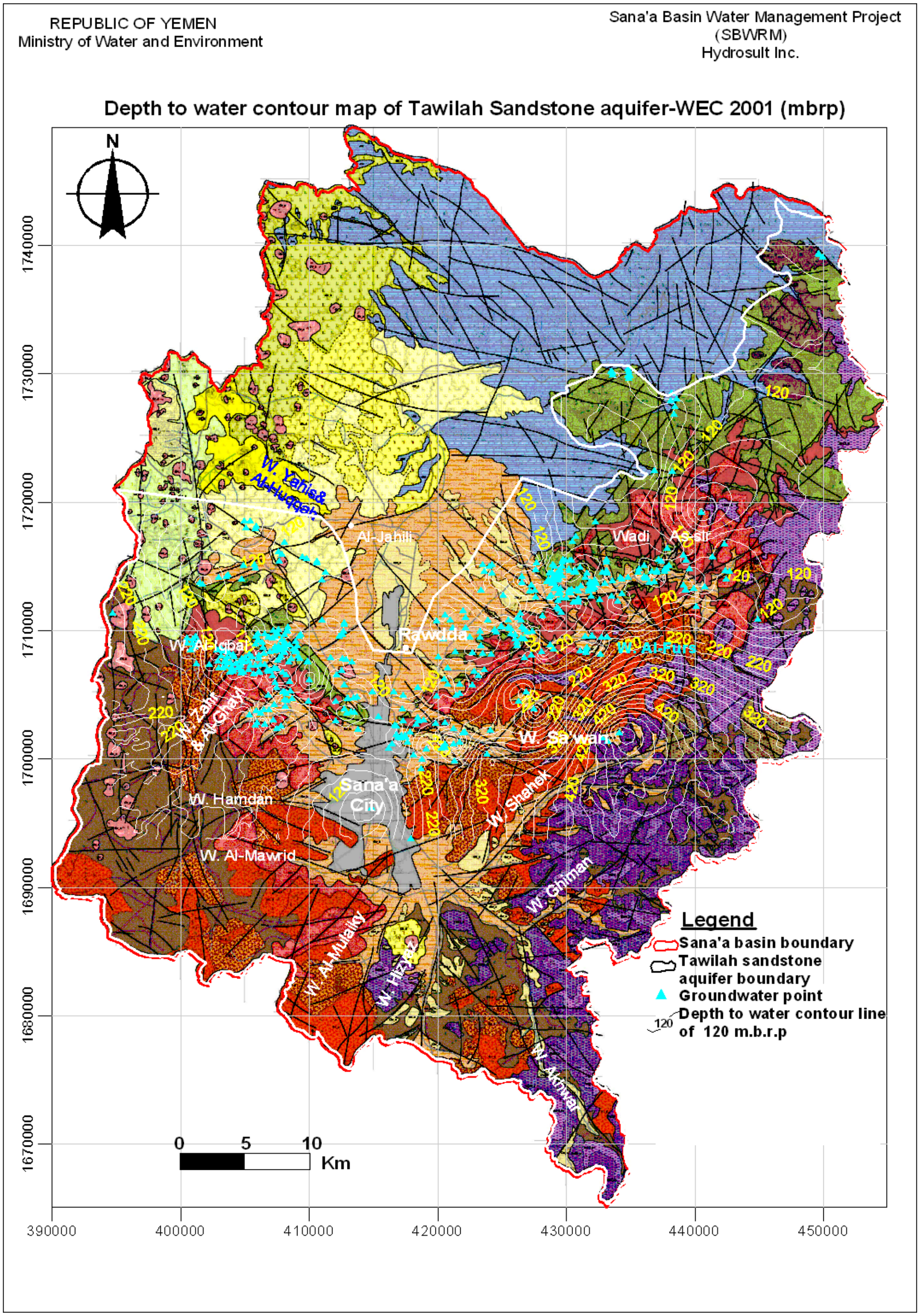

Figure 6-16 Depth-to-water contour map of Tawilah sandstone aquifer in Sana’a Basin during 2001 (based on sorted data extracted from WEC 2001)

