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Chapter 9. GROUNDWATER STORAGE IN SANA'A BASIN

EXECUTIVE SUMMARY

Recoverable groundwater storage in the Sana'a Basin was estimated from the saturated thickness of the aquifers, applying minimum values for the specific yield. The thickness of the water depth was determined in the alluvium and volcanic aquifer between the groundwater table and the bottom of the aquifer and in the sandstone aquifer between the groundwater table and the borehole penetration depth.

Recoverable groundwater storage in the Alluvium aquifer was estimated at the beginning of the development period in 1973 at 1.9 milliard cubic meters. Depletion of this storage is not distributed equally over the aquifer area. The depletion is most severe due to excessive pumping in some localities in the northern parts, especially Bayt Al-Hilali and Al-Khawi in the west and Al-Ghiras locality in the east. The effect of recharge by rain is also visible in the maps presented.

Recoverable groundwater storage in the Volcanic aquifer is estimated at three depth intervals based on WEC-data of 2001: 120-250 m, 250-350 m and 350-500 m. The total recoverable storage in the Volcanic aquifer is estimated at about 52 milliard cubic meter.

Recoverable groundwater storage in the Tawilah sandstone aquifer is estimated based on WEC-data of 2001 for two areas: area with shallow sandstone and area with deep sandstone, at four depths below static water level: 150 m, 250 m, 350 m and 450 m.

Total recoverable storage in the Tawilah sandstone aquifer is estimated at about 4.7 milliard cubic meters for the shallow part and 40.8 milliard cubic meters for the deep part.

The volumes stated above obviously need more studies to support them. They may be verified through ongoing water balance and modeling studies.

GENERAL OUTLINE

Replenishment of the groundwater system from rain events results in the accumulation of fresh water resources in the upper layers of the aquifer system. In addition, subsurface inflow of groundwater from areas outside the catchment boundary may occur, depending on the location of the groundwater basin divides with respect to this boundary. Together, these resources constitute the total volume of water that could be withdrawn from the system (i.e. commandable) as long as the natural setting and prevailing hydrological/hydrogeological conditions remain unchanged. Moreover, accessibility to the commandable water in storage may not be possible under current economic conditions or technological know-how. What could be obtained under such conditions (i.e. usable storage) may be significantly less than the commandable, depending on the overall situation. This would ideally be the case prior to any groundwater exploitation in the region, inside the Basin or out, within the limits to which the aquifer system extends.

Over the past thirty years or so, groundwater abstraction in the Basin has severely disturbed its natural system and at an extremely rapid rate since the early '80s. Surrounding regions, such as the Amran valley and Dhamar plain, have also been subject to serious over-exploitation. Adverse effects related to this uncontrolled heavy abstraction have manifested themselves most commonly in the form of widely spreading water level declines across the Basin. Other secondary effects that may eventually become a limiting factor in groundwater use in certain areas include a general increase in salinity level as well as the appearance of groundwater with a calcium chloride composition considered to be unusual (Al-Mooji, 2000).

These observations constitute undisputed evidence for the dynamic nature of water availability in the Basin. The complexity of the system should also be appreciated because of the various processes (both natural and human-induced) which contribute to maintaining balance in the system through addition to or withdrawal from the renewable resources. For example, while over-exploitation would certainly contribute to exhausting the usable storage, it may at the same time induce subsurface inflow from outside the Basin. By the same token, recharge inputs from irrigated and domestic areas would rise over the years as the amount of groundwater applied to these areas increases.

Obviously any estimates of the available groundwater resources in a large basin such as the Sana'a require a *continuous* record of geological, climatological, hydrological, etc. data from a *dense*, *representative* monitoring network across the basin. Nevertheless, and until such a network is established, estimates can be made to the best of information availability. Interpretation of any results obtained, however, should be treated with extreme care, bearing in mind that, at best, they may serve as indicators about a system with dynamics that are far from being understood completely.

Not all deliverables are equally important. Among the maps, the most important are the groundwater storage maps because they integrate all the information from the other maps, as far as they shed a light on aquifer storage.

Two different approaches have been taken to estimate renewable water resources in the Basin: calculation of total annual inflow and assessment of usable storage. Italconsult (1973) and Mosgiprovodkhoz (1986) applied the first method while the second was used by TSHWC (1992). Conducting the first groundwater investigation in the Basin, the Consultants had no information to enable them estimate inflow by the usual water balance method. On the basis of the limited information obtained during their study period, they determined the steady groundwater flows in the various aquifers and the perennial average spring flow occurring at the time, then applied a simplified Darcy equation to calculate the volume of groundwater flow. Total groundwater inflow to the Basin was estimated at 67 M m^3/year for a study area of 1128 km^2, essentially covering the south-central part of the Basin surrounding the city from east, west and south. Important findings from this preliminary estimate are outlined below.

9.1. Methodology of recoverable groundwater storage estimation

The groundwater storage map indicates the quantity of groundwater stored in the aquifer. This quantity may be expressed in relation to the recoverable volume of groundwater. Groundwater storage below a certain well depth is considered to be unavailable and is not to be included in the calculated groundwater storage volume.

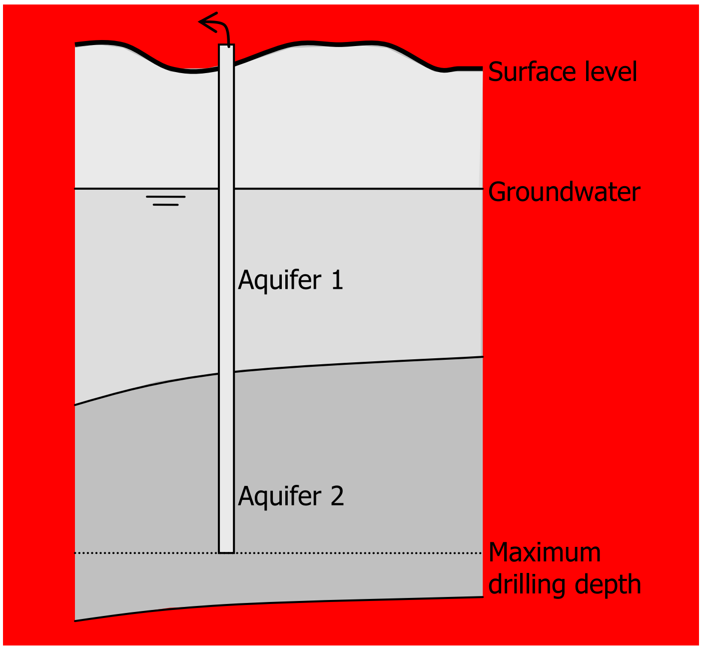

Figure 9-1 Schematic diagram showing the methodology of processing storage maps

Recoverable groundwater storage:

S = saturated thickness of the aquifer * effective porosity

The concept of groundwater storage is usually used in connection with limits on the allowable abstraction or depletion of the aquifers. The total storage of an aquifer is generally not available for abstraction because of strategic or other reasons, e.g. because groundwater needs to be reserved for periods of low recharge. Furthermore, it is technically difficult to empty an aquifer because this would require a large number of wells.

A groundwater storage map therefore is prepared under conditions of a maximum drilling depth. Several storage maps could be prepared using different drilling depths. These maps will indicate groundwater availability for different water management conditions. This will apply especially to the exploitation of the sandstone aquifer.

The effective porosity of the aquifer stores the volume of groundwater that can be drained by gravity. Effective porosity is more or less equal to the specific yield, which is the volume of groundwater released from the aquifer by pumping. Specific yield applies to unconfined conditions. The storage coefficient applies to confined conditions.

Accuracy of the estimation of recoverable groundwater storage depends to a large extent on the estimation of specific yield. Calibration of the transient groundwater model provides an estimate representing the observed changes in groundwater levels. This estimate can be considered appropriate for a regional approach. Still, differences in estimates of a factor of 2 or 3 should be expected. Therefore, calculations of groundwater storage should present a range of results using a minimum and maximum value of the specific yield. Water use planning should always remain on the safe side by using the minimum values.

Preferably, recoverable groundwater storage is to be presented in raster maps. The storage is calculated separately for each raster cell. The estimate of the specific yield may be verified from a water balance of each raster cell, although it should be realized that there are also inaccuracies in the estimates of the water balance components of recharge and discharge. Cells with large deviations in estimates may indicate areas with lower reliability of the groundwater storage estimate.

Alluvium aquifer

The alluvial aquifer in Sana'a Basin may be penetrated by boreholes over its full thickness. The recoverable groundwater storage is calculated using the total thickness of the saturated part of the aquifer. Data needed to calculate aquifer storage:

- Elevation of the groundwater table,
- Bottom level of the alluvial aquifer,
- Average specific yield.

Volcanic aquifer

The Quaternary and Tertiary Volcanic aquifers are treated as one aquifer. The Volcanic aquifer in the Sana'a Basin may be penetrated by boreholes over its full thickness. The recoverable groundwater storage is calculated using the total thickness of the saturated part of the aquifer. Data needed to calculate aquifer storage:

- Elevation of the groundwater table,
- Bottom level of the tertiary volcanic aquifer,
- Average specific yield.

Tawilah sandstone aquifer

The sandstone aquifer in Sana'a Basin may be penetrated fully and in the south, due to its large depth, only partly by boreholes. The recoverable groundwater storage is calculated using the thickness of the saturated part of the aquifer which can be penetrated. Data needed to calculate aquifer storage:

- Elevation of the groundwater table,
- Bottom level of the sandstone aquifer corrected for borehole penetration,
- Average specific yield.

9.2. Recoverable groundwater storage mapping

9.2.1. Recoverable groundwater storage mapping of Alluvium aquifer

Applying the above-mentioned method for estimating recoverable groundwater storage in Alluvium, six recoverable groundwater storage maps for Alluvium aquifer (Figures 9-2 to 9-7) were developed based on the sorted processed data presented in the literature (Italconsult 1973, Russian 1983, SAWAS 1993 and WEC 2001) and the well survey of Hydrosult and NWRA Sana'a Branch teamwork (Feb. 2007 and Sep. 2007). From these maps[1], the following conclusions may be drawn:

Since the Alluvium aquifer is considered the most depleted aquifer in Sana'a basin, as per the depletion maps of this aquifer, so its recoverable groundwater storage expects to decrease. Moreover, the small recharge rate from rainfall, beside the huge number of hand dug wells penetrating this aquifer, make its recoverable storage criticism.

- In 1973, pre-development time, it was noticed that the total mean recoverable groundwater storage approached a depth of 7.8 m, which supposes 1.9 milliard cubic meters. The more recoverable groundwater storage is condensed in the middle of the northern part of the aquifer, which reflects the continuous recharge from the different sub-basins, especially Wadi As-sir catchment.
- During the eighties, recoverable groundwater storage decreased by 10%. This is exhibited in the decrease in the red-colored area from 40% in Figure 9-2 to 30% in Figure 9-3. This conclusion coincides with the results of the Alluvium aquifer depletion.
- During the nineties, recoverable groundwater storage reached a mean value of 7.5 m for about 20% of the Alluvium aquifer area (red-colored area in Figure 9-4) and moved east in the northern part of the aquifer, especially Wadi As-sir, Wadi Al-Furs, Sa'awan and Rawdda localities. This may reflect a heavy rain season with high recharge rate during this time. This causes more or less replenishment of the alluvium aquifer, which reflects in the next interval (Figure 9-5).
- After about 30 years, since pre-development time (interval 1973-2001), although the Alluvium aquifer depletion problem was critical as a result of groundwater decline more than 10 m in the northern part of the aquifer, the high recharge during the nineties caused the highest recoverable groundwater storage (red-colored area) to move west (Figure 9-5). This explains the great number of dry hand-dug wells in this aquifer listed in the well inventory of WEC 2001 in the eastern borders of the aquifer.
- From pre-development time until now (Figure 9-6), the highest recoverable groundwater storage area in the alluvium aquifer is found in different patches and not one solid shape. This may be attributed to the presence of 'centers of depletion' resulting from excessive pumping rates in some localities in the northern parts, especially Bayt Al-Hilali and Al-Khawi in the west and Al-Ghiras locality in the east.
- The effect of the rainy season on groundwater storage in the Alluvium aquifer is clearly shown in Figure 9-7. The blue-colored area with recoverable groundwater storage of more than 10 m was present as patches in the most sub-basin outlets, especially Wadi As-sir, Wadi Sa'awan and Wadi Shahek (red and yellow colored areas in Figures 9-6 and 9-7). Also, the yellow-colored areas with recoverable groundwater storage of more than 5 m in the central part of the northern area of the aquifer were increased, especially at Bayt Al Hilali, Bayt Al Khawi and Bayt Allayfah. This may be attributed to temporary replenishment of the Alluvium aquifer during the two rainy seasons, i.e. during April and July.
- Recoverable groundwater storage exploitation constraints are essentially the groundwater quality and the source of pollution due to the presence of a sewage canal. Due to the lack of hydrogeochemical analyses, so the reflect of these constraints will study after the finishing of

[1] The area covered in the maps is different due to the locations of the available observation points

these analyses by the activity 4 but the first trial of study this constraint through groundwater salinity which ranges from 500 to 1200 μmhos/cm shows that the groundwater salinity of the northern parts is permissible for all uses.