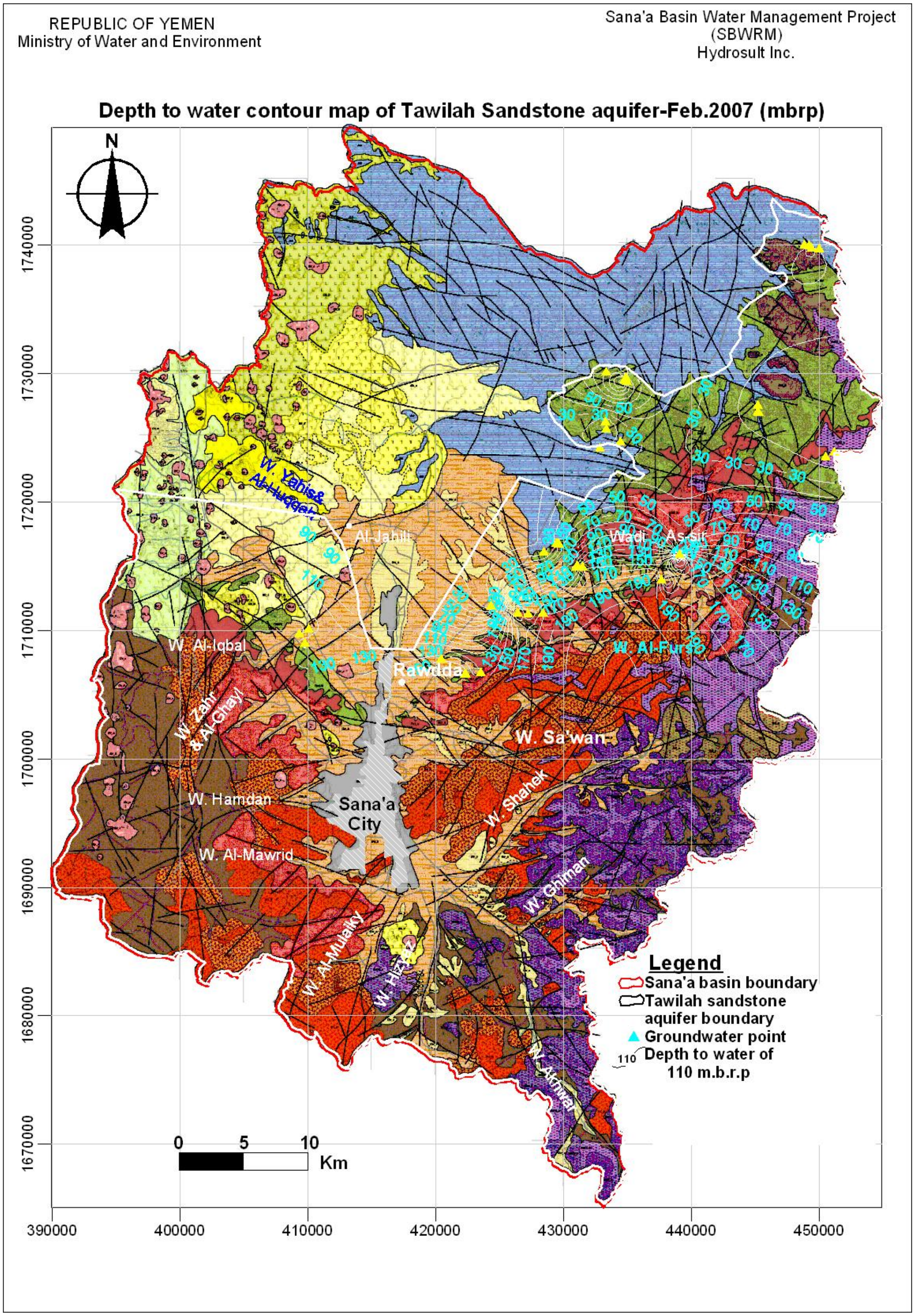

Figure 6-17 Depth-to-water contour map of Tawilah sandstone aquifer in Sana'a Basin (based on sorted data extracted from HYDROSULT Feb. 2007)

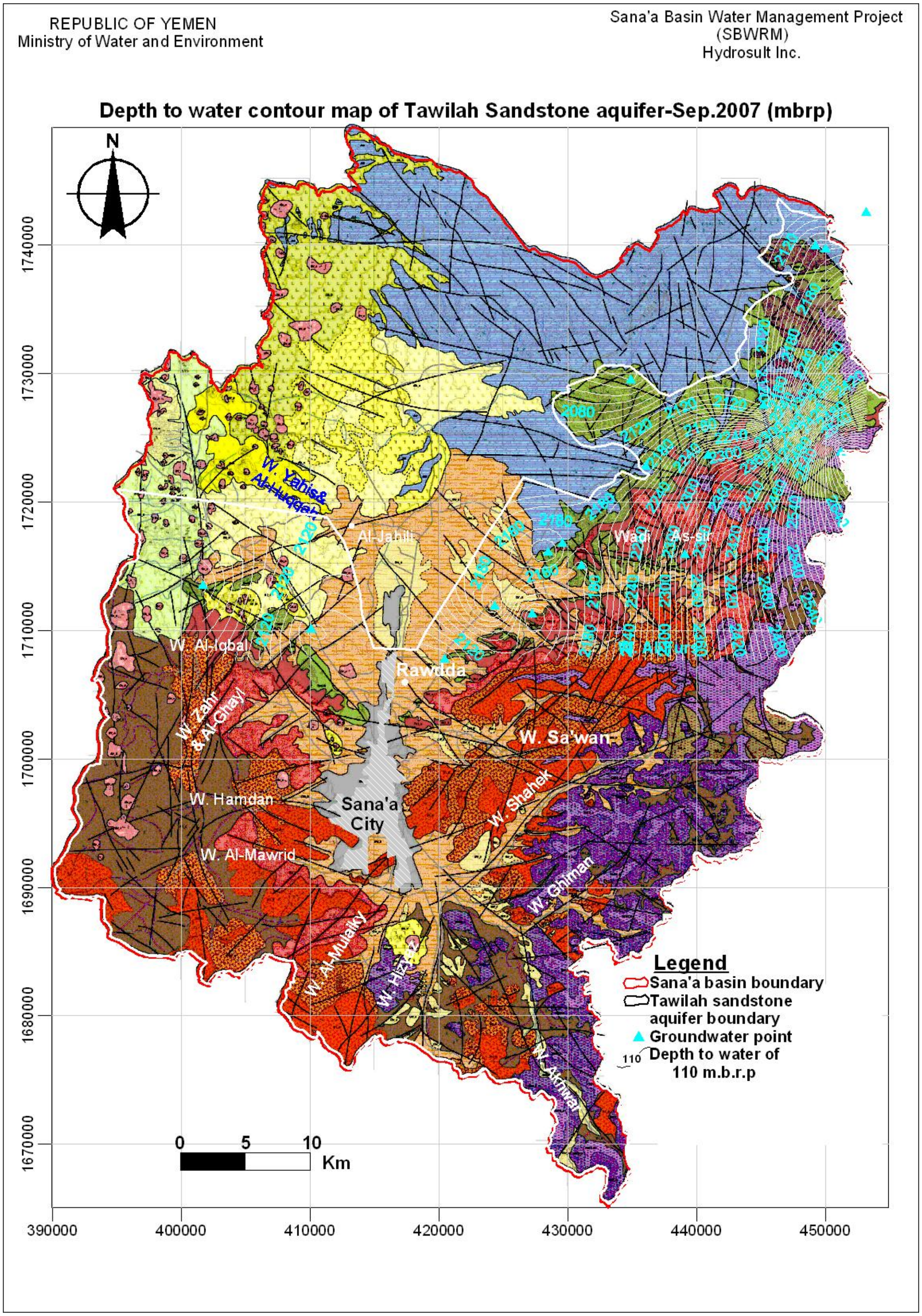

Figure 6-18 Depth-to-water contour map of Tawilah sandstone aquifer in Sana'a Basin (based on sorted data extracted from HYDROSULT Sep. 2007)

6.6.2 Groundwater piezometric mapping in Tawilah sandstone aquifer

Based on the groundwater points surveyed in 2007, two water table maps of the Tawilah sandstone aquifer were developed, for before and after the rainy season. Also, the groundwater piezometric contour maps during 1993 and 2001 were constructed based on data sets processed in the literature. These groundwater piezometric maps represent the same period of measurements as those used to precisely study the groundwater flow, as well as shed light on the historical and seasonal changes which form the basis of the groundwater depletion and storage study. From these four figures (Figures 6-19 to 6-22), the following conclusion were drawn:

- The direction of groundwater flow in the Tawilah sandstone aquifer is generally from east to west, as depicted in the groundwater piezometric maps constructed. This reflects that the highly fractured Tertiary volcanic cover in the east may act as recharge areas to the underlying Tawilah sandstone aquifer through its fractures and joints. Also, a recharge front is noticeable through the hydraulic connection of the Tawilah sandstone aquifer outside the basin in the east. This needs verification from the groundwater quality inside and outside the basin due east.
- The groundwater levels observed during the years:
    - in 1973, pre-development time, based on the records, ranged between 2,115 and 2,453 m asl with mean value of 2,250 m asl;
    - in 1993, ranged between 2,007 and 2,376 m asl with mean value of 2,153 m asl;
    - in 2001, ranged between 1,889 and 2,413 m asl with mean value of 2,142 m asl;
    - in 2007, before the rainy season, ranged between 2,009 and 2,706 m asl with mean value of 2,159 m asl;
    - in 2007, after the rainy season, ranged between 2,040 and 2,712 m asl with mean value of 2,193 m asl.
- The general convergence in the mean value of groundwater piezometric levels during the periods studied may reflect that the depletion problem of this aquifer is local and not regional as in the alluvium aquifer.
- During the 1993-2001 interval, the disappearance of high piezometric level areas in Figure 6-16 (red-colored area in Figure 6-19) reflects the low groundwater potentiality of the area in the east of the basin. The increase in yellow-colored area during 2001 (Figure 6-20), compared to the year 1993 (Figure 6-19), reflects the favorable groundwater potentiality of this location, which is consistent with the highly fractured system characteristic of this area. Also, the presence of local groundwater cones of depression in the Al Ghras area is indicative of the intensive groundwater mining process in the eastern NWSA well-fields.
- The effect of the rainy season on the groundwater regime in the shallow zone of the Tawilah sandstone aquifer, particularly in the eastern and northeastern outcrops, is clearly shown in the groundwater piezometric maps during Feb. 2007 and Sep. 2007 (Figures 6-21 and 6-22). The red-colored area with high groundwater level is greater in Figure 6-22 (after rainy season) than that in Fig 6-21 (before rainy season).
- Far from the heavily-pumped locations, the configuration of contour lines is almost without notable change. The hydraulic gradient in the blue-colored areas in the eastern part of Tawilah sandstone aquifer was 11.25 $x10^{-3}$, 17.5 $x10^{-3}$, 20 $x10^{-3}$ and 19 $x10^{-3}$ during the years 1993, 2001, Feb. 2007 and Sep. 2007 respectively, while it reached 16 $x10^{-3}$, 50 $x10^{-3}$ and 45 $x10^{-3}$ during 1993, Feb. 2007 and Sep. 2007 respectively for the red-colored areas. The heavy flow during the interval 1993-2001 may increase the hydraulic gradient during 2007. The hydraulic gradients, which can be directly derived from these maps, are the basis for estimating the rate of groundwater flow through cross-sections, for example, through the area boundaries.
- Flat groundwater piezometric slopes of the eastern elevated hills reveal a high hydraulic conductivity of the water-transmitting material. Hence, if in a certain flow direction the spacing of contour lines is narrow, the hydraulic conductivity of the material becomes lower. This demonstrates a considerable

consistency with the hydraulic conductivity measurements (chapter 5). Generally speaking, the groundwater piezometric maps demonstrate the existence of a predominantly directed groundwater flow, slightly divergent from the main source of recharge in the east. The maps show a large number of "flow domains" related to the larger and smaller fractures that recharge the aquifer from northeastern and eastern direction in the Nihm area.

- It is important to mention here that the groundwater flow direction and the groundwater levels in Quaternary alluvium, Tertiary volcanics, and Cretaceous sandstone aquifers are hydraulically connected in some places and separated in others. So, the expression of one inseparable aquifer complex represented by Quaternary alluvium, Tertiary volcanics, and Cretaceous sandstone aquifers as considered by the Italconsult study is an unscientific assumption.