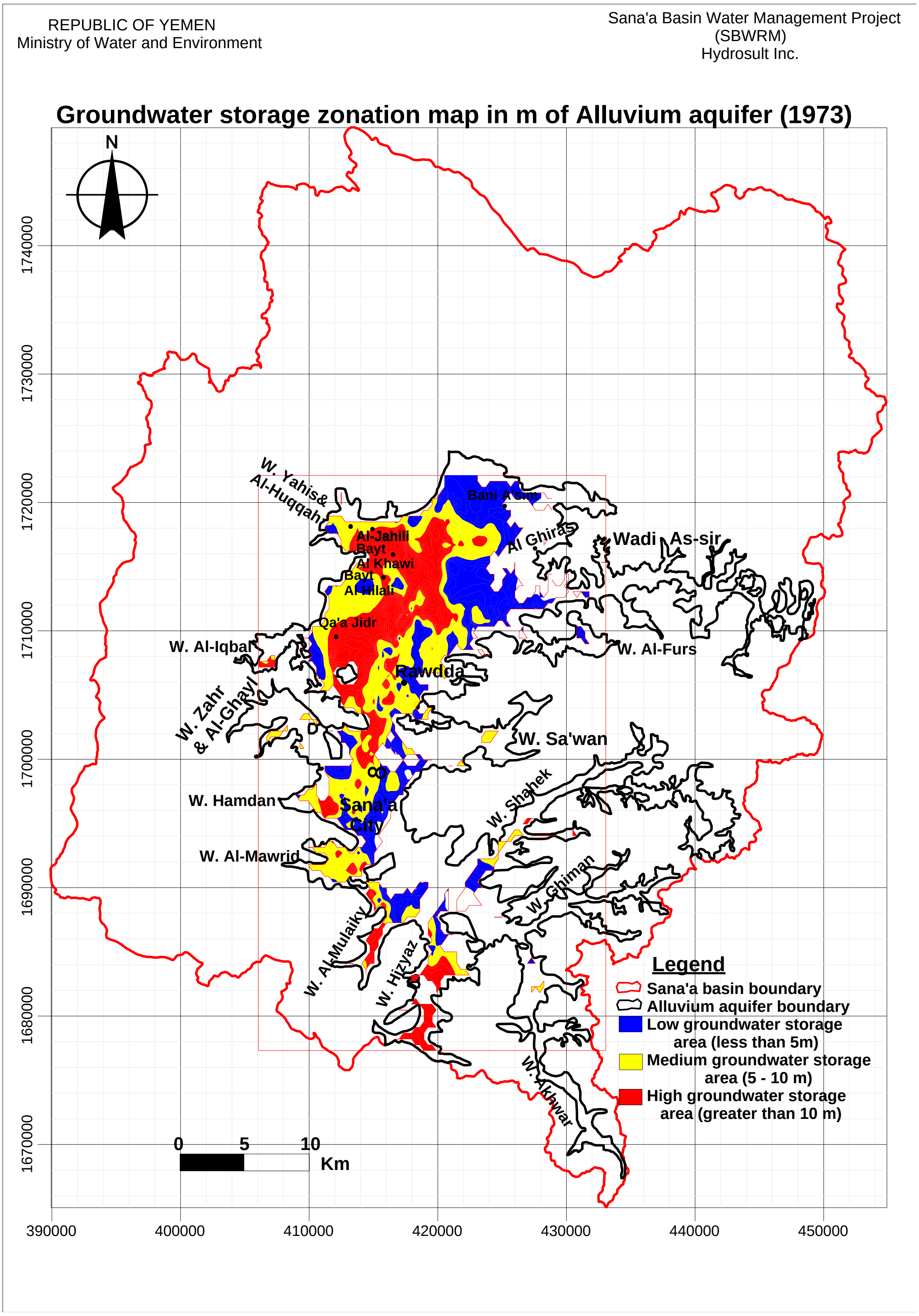

Figure 9-2 Recoverable groundwater storage map of Alluvium aquifer (m) during 1973

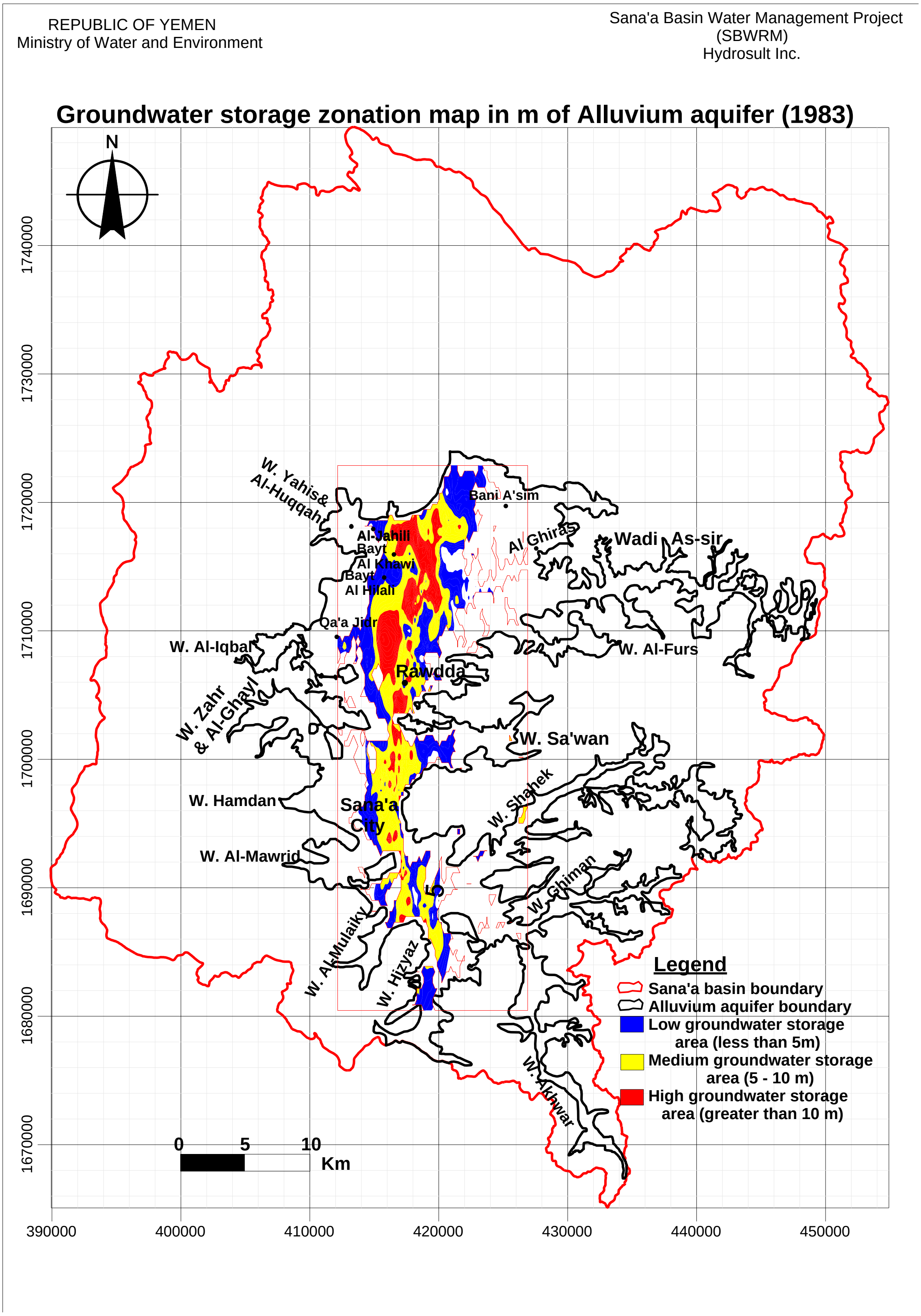

Figure 9-3 Recoverable groundwater storage map of Alluvium aquifer (m) during 1983

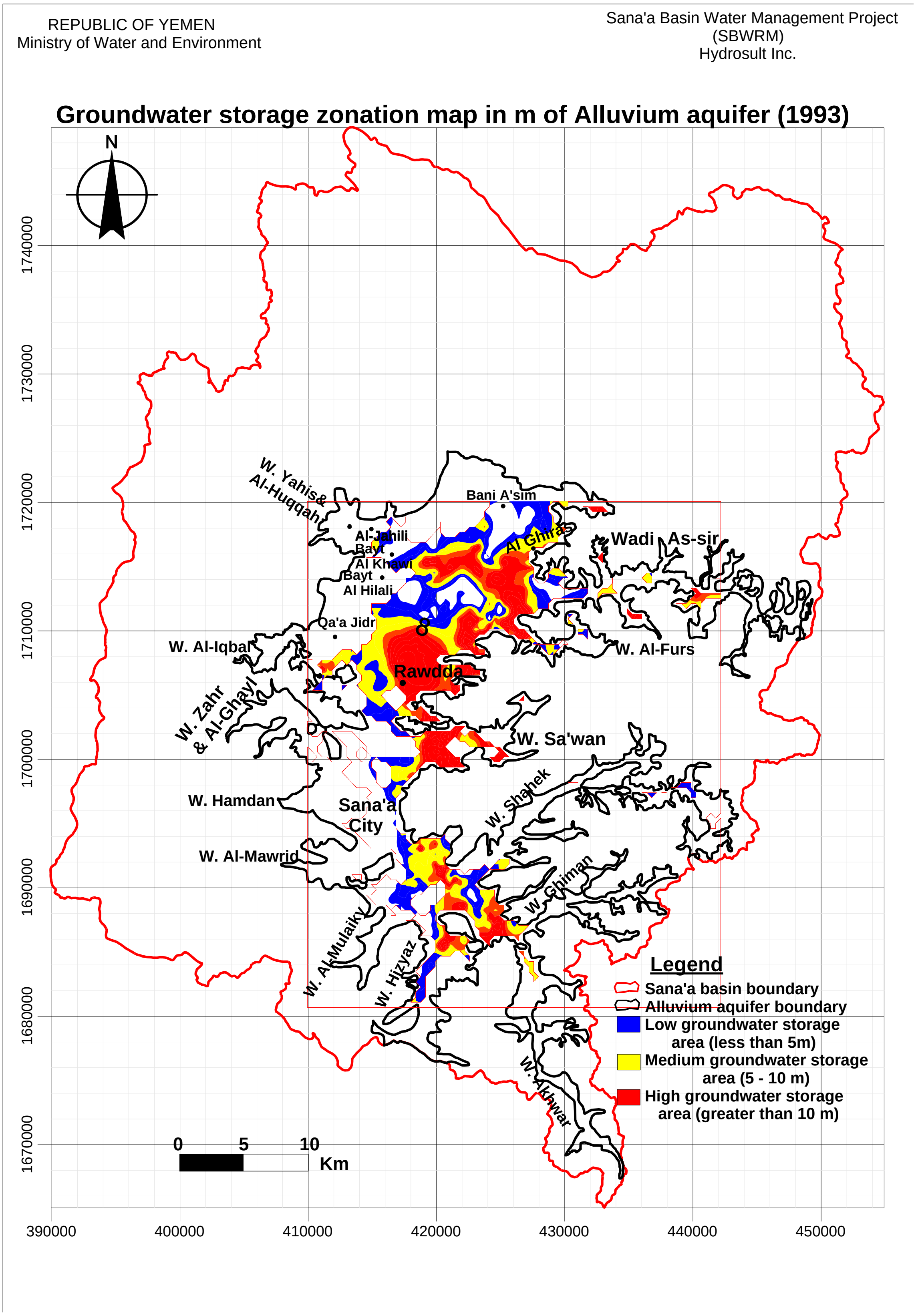

Figure 9-4 Recoverable groundwater storage map of Alluvium aquifer (m) during 1993

REPUBLIC OF YEMEN
Ministry of Water and Environment

Sana'a Basin Water Management Project
(SBWRM)
Hydrosult Inc.

Groundwater storage zonation map in m of Alluvium aquifer (2001)

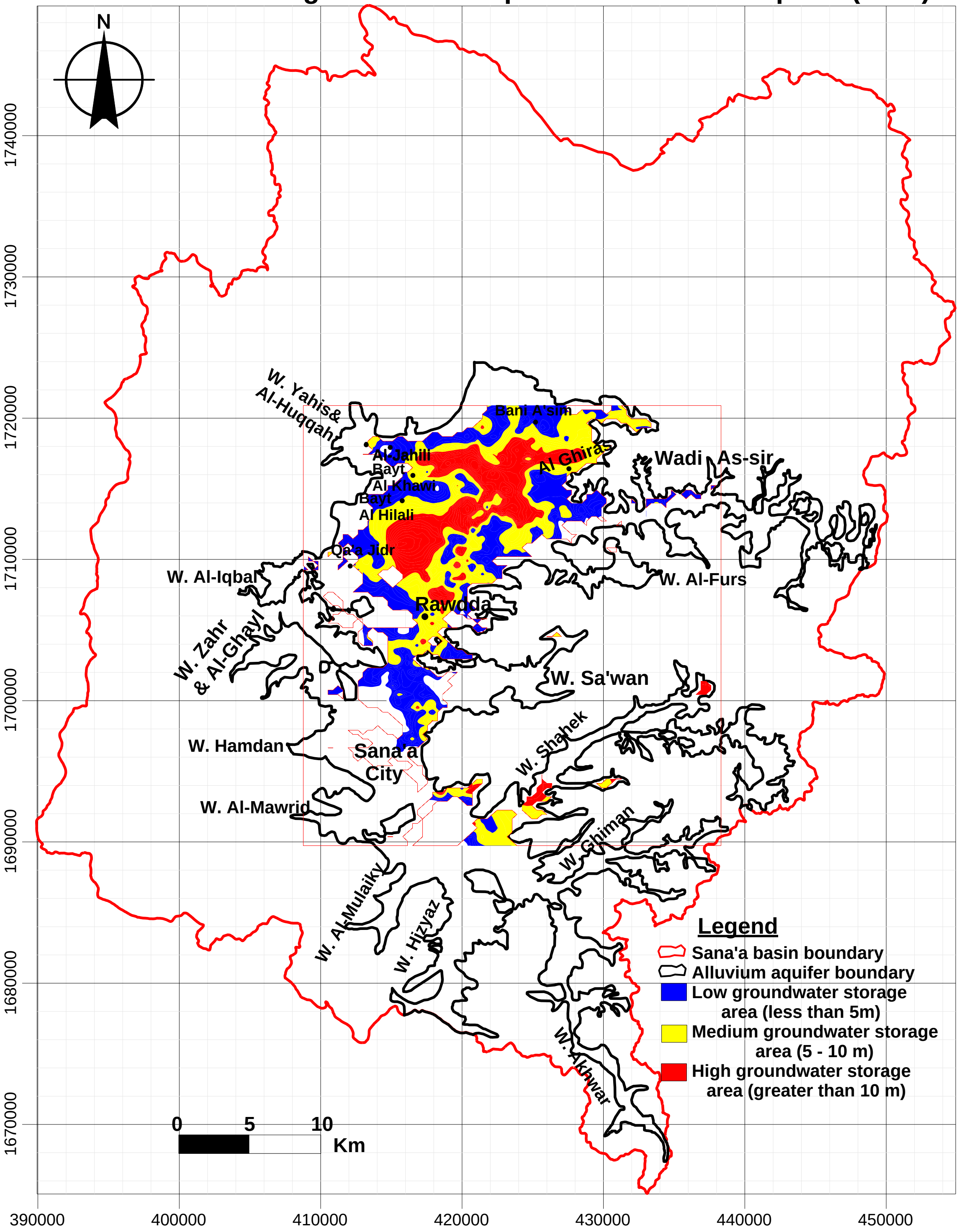

Figure 9-5 Recoverable groundwater storage map of Alluvium aquifer (m) during 2001

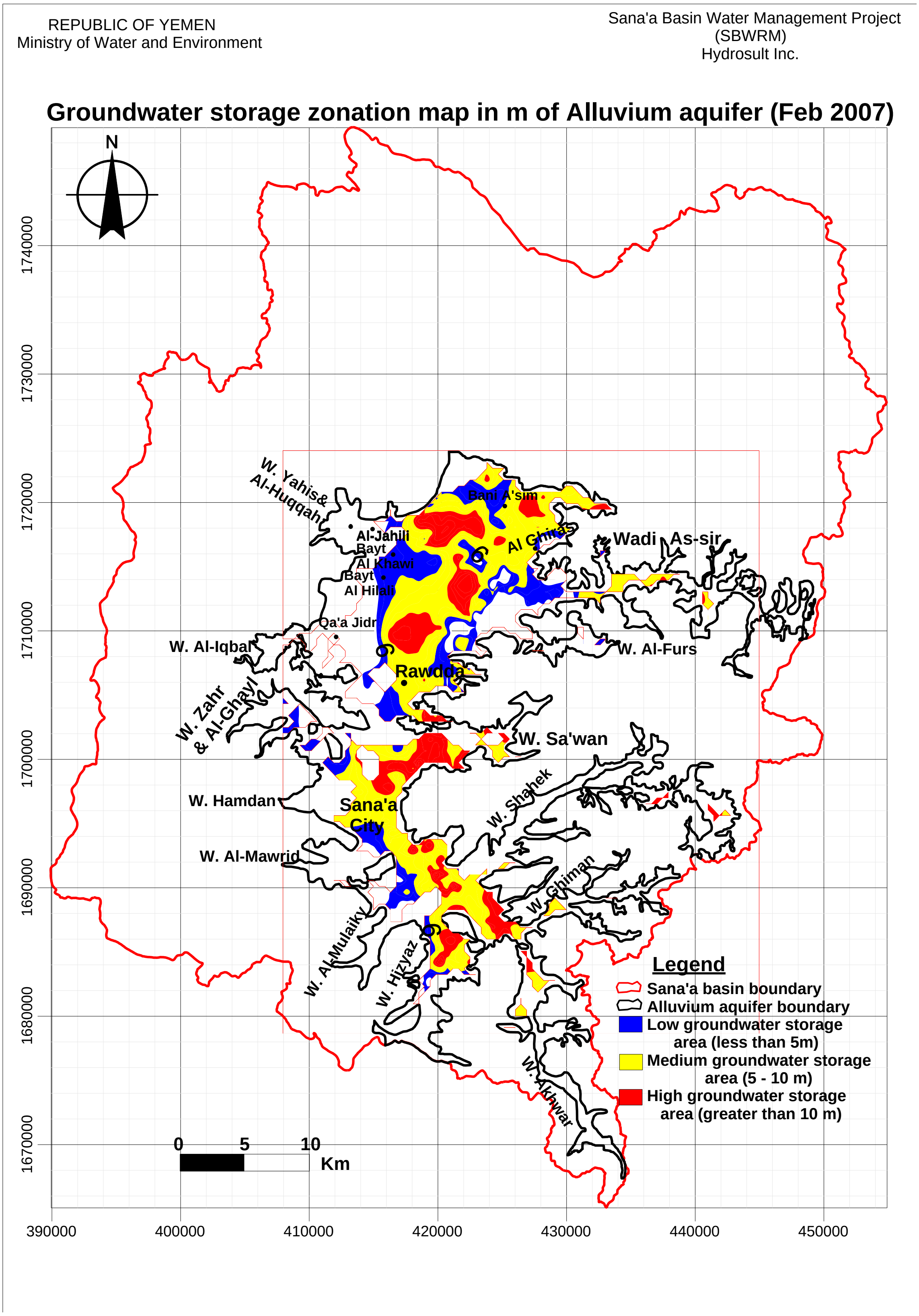

Figure 9-6 Recoverable groundwater storage map of Alluvium aquifer (m) during February 2007

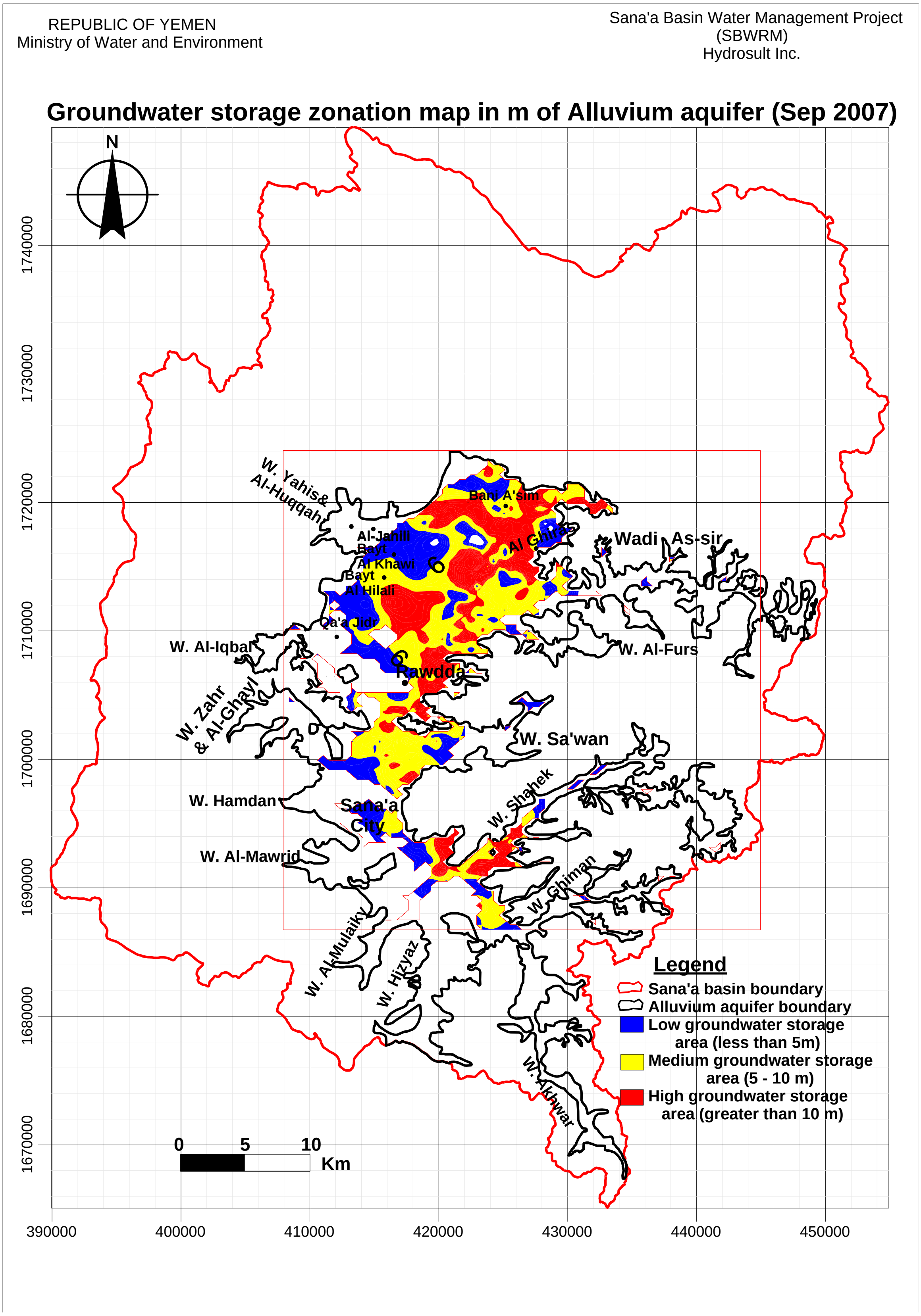

Figure 9-7 Recoverable groundwater storage map of the Alluvium aquifer (m) during September 2007

9.2.2. Recoverable groundwater storage mapping of Tertiary Volcanic aquifer

Three recoverable groundwater storage maps for Quaternary and Tertiary Volcanic aquifer (Figures 9-8, 9-10 and 9-12) were developed based on the sorted processed data present in WEC 2001 and the Volcanic wells surveyed during this study. The Quaternary and Tertiary Volcanics were considered as one aquifer to facilitate storage estimations. The saturated thickness in every well surveyed was sorted and classified depending on the total depth of the wells surveyed. The most suitable thickness classes were 120-250 m, 250-350 m and 350-500 m. Classes above or below were canceled to prevent anomalies. Following is a brief description of storage volumes in the wells surveyed in Volcanic aquifer.

Depth interval 120-250 m:

The recoverable groundwater storage of Volcanic aquifer through saturated thickness of 130 m starting from the static water level reaches 8.8 km^3. Spatial distribution of this recoverable storage, as shown in Figure 9-9 ,is divided into four classes:

- The first class covers an area of 650.7 km^2 and ranges between 1 and 4 m in depth, which means that groundwater storage volume in this class reaches 1.6 km^3.
- The second class covers an area of 918 km^2 and contains a depth of 4 to 8 m of groundwater storage, which means that recoverable storage reaches 5.5 km^3.
- The third class storage ranges from 8 to 12 m in depth, which reflects the presence of 1.3 km^3 of recoverable groundwater storage.
- Estimated recoverable groundwater storage of the fourth class reaches 329.4 MCM, resulting from storage depths ranging from 12 to 15 m (Table 9-1).

Lack of data prevents estimation of recoverable groundwater storage over all the Volcanic aquifer. The spatial distribution zonation map (Figure 9-9) shows that the recoverable groundwater storage related to this interval of aquifer saturated thickness decreases from south to north while the storage aquifer surface area increases in the same direction. In addition, Figure 9-8 shows the linear relation between recoverable groundwater storage volume and storage surface area. Assuming a surface area of zero value, this means that below any boundary of these four classes, recoverable groundwater storage reaches 191 MCM.

The only recoverable groundwater storage exploitation constraint of the Tertiary Volcanic aquifer is essentially the groundwater quality, as this aquifer is considered the unique alternative to the depleted Tawilah sandstone aquifer. Since this aquifer possesses fresh water, there are no constraints on recoverable groundwater storage.

Table 9-1 Storage area and recoverable groundwater storage volume of Volcanic aquifer through saturated thickness of 130 m (120 to 250 m depth)

Depth (m)	Area color	Surface area (km^2)	Storage depth (m)		Average storage depth (m)	Storage water in million m^3
			From	To		
120-250	Red	650.7	1	4	2.5	1626.75
	Cyan	918	4	8	6	5508
	Yellow	131.4	8	12	10	1314
	Blue	24.4	12	15	13.5	329.4
Total water storage in million m^3						8778.15

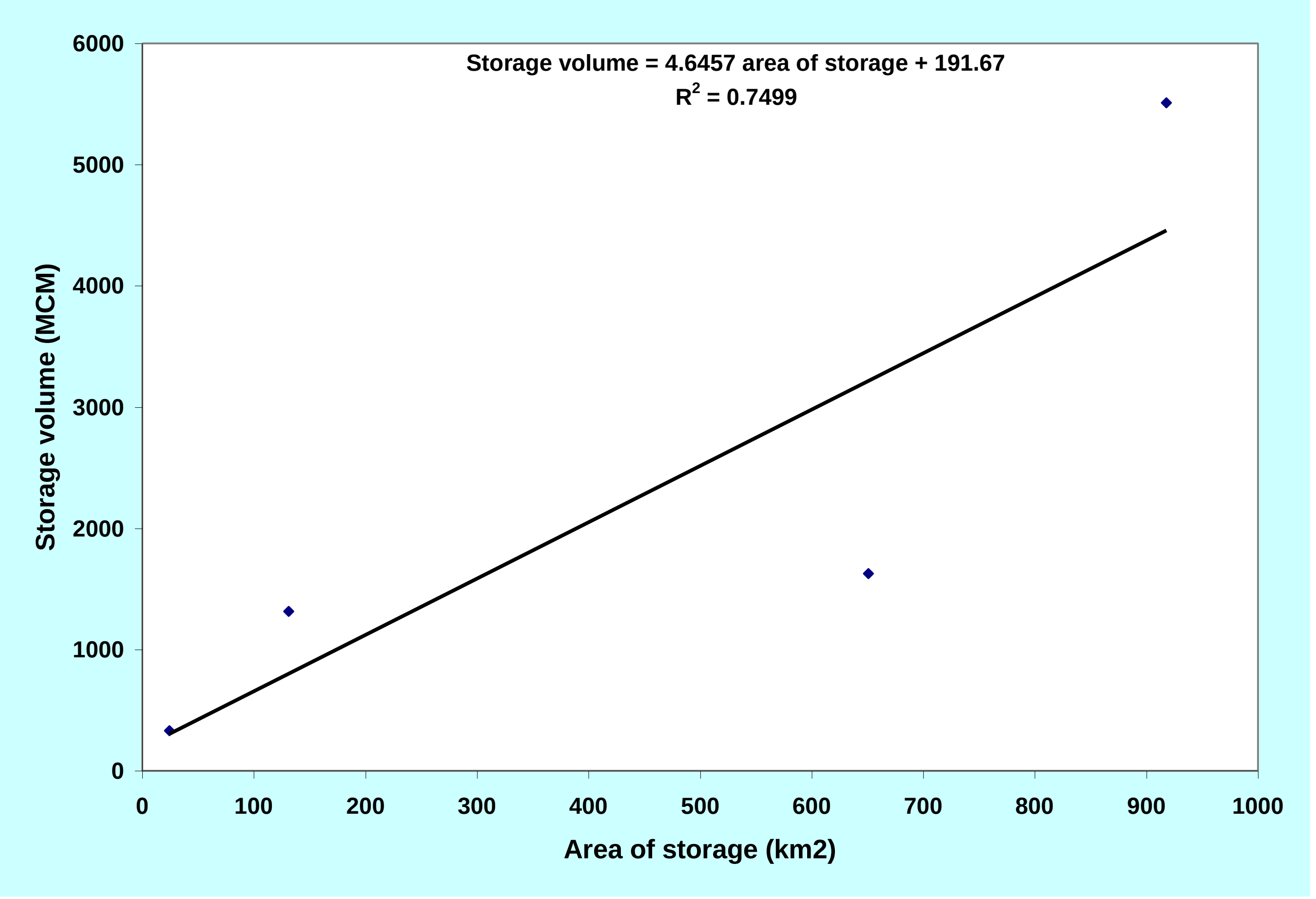

Figure 9-8 Graph showing relation between storage area and recoverable groundwater storage volume in Volcanic aquifer in Sana'a basin through saturated thickness of 120-250 m in depth from ground surface