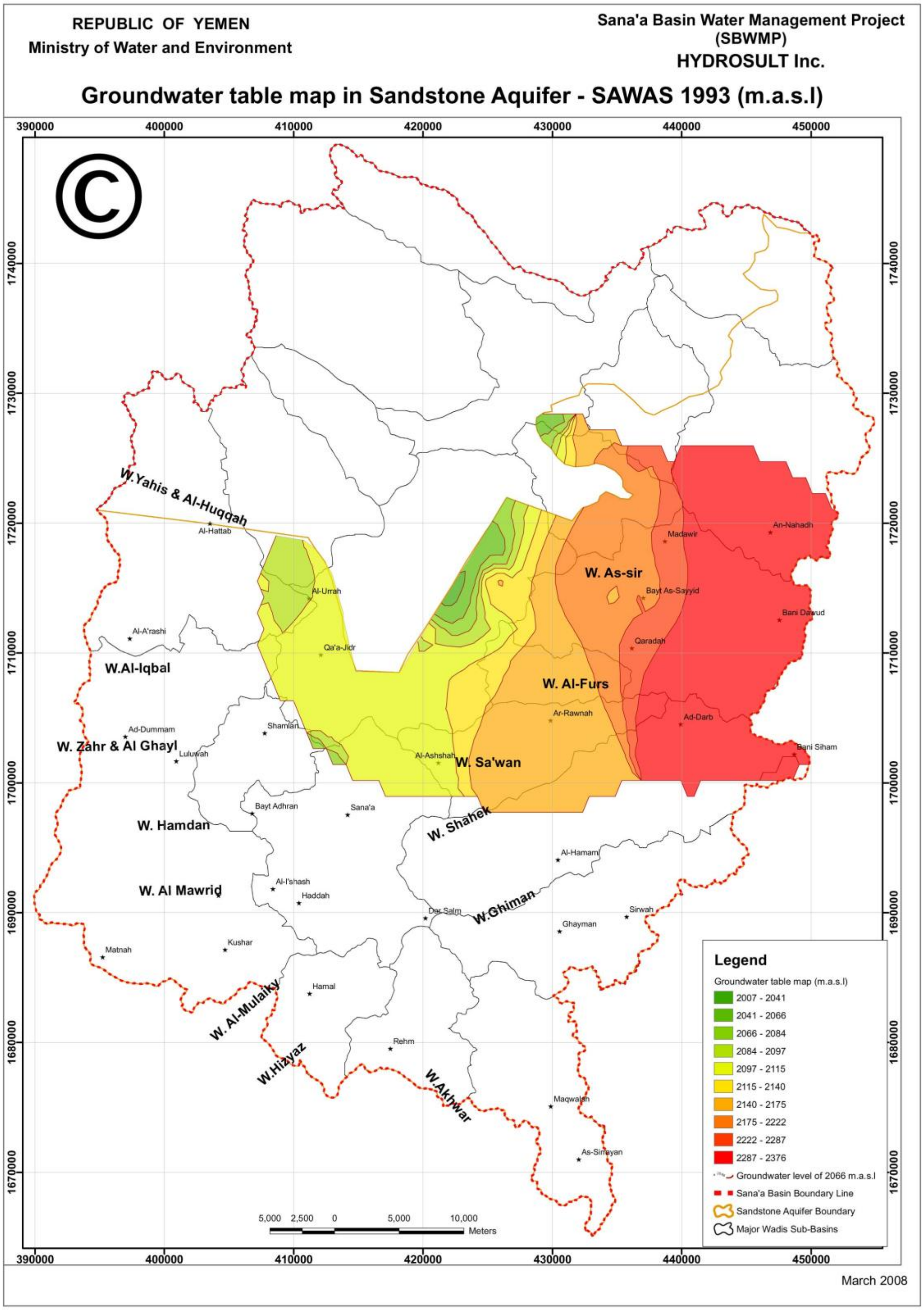

Figure 6-19 Groundwater piezometric map of Tawilah sandstone aquifer in Sana'a Basin during 1993 (based on the data processed from SAWAS 1993)

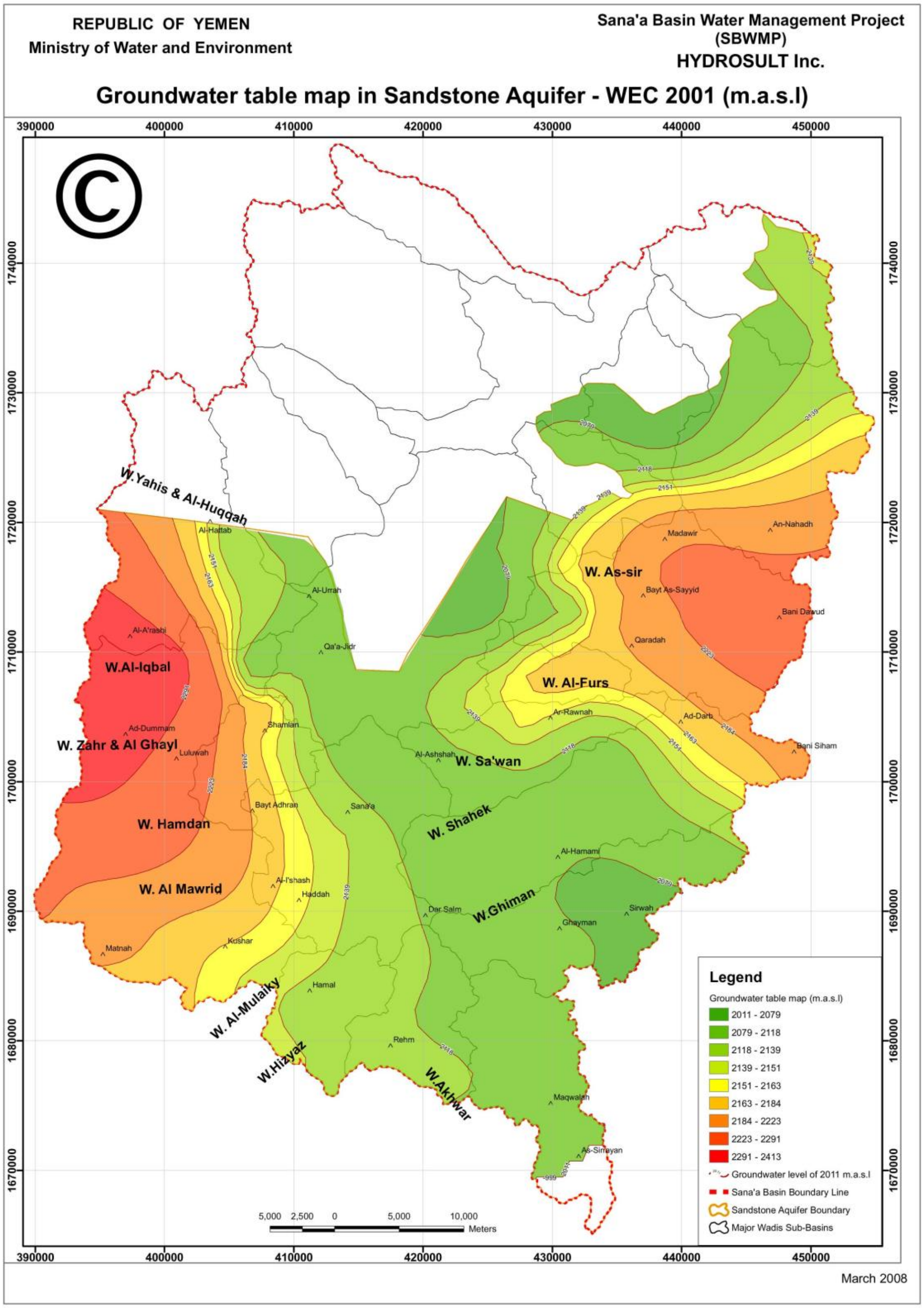

Figure 6-20 Groundwater piezometric map of Tawilah sandstone aquifer in Sana'a Basin during 2001 (based on the data processed from well inventory of WEC 2001)

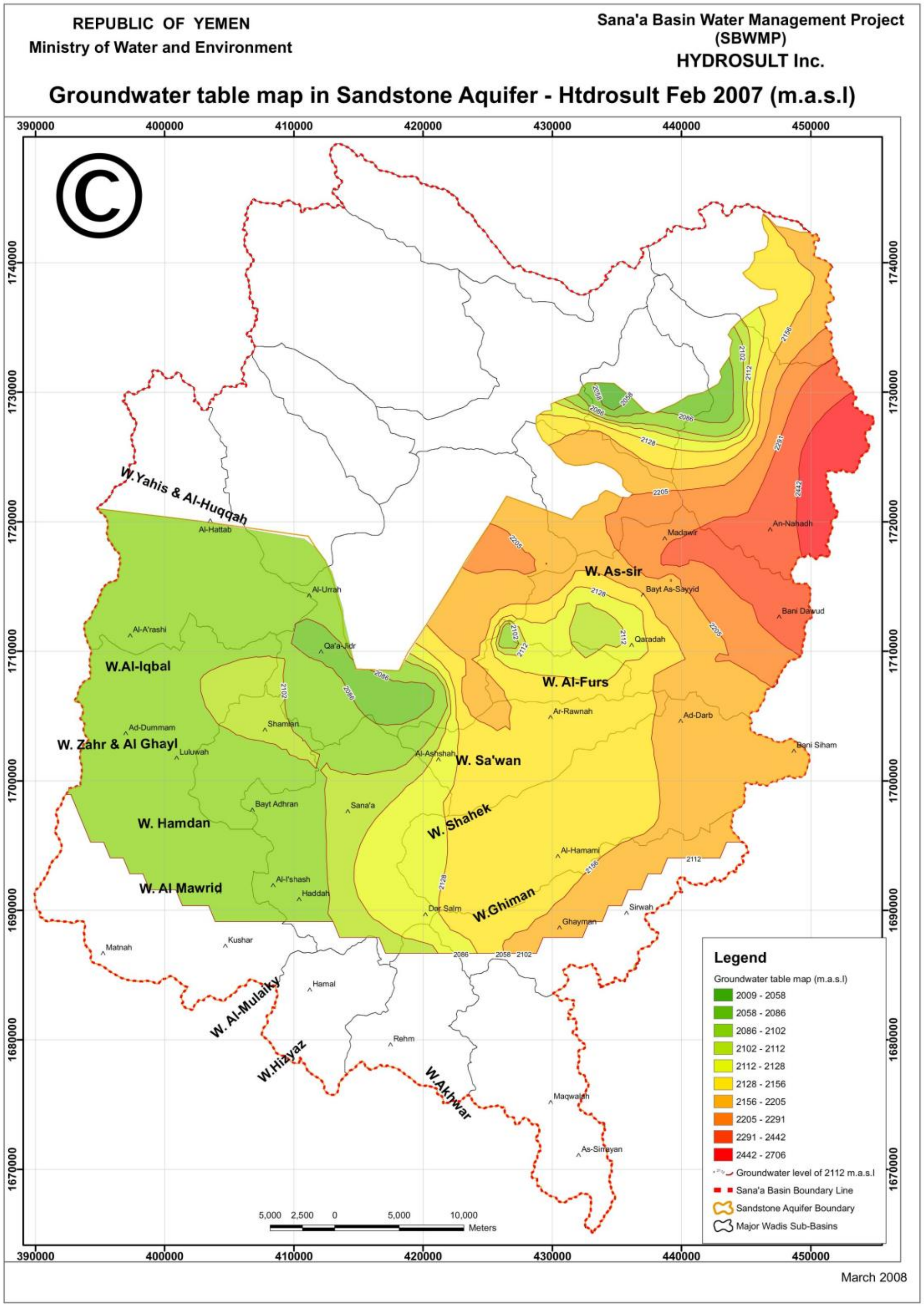

Figure 6-21 Groundwater piezometric map of Tawilah sandstone aquifer in Sana'a Basin during Feb. 2007 (based on data surveyed by HYDROSULT 2007)