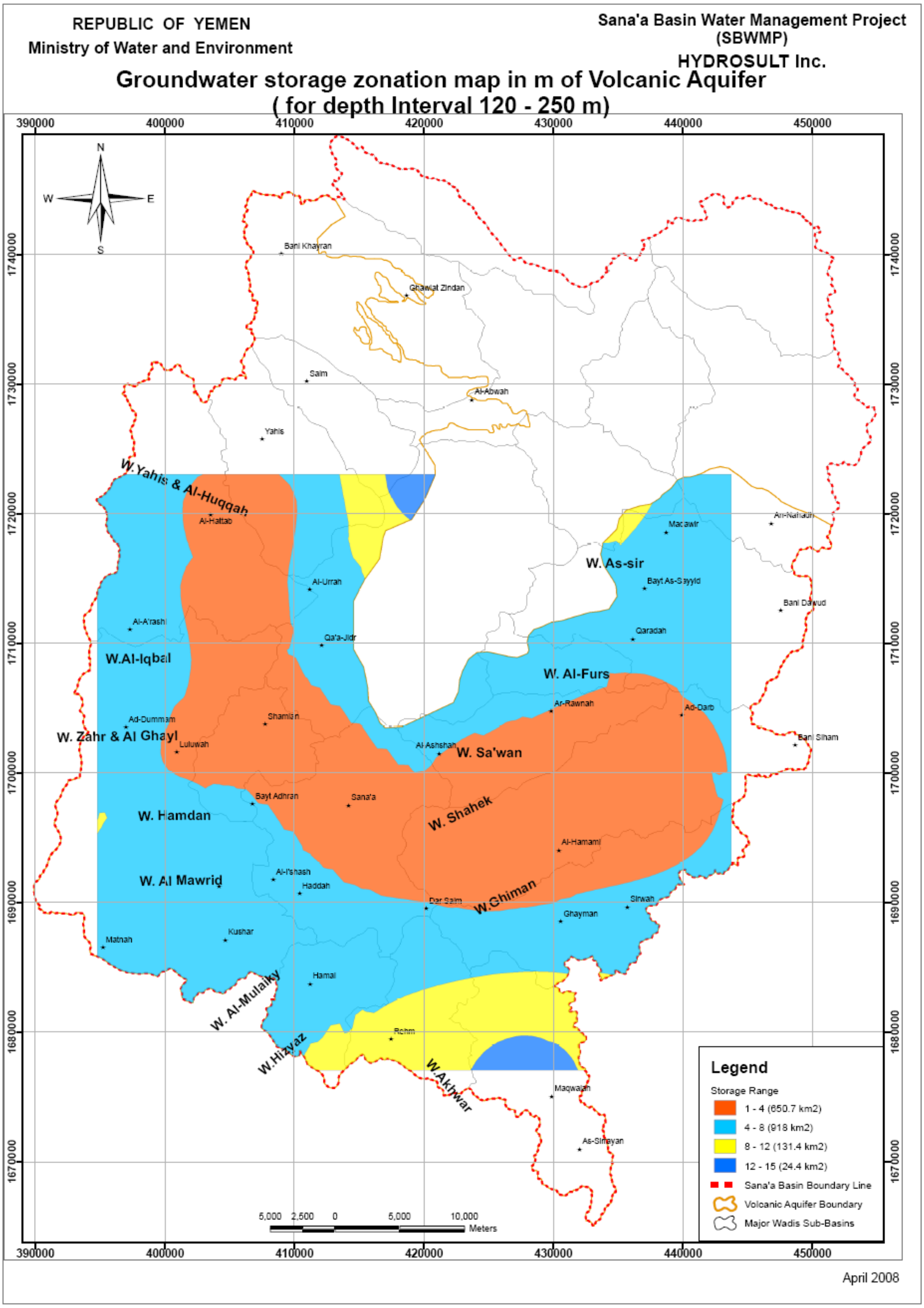

Figure 9-9 Recoverable groundwater storage map of Volcanic aquifer through saturated thickness of 120-250 m, based on wells surveyed by WEC 2001 and Hydrosult 2007

Depth interval of 250 to 350 m:

Recoverable groundwater storage of the Volcanic aquifer through saturated thickness of 100 m starting from depth intervals of 250 to 350 m below ground surface reaches 9.3 km^3. Spatial distribution of this recoverable storage, as shown in Figure 9-10, is divided into three classes:

- The first class covers an area of 783.3 km^2 and ranges between 1 and 6 m in depth starting at 250 m below ground surface, which means that groundwater storage volume in this class reaches 2.7 km^3.
- The second class covers an area of 575.7 km^2 and contains 6 to 13 m depth of groundwater storage, which means that recoverable storage reaches 5.5 km^3.
- The third class storage ranges from 13 to 20 m depth, which reflects the presence of 1.1 km^3 of recoverable groundwater storage (Table 9-2).

The wells surveyed cover only the western side of this aquifer and give an incomplete estimation of recoverable groundwater storage. The spatial distribution zonation map Figure 9-10 shows that recoverable groundwater storage related to this interval of aquifer saturated thickness decreases from west to east while storage aquifer surface area increases in the same direction. The coincidence between the decrease direction of recoverable groundwater storage and general direction of flow in this aquifer may be attributed to the hypothesis that storage at this depth recharges from rainfall.

In addition, Figure 9-11 shows the linear relation between recoverable groundwater storage volume and storage surface area. Assuming a surface area of zero value, this means that, below any boundary of these four classes, recoverable groundwater storage reaches 1.4km^3.

The only recoverable groundwater storage exploitation constraint of the Tertiary Volcanic aquifer is essentially the groundwater quality as this aquifer is considered the unique alternative to the depleted Tawilah sandstone aquifer. Since this aquifer possesses fresh water, there are no constraints on recoverable groundwater storage.

Table 9-2 Storage area and recoverable groundwater storage volume of Volcanic aquifer through saturated thickness of 100 m (250 to 350 m depth)

Depth (m)	Area color	Surface area (km^2)	Storage depth (m)		Average storage depth (m)	Storage water in million m^3
			From	To		
250-350	Red	--	--	--	--	--
	Cyan	783.3	1	6	3.5	2741.55
	Yellow	575.7	6	13	9.5	5469.15
	Blue	68.7	13	20	16.5	1133.55
Total water storage in million m^3						9344.24

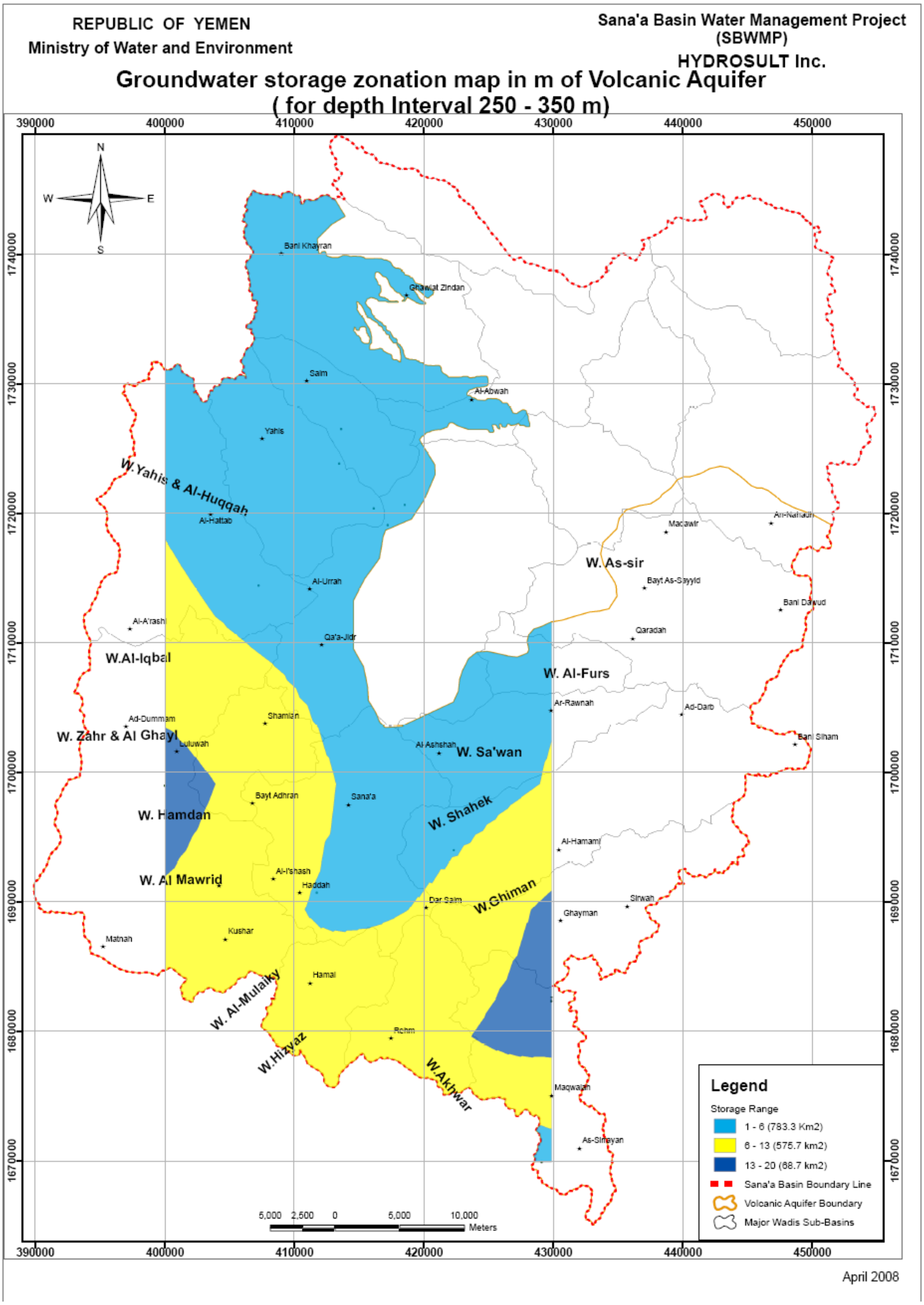

Figure 9-10 Recoverable groundwater storage map of Volcanic aquifer through saturated thickness of 250-350 m, based on wells surveyed by WEC 2001 and Hydrosult 2007

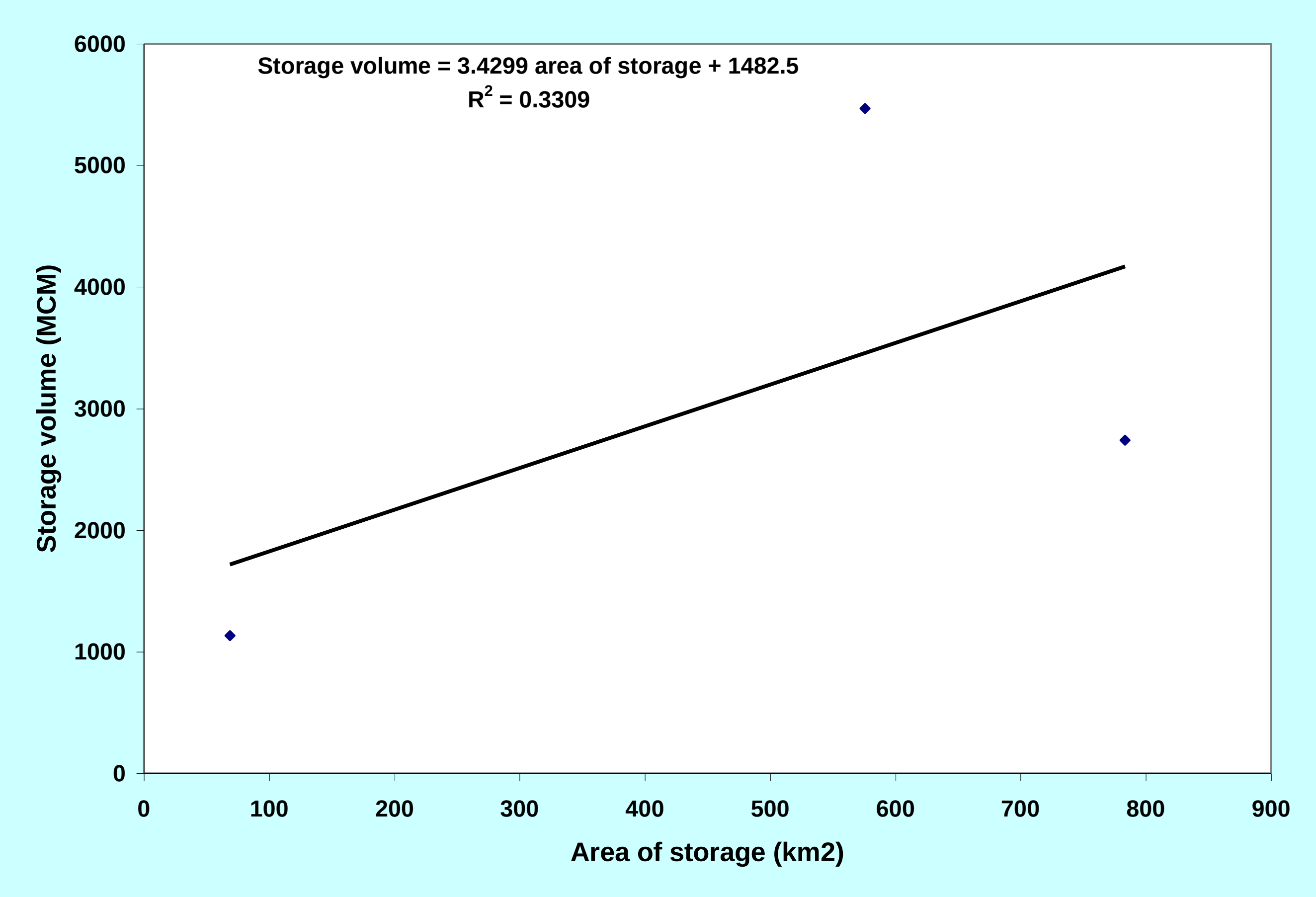

Figure 9-11 Graph showing relation between storage area and recoverable groundwater storage volume in Volcanic aquifer in Sana'a basin through saturated thickness 250-350 m in depth below ground surface