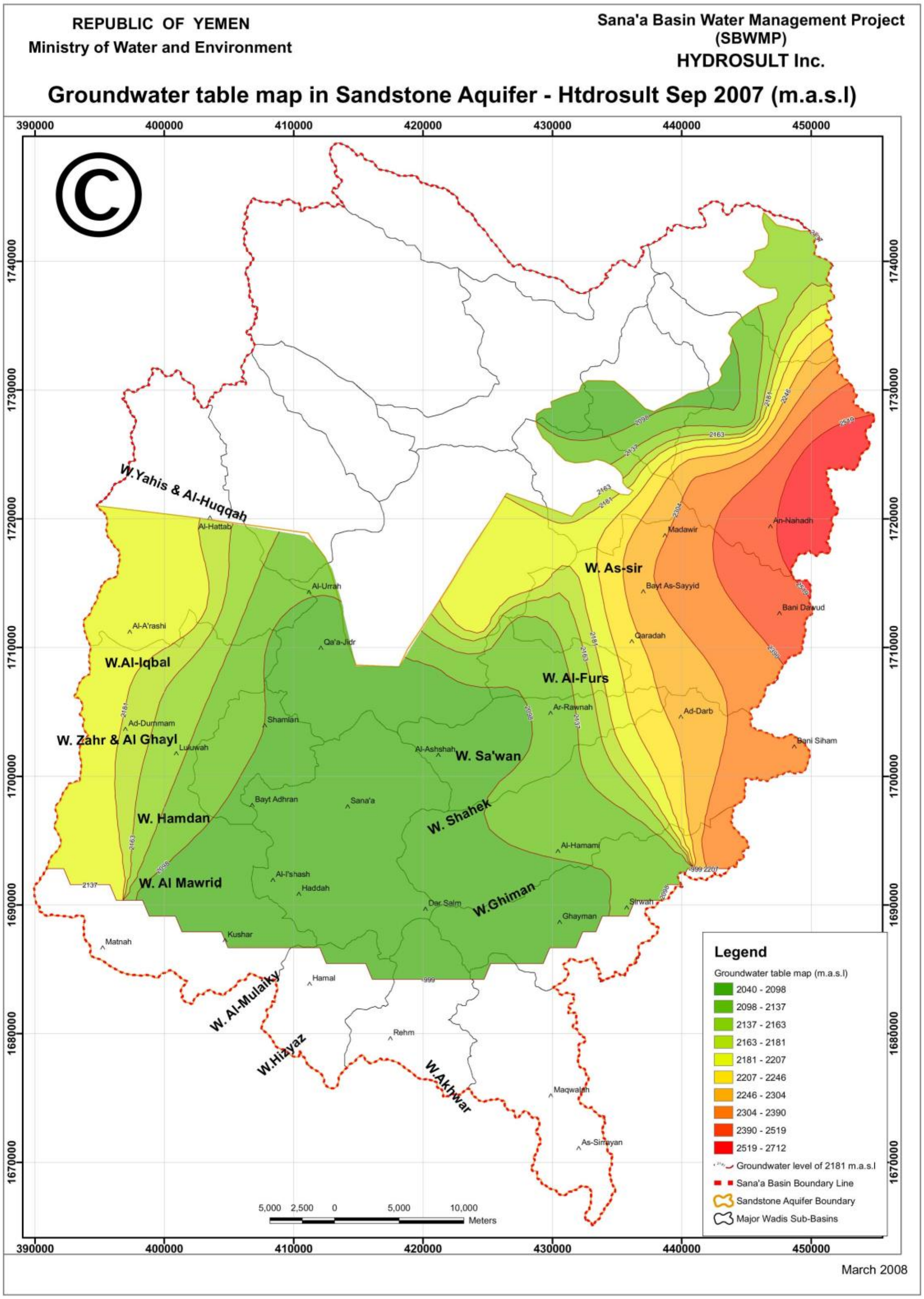

Figure 6-22 Groundwater piezometric map of Tawilah sandstone aquifer in Sana'a Basin during Sep. 2007 (based on data surveyed by HYDROSULT 2007)

6.7 Groundwater recharge

Since the 1970s, several studies have estimated the amount of groundwater recharge in the Sana'a Basin. Methods applied for the estimation are categorized into two types. One is the method based on Darcy's Law, another is the method using a recharge coefficient. Table 6-9 describes the recharge amount estimated in the previous studies (JICA, 2007).

Table 6-9 Estimation of groundwater recharge in the Sana'a Basin (JICA, 2007)

Study	Term	Organization	Consultant	Method	Estimated Recharge (Mm^3/y)
Water Supply for Sana'a and Hodeida; Sana'a Basin Groundwater Studies	1970-1973	NWSA	Italconsult	Darcy	59
Water Supply for Sana'a Phase 2	1980, 1983	NWSA	Howard and Humphreys & Sons	Darcy	45-28
Sana'a Basin Water Resources Scheme	1986	MAF	Mosgiprovodkhoz	Recharge coefficient	63
Assistance to the High Water Council in Preparation of a Master Water Plan	1988-1992	HWC	Individual Experts	Recharge coefficient	42
Sources for Sana'a Water Supply (SAWAS)	1987-1996	NWSA	TNO. Institute of Applied Geoscience	Darcy	35
Sana'a Basin Water Resources Management Study (SBWRM-PPT)	2001	NWRA	Sana'a University, WEC	Recharge coefficient	46
Water Balance and Hydrological Monitoring (SBWMP)	2007	NWRA	Dr. A. Noman and Eng. W. Mulat	Recharge coefficient	50.7

The estimated amount using Darcy's Law is based on transmissivity and assumption of a simplified aquifer. On the other hand, the recharge coefficients applied for estimation are empirical values, which are not obtained experimentally. Although there are some assumptions for the estimations, the values calculated, which range widely from 28 to 63 M m^3 annually, are reasonable from the hydrogeological point of view. For this study, the figure of 50.7 M m^3/year is adopted as an annual recharge amount inside Sana'a Basin. The amount is calculated on the basis of a recharge amount estimated for each sub-basin, as shown in Table 6-10, which can be utilized for sub-basin-wide consideration for water resource management.

Table 6-10 Estimated groundwater recharge in sub-basins

No.	Sub Basin	Estimated Recharge (Mm^3)	No.	Sub Basin	Estimated Recharge (Mm^3)
1	Wadi al Mashamini	0.86	12	Wadi al Furs	0.79

No.	Sub Basin	Estimated Recharge (Mm^3)	No.	Sub Basin	Estimated Recharge (Mm^3)
2	Wadi al Madini	2.73	13	Wadi al Iqbal	2.31
3	Wadi Al-Kharid	1.76	14	Wadi Zahr & al Ghayl	7.11
4	Wadi al Ma'adi	1.71	15	Wadi Hamdan	0.82
5	Wadi A'sir	4.27	16	Wadi al Mawrid	1.54
6	Wadi Khulaqah	1.54	17	Wadi Sa'Wan	1.41
7	Wadi Qasabah	0.83	18	Wadi Shahik	4.12
8	Wadi al Huqqah	1.36	19	Wadi Ghayman	1.24
9	Wadi Bani Hwat	5.58	20	Wadi al Mulakhy	1.66
10	Wadi Thumah	1.00	21	Wadi Hizyaz	1.92
11	Wadi as Sirr	3.81	22	Wadi Akhwar	2.32
Total					50.7

Source; Dr. A. Noman and Eng. W. Mulat (2007), Water Balance and Hydrological Monitoring

In addition to recharge by infiltration of precipitation, return flow of irrigation and infiltration of treated wastewater used to be regarded as recharge amounts in some studies. Although there is a possibility for recharge, this return flow is not considered as source of recharge in this study. Since improvements in irrigation efficiency make the recharge amount small and since treated wastewater will be used for irrigation in the future, this assumption is considered to be on the safe side.

6.8 Groundwater discharge

6.8.1 Public water supply

The main source of public water supply for Sana'a City, which is operated by Sana'a Water and Sanitation Local Corporation (SWSLC), is groundwater abstracted from three main well fields called Eastern well field, Western well field and Sana'a well field. SWSLC owns approximately 130 wells, of which approximately 80 wells are functional. The remainder are not functional due to decrease in production (lowering of the water table), technical problems and drilling failure. Production of water for Sana'a City water supply over the past nine years is shown in Table 6-11 (JICA, 2007).

Table 6-11 Production and consumption of water (1988-2006)

Year	No. of wells	Water Produced	Water Consumed
1998	56	19,146,980	13,231,847
1999	62	17,289,380	12,201,750

Year	No. of wells	Water Produced	Water Consumed
2000	63	17,304,271	11,343,467
2001	64	16,779,443	10,336,823
2002	65	18,468,664	11,771,810
2003	68	20,320,782	12,868,174
2004	78	21,843,914	13,222,526
2005	77	24,347,334	13,785,339
2006	78	24,083,969	14,744,341

Source: Sana'a Water and Sanitation Local Corporation Unit: cubic meters

During the period of 1998 to 2006, production of water increased by 26% and the number of wells operating increased by 39%. The production amount in the year 2005 is reported to be 24.4 M m^3 of which 12.5 M m^3 is billed domestic consumption and supplied for 672,141 inhabitants with a unit consumption of 50.8 lpcd (JICA, 2007).

6.8.2 Private water supply

The estimated population of Sana'a City for 2005, based on 2004 census data, is 1.84 million inhabitants and the population served by the public network is 672,141 inhabitants. Approximately 1.17 million inhabitants were not connected to the public water supply system. These inhabitants obtained water from private water sources, such as private piped networks, water tankers and treated water in containers. Consumption of domestic water from private water supply was estimated for the year 1997 at an average per capita consumption of 70 lpcd. Water consumption from private water supply is estimated as shown in Table 6-12, adopting an average consumption of 70 lpcd (JICA, 2007).

Table 6-12 Domestic water consumption from private water supply

		Total Estimated Population	Population served	Average per capita water consumption	Water consumption
Source	Year	(inhabitants)	(inhabitants)	(lpcd)	Mm^3/y
(1)	1997	1,123,942	292,225	70	7.45
	2005	1,640,091	539,401	70	13.78
(2)	2005	1,841,562	1,169,421	70	29.89
	2006	1,937,783	1,241,642	70	31.70

Source: (1) Dar Al-Handasah (2000): Population Based on 1975, 1986, 1994 Census, before modification of district boundaries. Population for 1994 was 954,448

(2) Study Team. Population based on 2004 Census, after modifications of district boundaries. Population for 1994 was 1,003,627

6.8.3 Rural water supply

Planning and execution of rural water supply projects is undertaken by the General Authority for Rural Water Supply Projects (GARWSP). However, no. suitable data or study was available regarding water use conditions for rural water supply.

WEC (2001) carried out the estimation of water consumption by water-use zone with a per capita consumption of water of 21 lpcd for rural areas, based on the estimated population in Sana'a Basin by districts and water-use zones. However, GARWSP adopted an average water consumption per capita of 40 lpcd and a 2.5% population growth rate for the rural area. Therefore, in this study, unit water consumption and population growth rates used by GARWSP are adopted and water demand is estimated based on the population of each sub-basin. Table 6-13 shows the estimated domestic water consumption for rural areas (JICA, 2007).

Table 6-13 Estimated domestic water consumption for rural areas

Sub-Basin		2004		2005		2006	
		Pop.	Water Cons.	Pop.	Water Cons.	Pop.	Water Cons.
1	Wadi Al Mashamini	5,346	78,051	5,480	80,002	5,617	82,002
2	Wadi Al Madini	13,674	199,641	14,016	204,632	14,366	209,747
3	Wadi Al-Kharid	9,067	132,384	9,294	135,694	9,526	139,086
4	Wadi Al Ma'adi	2,360	34,451	2,419	35,312	2,479	36,195
5	Wadi A'sir	4,449	64,951	4,560	66,575	4,674	68,240
6	Wadi Khulaqah	1,645	24,024	1,687	24,625	1,729	25,240
7	Wadi Qasabah	4,511	65,866	4,624	67,513	4,740	69,201
8	Wadi Al Huqqah	11,545	168,564	11,834	172,778	12,130	177,097
9	Wadi Bani Huwat	14,647	213,848	15,013	219,194	15,389	224,674
10	Wadi Thumah	2,008	29,319	2,058	30,052	2,110	30,803
11	Wadi As Sirr	34,529	504,120	35,392	516,723	36,277	529,641
12	Wadi Al Furs	9,937	145,080	10,185	148,707	10,440	152,425
13	Wadi Al Iqbal	25,552	373,057	26,191	382,383	26,845	391,943
14	Wadi Zahr & Al Ghayl	39,299	573,758	40,281	588,102	41,288	602,805
15	Wadi Hamdan	7,355	107,383	7,539	110,068	7,727	112,820
16	Wadi Al Mawrid	10,566	154,259	10,830	158,115	11,101	162,068
17	Wadi Sa'wan	18,841	275,082	19,312	281,959	19,795	289,008
18	Wadi Shahik	27,327	398,975	28,010	408,949	28,710	419,173
19	Wadi Ghayman	17,874	260,967	18,321	267,492	18,779	274,179
20	Wadi Al Mulaikhy	7,277	106,251	7,459	108,908	7,646	111,630
21	Wadi Hizyaz	10,498	153,274	10,761	157,106	11,030	161,034
22	Wadi Akhwar	16,424	239,790	16,835	245,785	17,255	251,930
Total		294,733	4,303,095	302,101	4,410,672	309,653	4,520,939

Unit: Population: inhabitants, Consumption: cubic meters per year

Source: Population of 2004: calculated based on 2004 Census results and for 2006 was estimated adopting population growth rate of 2.5%, which is adopted by GARWSP

Water Consumption: calculated adopting average per capita water consumption of 40 l/c/d, which is adopted by GARWSP for water supply projects

Note that the results of the above table should be considered as a rough estimation of the quantity of water abstracted to serve the rural population, independent of the source of water. Detailed information such as total number of population benefited by the public water supply system and/or private water supply, locations of each water supply project were not available. However, according to the NWSSIP, the percentage of rural population with access to safe water accounts for only 25% of the entire country of Yemen. Applying this rate for Sana'a Basin in the year 2005 is equivalent to 75,526 inhabitants with access to safe water, and 1.1 M m^3 of water abstracted to serve the population through the public water supply system.