Depth interval of 350 to 500 m:

Recoverable groundwater storage of Volcanic aquifer through saturated thickness of 100 m starting from depth interval of 350 to 500 m below ground surface reaches 33.9 km^3. Spatial distribution of this recoverable storage as shown in Figure 9-12 is divided into three classes:

- The first class covers an area of 784.6 km^2 and ranges between 1 and 16 m in depth starting from a depth of 350 m below ground surface, which means that groundwater storage volume in this class reaches 6.6 km^3.
- The second class covers an area of 757 km^2 and contains 16 to 33 m in depth of groundwater storage, which means that recoverable storage reaches 18.5 km^3.
- The third class storage ranges from 33 to 50 m in depth, which reflects 8.7 km^3 of recoverable groundwater storage (Table 9-3).

The deep wells surveyed cover only the most area of this aquifer and give a more or less complete estimation of recoverable groundwater storage. The spatial distribution zonation map (Figure 9-12) shows that recoverable groundwater storage related this interval of aquifer saturated thickness decreases from east to west while the storage aquifer surface area increases in the same direction. The coincidence between the decrease direction of recoverable groundwater storage and the general direction of flow in this aquifer may be attributed to the hypothesis that storage at this depth recharges from catchment outside the basin.

In addition, Figure 9-13 shows the linear relation between recoverable groundwater storage volume and storage surface area. Assuming a surface area of zero value, this means that below any boundary of these four classes, recoverable groundwater storage reaches 7.7 km^3.

Since this aquifer possesses fresh water, there are no constraints on recoverable groundwater storage, since salinity of the deep zones ranges from 220 to 700 ppm (see chapter 7).

Table 9-3 Storage area and recoverable groundwater storage volume of Volcanic aquifer through saturated thickness of 150 m (350 to 500 m depth)

Depth (m)	Area color	Surface area (km^2)	Storage depth (m)		Average storage depth (m)	Storage water in million m^3
			From	To		
350-500	Red	--	--	--	--	--
	Cyan	784.6	1	16	8.5	6669.1
	Yellow	757	16	33	24.5	18546.5
	Blue	210	33	50	41.5	8715
Total water storage in million m^3						33930.6

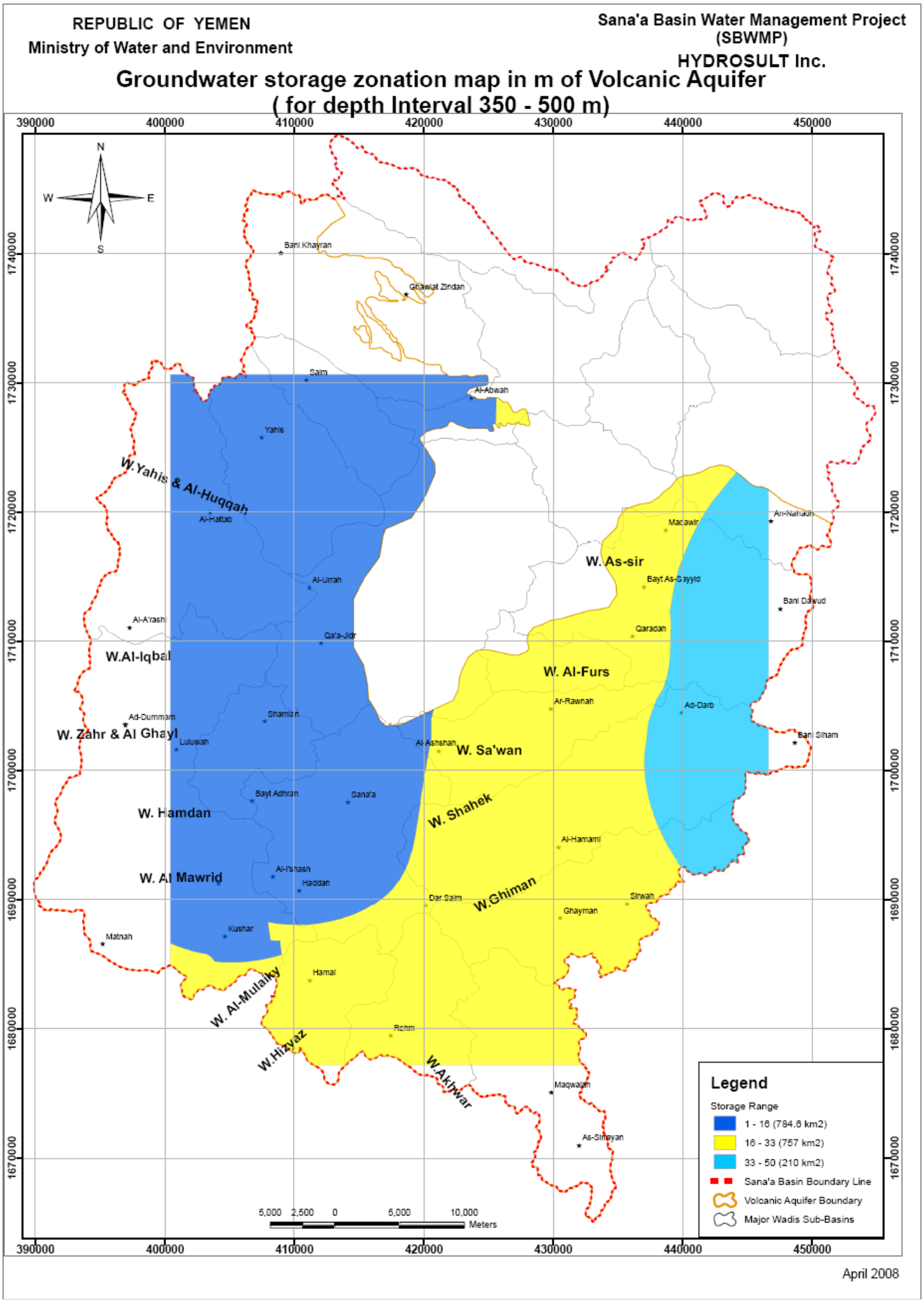

Figure 9-12 Recoverable groundwater storage map of Volcanic aquifer through saturated thickness 350-500 m, based on wells surveyed by WEC 2001 and Hydrosult 2007

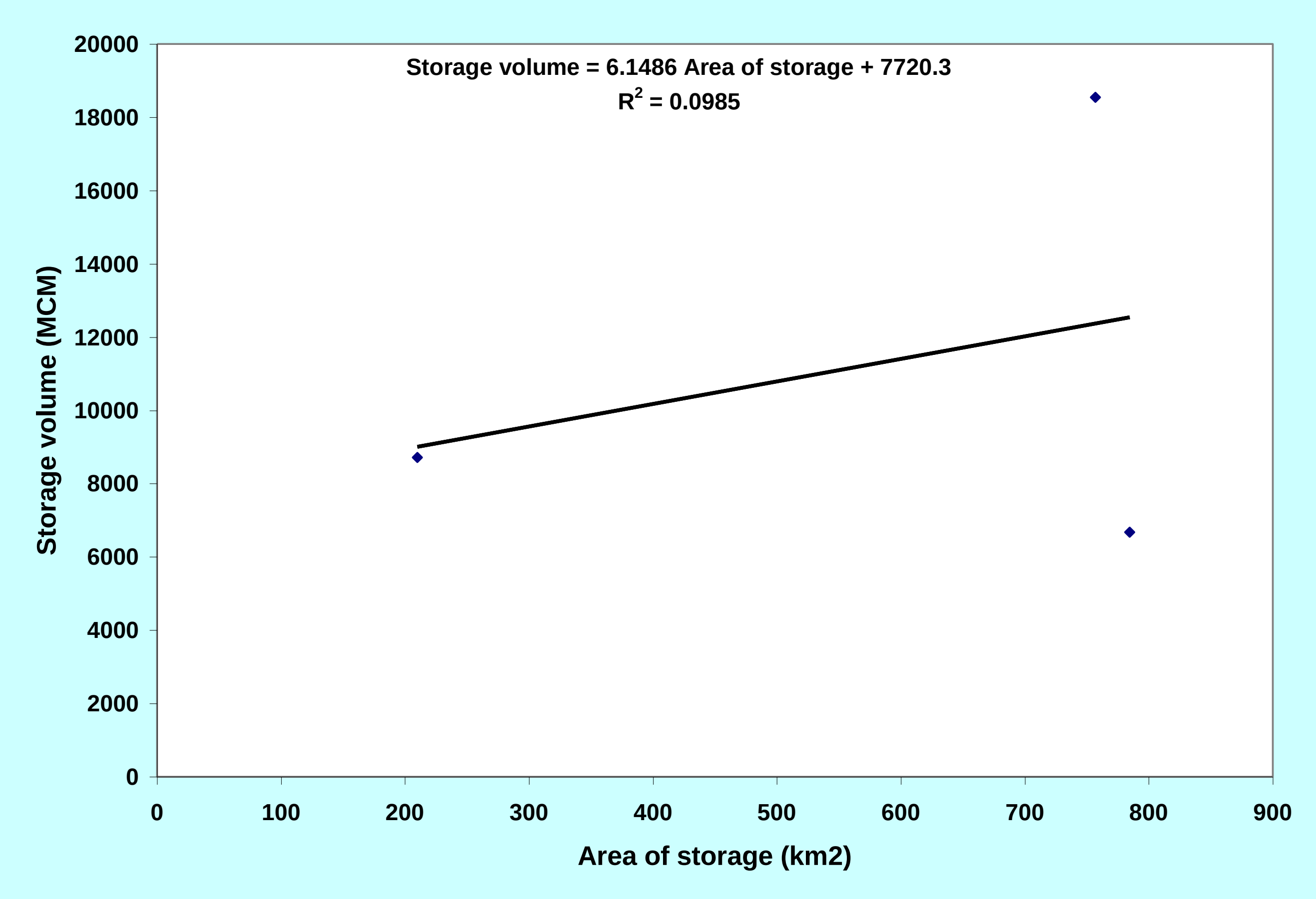

Figure 9-13 Graph showing relation between storage area and recoverable groundwater storage volume in Volcanic aquifer in Sana'a basin through saturated thickness 350-500 m in depth below ground surface

9.2.3. Recoverable groundwater storage mapping of Tawilah sandstone aquifer

The constraint to recoverable groundwater storage exploitation here is essentially the groundwater quality, as Tawilah sandstone aquifer is the unique source of drinking water for Sana'a City and surrounding rural villages. The permissible limit for drinking groundwater from this aquifer, as concluded in chapter 7, reflects the degree of acceptance as a whole, since this aquifer possesses fresh water. So there are no constraints with recoverable groundwater storage in cases of shallow zones in aquifer outcrops. In addition, the deep zone has fresher water.

Four recoverable groundwater storage maps for the outcrops of Tawilah sandstone aquifer (Figures 9-14, 9-16, 9-18 and 9-20) were developed based on the sorted processed data in WEC 2001 and for different depth intervals below static water level reaching 150, 250, 350 and 450 m. In the following is presented a brief description of storage volumes in the wells surveyed in Tawilah sandstone aquifer.

Depth to 150 m below static water level:

Recoverable groundwater storage for the outcrops of Tawilah sandstone aquifer through saturated thickness of 150 m below the static water level reaches 762 MCM. The spatial distribution of this recoverable storage, as shown in Figure 9-15 ,is divided into three classes:

- The first class covers an area of 46.3 km^2 and ranges between 2 and 3 m, which means that groundwater storage volume in this class approaches 115.7 MCM.
- The second class covers an area of 134.6 km^2 and contains 3 to 4 m depth of groundwater storage, which means that recoverable storage reaches 471.1 MCM.

- The third class of storage ranges from 4 to 7 m in depth, which reflects the presence of 175.45 MCM of recoverable groundwater storage (Table 9-4).

The small area of the Tawilah sandstone outcrops under unconfined conditions show little recoverable groundwater storage volume as a whole. The spatial distribution zonation map (Figure 9-15) shows that recoverable groundwater storage related to this interval of aquifer saturated thickness decreases from NE to SW while the storage aquifer surface area increases in the same direction. In addition, Figure 9-14 shows the linear relation between recoverable groundwater storage volume and storage surface area. Assuming a surface area of zero value, this means that below any boundary of these outcrops, the recoverable groundwater storage reaches 21 MCM.

Table 9-4 Storage area and recoverable groundwater storage volume of Tawilah sandstone aquifer through saturated thickness of 150 m, starting from the static water level

Depth (m)	Area color	Surface area (km^2)	Storage depth (m)		Average storage depth (m)	Storage water in million m^3
			From	To		
150	Red	--	--	--	--	--
	Cyan	46.3	2	3	2.5	115.75
	Yellow	134.6	3	4	3.5	471.1
	Blue	31.9	4	7	5.5	175.45
Total water storage in million m^3						762.3

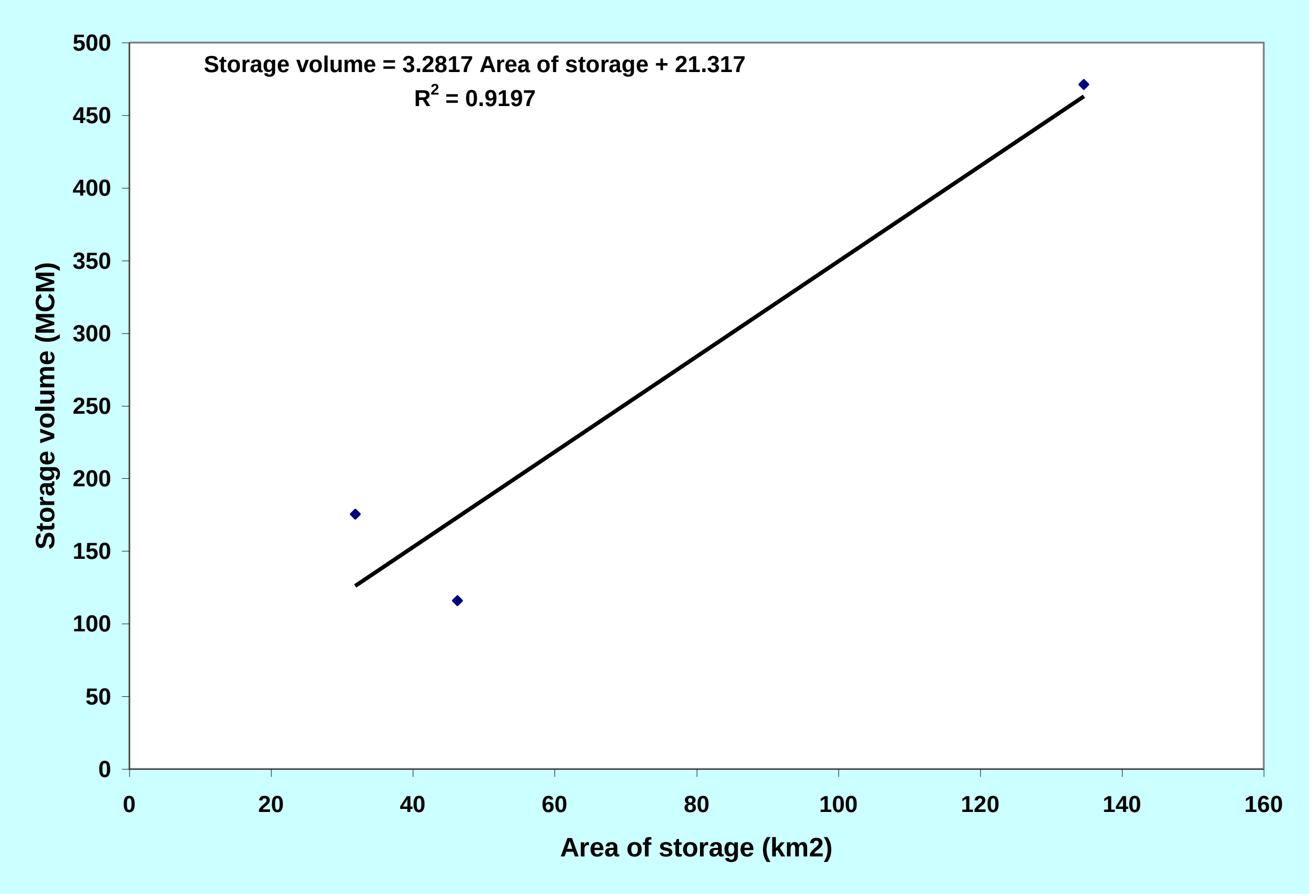

Figure 9-14 Graph showing relation between storage area and recoverable groundwater storage volume in Tawilah sandstone aquifer in Sana'a basin through saturated thickness of 100 m depth from static water level

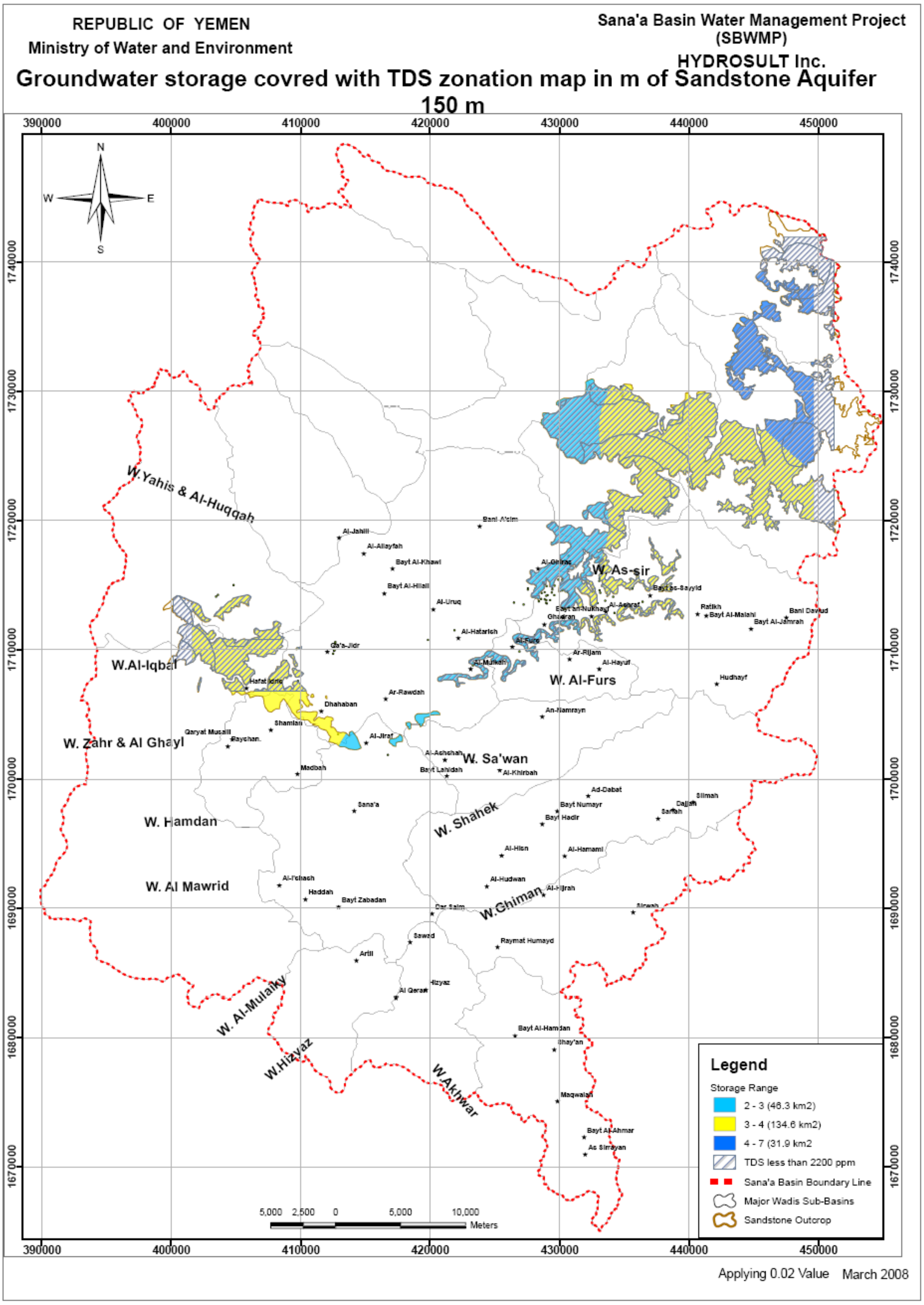

Figure 9-15 Recoverable groundwater storage map of Tawilah sandstone aquifer (m) at 150 m depth from static water level

Depth interval of 150 to 250 m:

Recoverable groundwater storage of the outcrops of Tawilah sandstone aquifer through saturated thickness from 150 to 250 m below the static water level reaches 610 MCM. Spatial distribution of this recoverable storage, as shown in Figure 9-16, is divided into four classes:

- The first class covers an area of 0.5 km^2 and ranges between 1 and 5 m, which means that the groundwater storage volume in this class approaches 1.5 MCM.
- The second class covers an area of 44.5 km^2 and covers 5 to 7 m in depth of groundwater storage, which means that recoverable storage reaches 267 MCM.
- The third class storage ranges from 7 to 9 m in depth, which reflects the presence of 290 MCM of recoverable groundwater storage (Table 9-1).

The small area of the Tawilah sandstone outcrops under unconfined conditions shows little recoverable groundwater storage volume as a whole with respect to the Volcanic aquifer. The spatial distribution zonation map (Figure 9-16) shows that recoverable groundwater storage related to this interval of aquifer saturated thickness decreases from NE to SW, while the storage aquifer surface area increases in the same direction. In addition, Figure 9-17 shows the linear relation between recoverable groundwater storage volume and storage surface area. Assuming a surface area of zero value, this means that below any boundary of these outcrops recoverable groundwater storage reaches 13 MCM.

Table 9-5 Storage area and recoverable groundwater storage volume of Tawilah sandstone aquifer through saturated thickness from 150 to 250 m, starting from static water level

Depth (m)	Area color	Surface area (km^2)	Storage depth (m)		Average storage depth (m)	Storage water in million m^3
			From	To		
250	Red	0.51	1	5	3	1.53
	Cyan	44.5	5	7	6	267
	Yellow	36.3	7	9	8	290.4
	Blue	4.6	9	13	11	50.6
Total water storage in million m^3						609.53

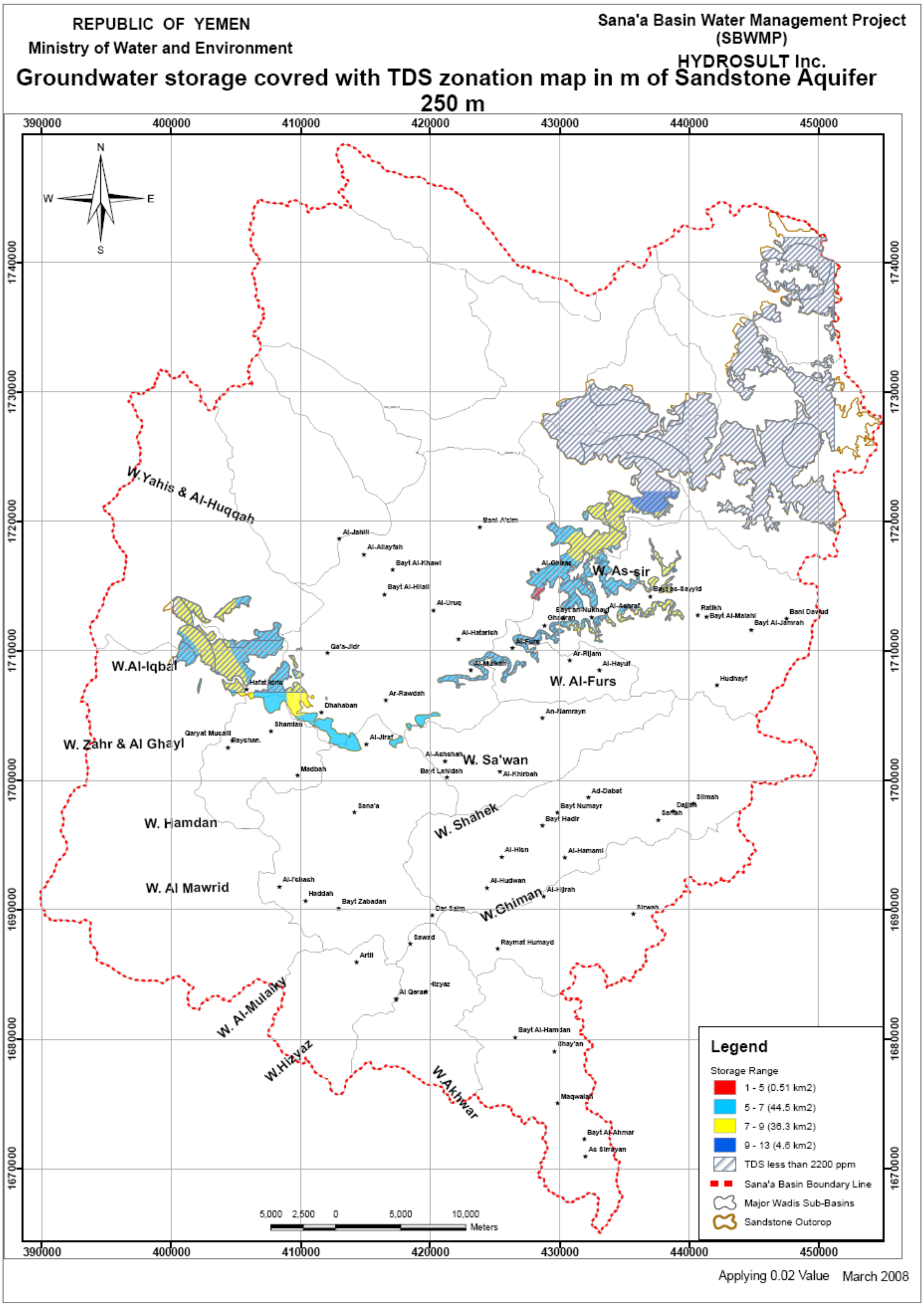

Figure 9-16 Recoverable groundwater storage map of Tawilah sandstone aquifer (m) from 150 to 250 m depth from static water level