6.8.4 Agricultural water use

Annual water consumption for the purpose of irrigation, which was estimated by WEC-ITC (2001) by calculating the actual evapotranspiration (ETa) through the analysis of cropping patterns based on satellite imagery, was calculated at 151.4 M m^3, assuming an irrigation water efficiency of 40%. The well inventory (2002) estimated the annual water abstraction at 217.5 M m^3 through interviews with well owners and on-site measurement. GAF (2007) estimated annual water consumption for irrigation at 139.47 M m^3, applying 60% as the irrigation water use efficiency, and by using the same methodology as WEC-ITC (2001) by sub-basin. Irrigated area and quantity of water consumed by agriculture for each sub-basin is shown in Table 6-14 (JICA, 2007).

6.8.5 Industrial water use

Water supply for industries from the public network is minimal, according to information from SWSLC. Water for most of the industries is supplied by their own well and it is supposed that the water abstraction is unregulated and unrecorded. Consequently, information regarding industrial water consumption is very scarce. In the JICA 2007 study, present water demand from the industrial sector, which is shown in Table 6-15, was estimated on the results of the study carried out by WEC (2001). This used an alternative approach involving the use of "gross value of production (GVP)" and "gross water requirement method". Due to unavailability of recent data regarding GVP from industries within Sana'a Basin, water required up to 2005 was estimated based on results from 1995.

6.8.6 Tourism water use

No. studies have been carried out to estimate the water requirements for the tourism sector. Due to unavailability of data, water consumption for 2005 was estimated under many assumed conditions as shown below. The estimated water consumption of the tourism sector is shown in Table 6-16 (JICA, 2007).

Table 6-14 Irrigated area and water abstraction of each sub-basin

Source		WEC-ITC (2001)		Well Inventory 2002		Modified GAF (2007)	
Year		2000*		2002		2004/2005**	
Sub-Basin		Irrigated area	Abstraction	Irrigated area	Abstraction	Irrigated area	Abstraction
1	Wadi Al- Mashamini	-	-	78	0.5	69	0.89
2	Wadi Al Madini	663	1.5	412	2.6	352	4.53

Source		WEC-ITC (2001)		Well Inventory 2002		Modified GAF (2007)	
Year		2000*		2002		2004/2005**	
Sub-Basin		Irrigated area	Abstraction	Irrigated area	Abstraction	Irrigated area	Abstraction
3	Wadi Al-Kharid	659	4.2	408	3.6	238	3.03
6	Wadi Khulaqah			285	2.4	181	2.33
4	Wadi Al Ma'adi	187	0.8	455	2.2	100	1.29
5	Wadi A'sir	1,108	11.7	516	6.9	593	7.65
7	Wadi Qasabah	3,181	15.0	226	2.1	186	2.40
8	Wadi Al Huqqah			1,935	14.8	1,176	14.48
13	Wadi Al Iqbal			2,871	15.9	1,538	34.87
9	Wadi Bani Huwat	5,561	22.7	6,888	55.9	4,826	33.71
10	Wadi Thumah	393	2.0	286	2.1	126	12.08
11	Wadi As Sirr	3,461	33.4	3,874	39.7	2,603	16.56
12	Wadi Al Furs	1,198	11.9	1,302	13.2	856	5.74
14	Wadi Zahr & Al Ghayl	2,387	27.6	1,524	11.1	1,297	16.30
15	Wadi Hamdan	774	7.1	312	1.8	789	10.16
16	Wadi Al Mawrid	1,081	5.5	811	8.5	739	8.76
17	Wadi Sa'wan	870	2.7	1,442	7.5	1,055	10.05
18	Wadi Shahik	650	1.3	1,454	10.5	1,032	10.30
19	Wadi Ghayman	893	2.6	590	3.8	533	5.50
21	Wadi Hizyaz			279	2.7	206	2.64
22	Wadi Akhwar			419	7.3	191	2.45
20	Wadi Al Mulaikhy	314	1.4	211	2.4	269	3.48
Total		23,380	151.4	26,577	217.5	18,953	209.20

Unit: area in hectares, abstraction in million cubic meters

* Estimate adopting irrigation efficiency of 40%, ** Estimate adopting irrigation efficiency of 40%

Table 6-15 Estimated water consumption for the industrial sector in 2005

Industrial sub-sector	Manufacturing		Mining and quarrying		Total Water Requirement
Year	Gross Value Output	Water Requirement	Gross Value Output	Water Requirement	
1995	14,484.291	3.29	485.192	0.00157	3.29
1996	14,894.196	3.38	532.741	0.00172	3.38
1997	15,315.702	3.48	584.949	0.00189	3.48
1998	15,749.137	3.57	642.274	0.00208	3.58

Industrial sub-sector	Manufacturing		Mining and quarrying		Total Water Requirement
Year	Gross Value Output	Water Requirement	Gross Value Output	Water Requirement	
1999	16,194.837	3.67	705.217	0.00228	3.68
2000	16,653.151	3.78	774.329	0.00250	3.78
2001	17,435.849	3.96	821.563	0.00265	3.96
2002	18,255.334	4.14	871.678	0.00282	4.14
2003	19,113.335	4.34	924.850	0.00299	4.34
2004	20,011.661	4.54	981.266	0.00317	4.54
2005	20,952.210	4.75	1,041.124	0.00336	4.76

Unit: Gross value: Million Yemeni Rials, Water requirement: million cubic meters

Table 6-16 Estimated water consumption for the tourism sector in 2005

Classification	Total Hotels	Total Number of Beds	Beds Occupied	Unit Water Consumption	Total Water Consumption
	(no.)	(no.)	(no.)	(lpcd)	(M m^3)
Traditional	44	3,653	1,461	120	0.06
One Star	126	4,420	1,768	180	0.12
Two Stars	45	2,570	1,028	180	0.07
Three Stars	25	1,250	500	180	0.03
Four Stars	19	650	260	350	0.03
Five Stars	3	921	368	350	0.05
Total	262	13,464	5,386		0.36