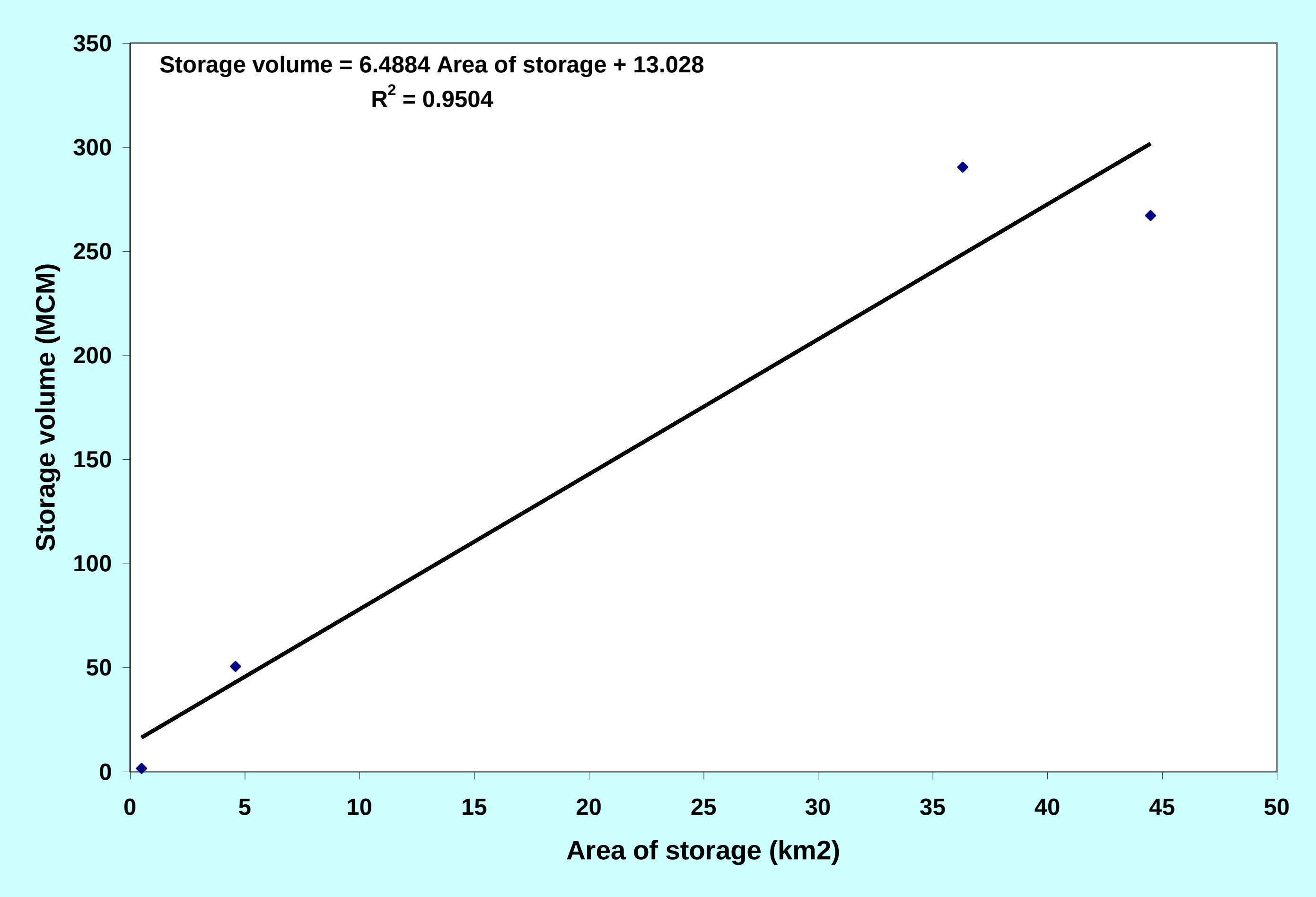

Figure 9-17 Graph showing relation between storage area and recoverable groundwater storage volume in Tawilah sandstone aquifer in Sana'a basin through saturated thickness of 150 to 250 m depth from static water level

Depth interval of 250 to 350 m:

Recoverable groundwater storage of the outcrops of Tawilah sandstone aquifer through saturated thickness from 250 to 350 m below static water level reaches 2.7 km^3. Spatial distribution of this recoverable storage as shown in Figure 9-18 is divided into three classes:

- The first class covers an area of 1 km^2 and ranges between 10 and 14 m, which means that groundwater storage volume in this class approaches 48.5 MCM.
- The second class covers an area of 148.7 km^2 and covers 10 to 12 m depth of groundwater storage, which means that recoverable storage reaches 1.6 km^3.
- The third class storage ranges from 12 to 19 m depth, which reflects the presence of 1 km^3 of recoverable groundwater storage (Table 9-6).

The spatial distribution zonation map (Figure 9-18) shows that recoverable groundwater storage related to this interval of aquifer saturated thickness decreases from NE to SW in the NE outcrops of the aquifer and in reverse direction at NW outcrops while the storage aquifer surface area increases in the same direction. In addition, Figure 9-19 shows the linear relation between recoverable groundwater storage volume and storage surface area. Assuming a surface area of zero value, this means that, below any boundary of these outcrops, recoverable groundwater storage reaches 103 MCM.

Table 9-6 Storage area and recoverable groundwater storage volume of Tawilah sandstone aquifer through saturated thickness of 350 m, starting from static water level

Depth (m)	Area color	Surface area (km^2)	Storage depth (m)		Average storage depth (m)	Storage water in million m^3
			From	To		
350	Red	--	--	--	--	--
	Cyan	5.7	8	9	8.5	48.45
	Yellow	148.7	10	12	11	1635.7
	Blue	66.9	12	19	15.5	1036.95
Total water storage in million m^3						2721.1

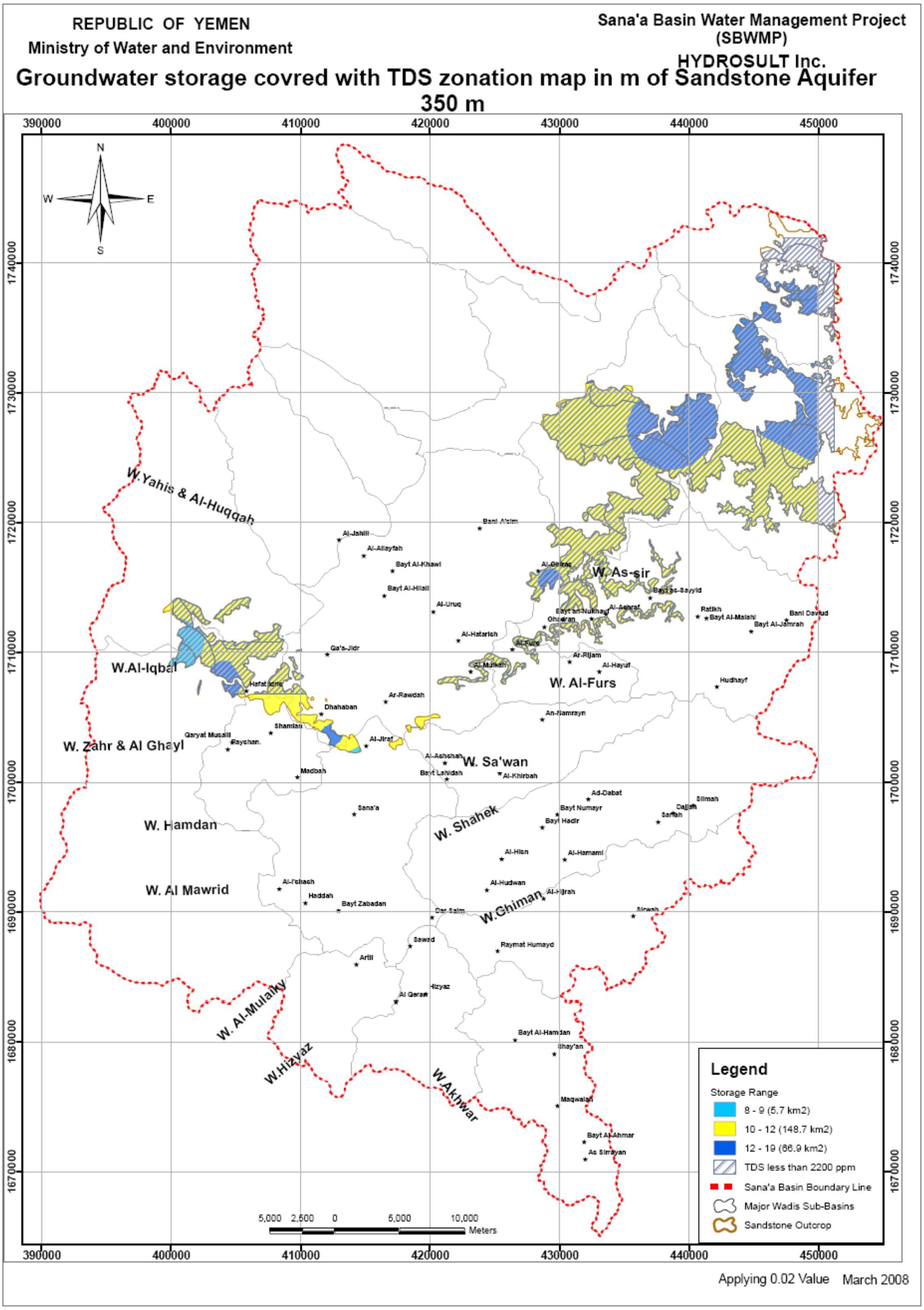

Figure 9-18 Recoverable groundwater storage map of Tawilah sandstone aquifer (m) from 250 to 350 m depth from static water level

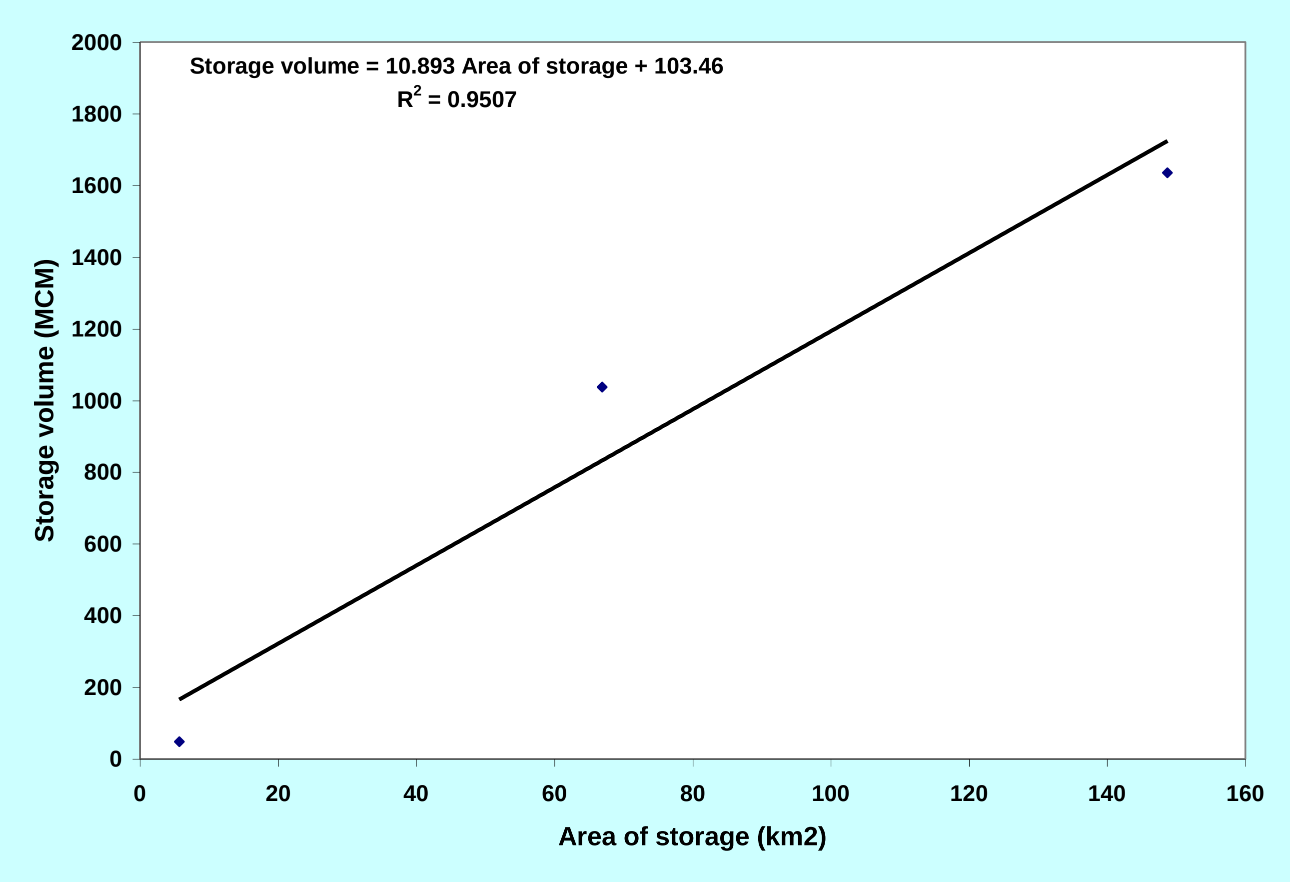

Figure 9-19 Graph showing relation between storage area and recoverable groundwater storage volume in Tawilah sandstone aquifer in Sana'a basin through saturated thickness from 250 to 350 m depth from static water level

Depth interval of 350 to 450 m:

Recoverable groundwater storage of the outcrops of Tawilah sandstone aquifer through saturated thickness from 350 to 450 m below the static water level reaches 620 km^2. The spatial distribution of this recoverable storage as shown in Figure 9-20 is divided into three classes:

- The first class covers an area of 1 km^2 and ranges between 10 and 14 m, which means that groundwater storage volume in this class approaches 12 MCM.
- The second class covers an area of 20.4 km^2 and covers 14 to 17 m depth of groundwater storage, which means that recoverable storage reaches 316 km^2.
- The third class storage ranges from 17 to 20 m in depth, which reflects the presence of 292.3 km^2 of recoverable groundwater storage (Table 9-7).

The spatial distribution zonation map (Figure 9-20) shows that the recoverable groundwater storage related to this interval of aquifer saturated thickness decreases from NE to SW in the NE outcrops of the aquifer and in reverse direction at NW outcrops, while the storage aquifer surface area increases in the same direction. In addition, Figure 9-21 shows the linear relation between recoverable groundwater storage volume and storage surface area. Assuming a surface area of zero value, this means that, below any boundary of these outcrops, recoverable groundwater storage reaches 2.5 MCM.

Table 9-7 Storage area and recoverable groundwater storage volume of Tawilah sandstone aquifer through saturated thickness of 250 m, starting from static water level

Depth (m)	Area color	Surface area (km^2)	Storage depth (m)		Average storage depth (m)	Storage water in million m^3
			From	To		
450	Red	--	--	--	--	--
	Cyan	1	10	14	12	12
	Yellow	20.4	14	17	15.5	316.2
	Blue	15.8	17	20	18.5	292.3
Total water storage in million m^3						620.5

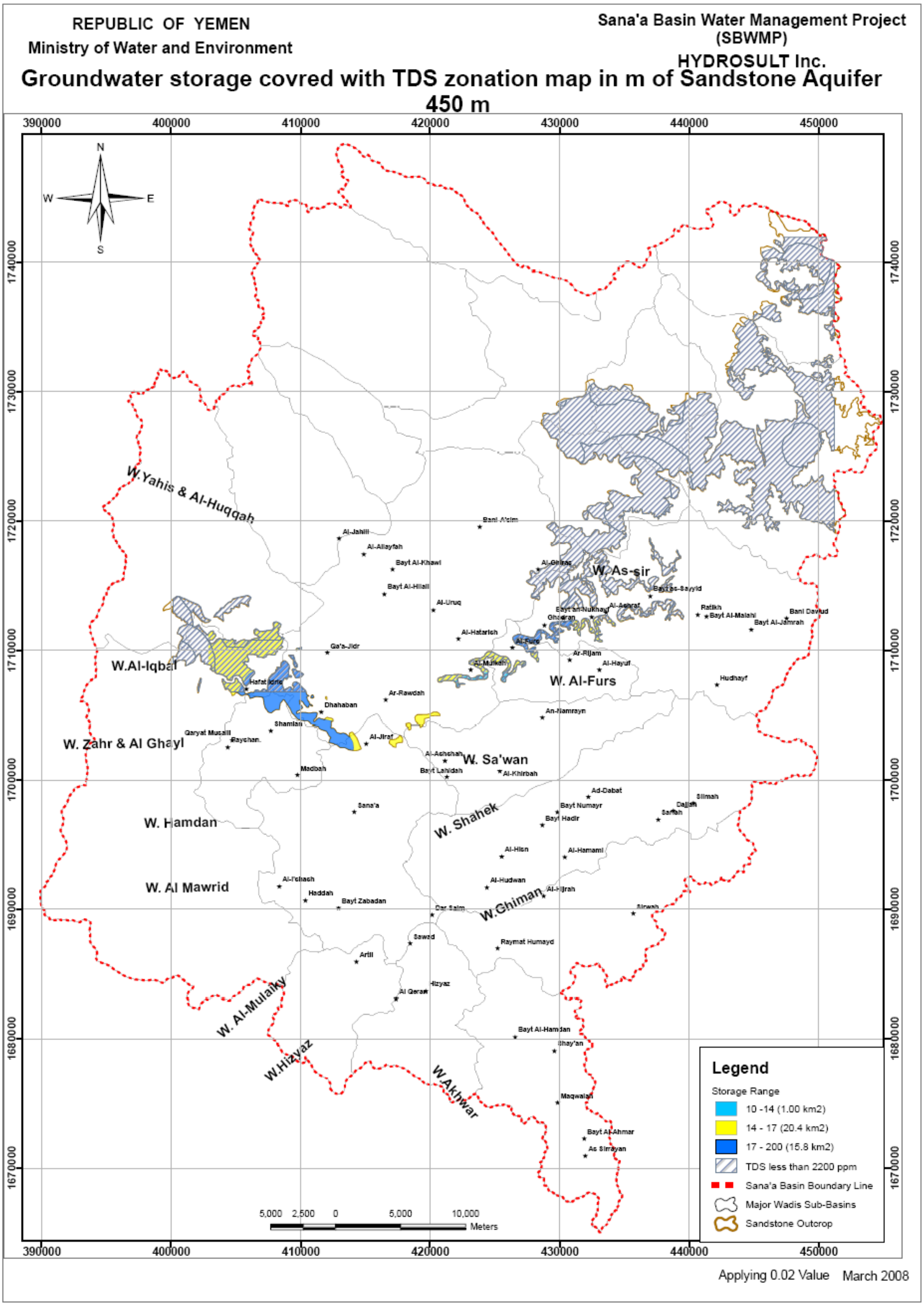

Figure 9-20 Recoverable groundwater storage map of Tawilah sandstone aquifer (m) from 350 to 450 m depth from static water level

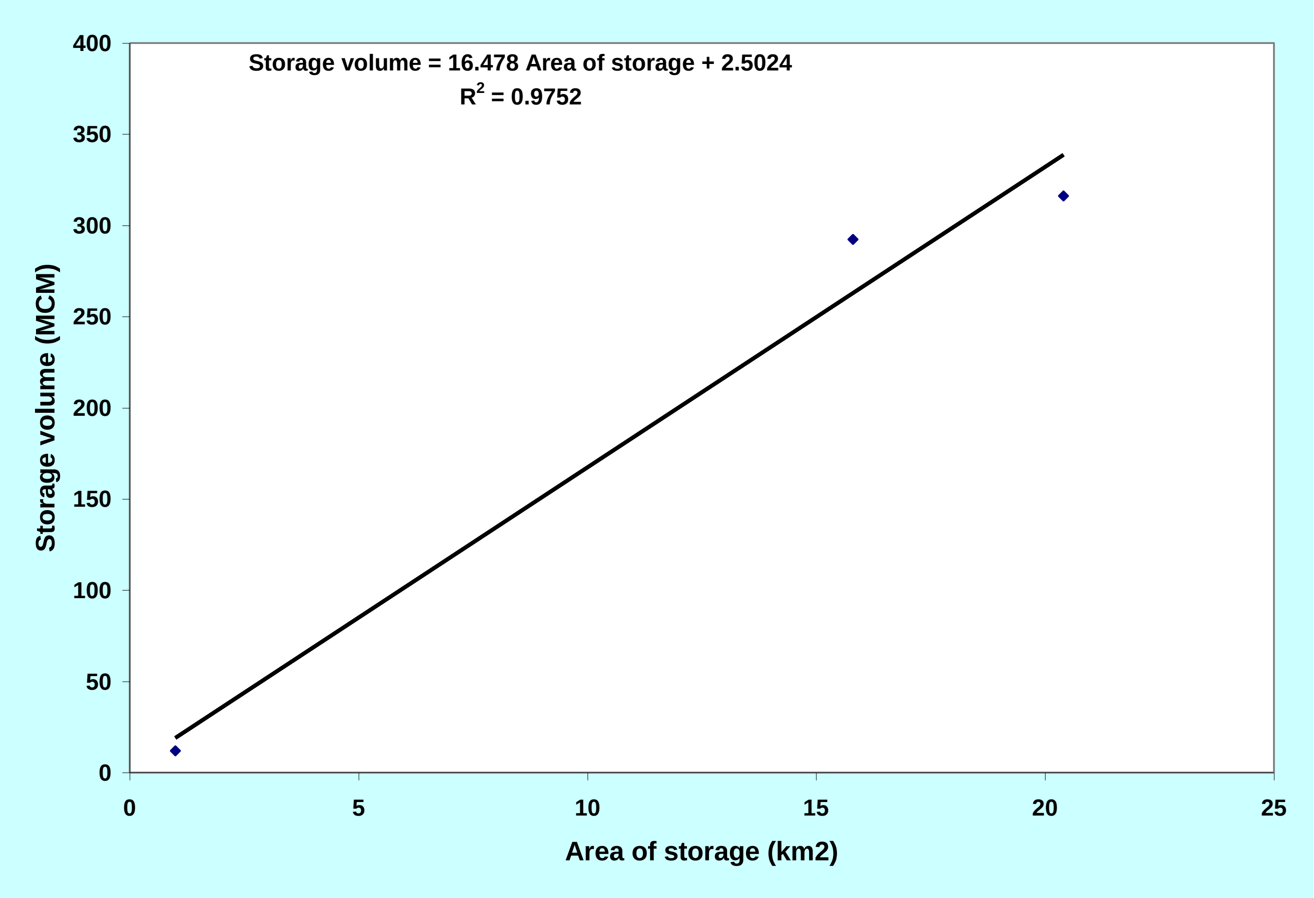

Figure 9-21 Graph showing relation between storage area and recoverable groundwater storage volume in Tawilah sandstone aquifer in Sana'a basin through saturated thickness 350 to 450 m in depth from static water level

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5- On the other hand, recoverable groundwater storage of the deep zone of Tawilah sandstone aquifer was studied separately through developing four maps based on the sorted processed data present in WEC 2001 and for different depth intervals below land surface reach 150, 250, 350 and 450 m (Figures 9-22, 9-23, 9-24 and 9-25). The purpose of this trial is to check whether or not there is a difference in storage between shallow and deep zone. It is noticed from the figures and Table 9-8 that recoverable groundwater storage in the deep zone of the Tawilah sandstone aquifer reaches 40.8 km^3, while it reaches 4.7 km^3 in the case of the shallow zone of the aquifer (outcrops). It is greater than that in the shallow zone by about ten times, although the shallow zone receives annual recharge from rainfall. This may be attributed to the high recharge rate from outside the Sana'a basin, especially the adjacent eastern basin. The current rainfall-runoff study will help to explain this point. This finding needs more studies to support it.

Also, one should realize that only a fraction of this water can be abstracted, depending on depth and distribution of the abstraction wells. This volume can be verified through the ongoing water balance and modeling studies.

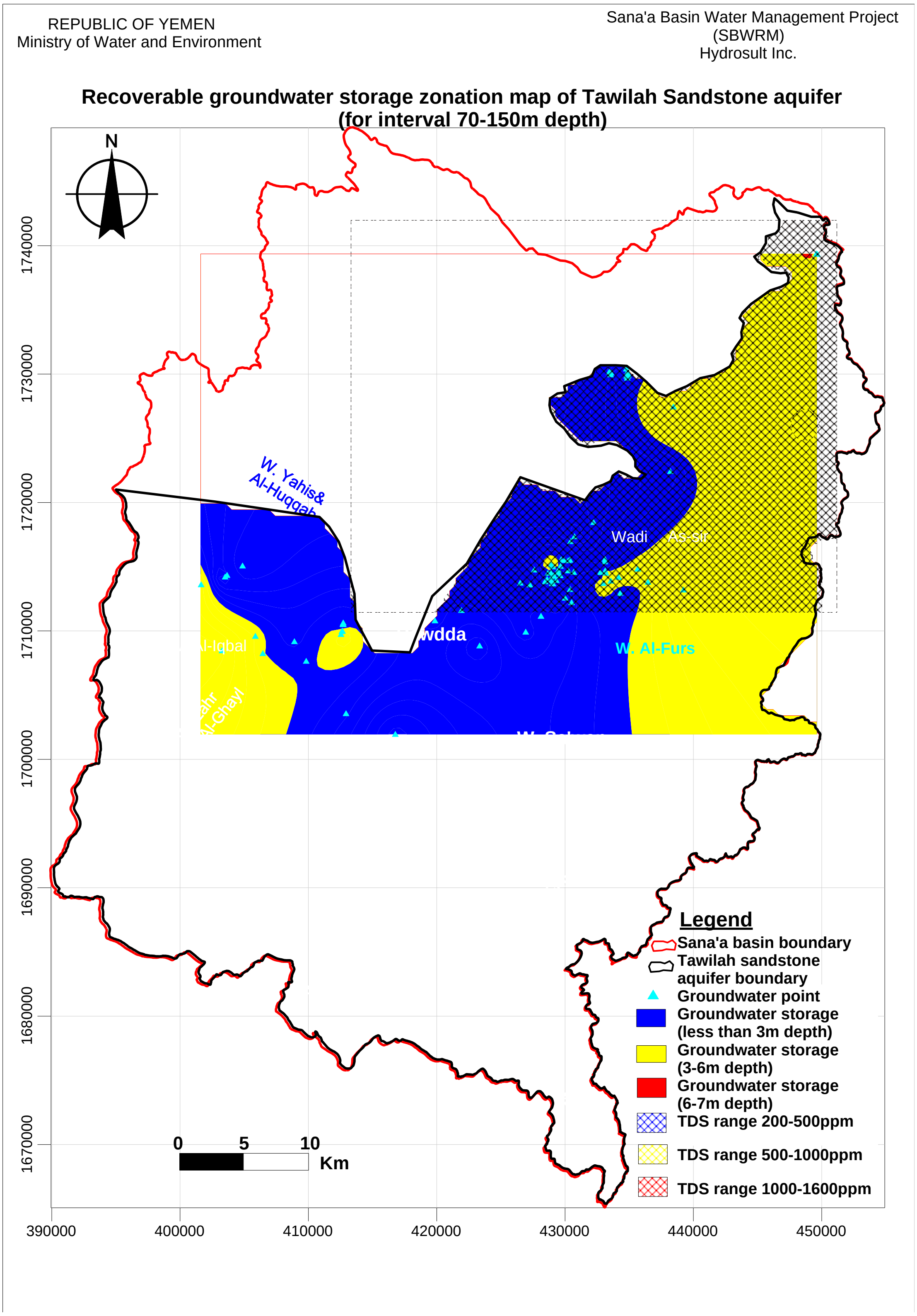

Figure 9-22 Recoverable groundwater storage map of the deep zone of Tawilah sandstone aquifer (m) at 150 m depth

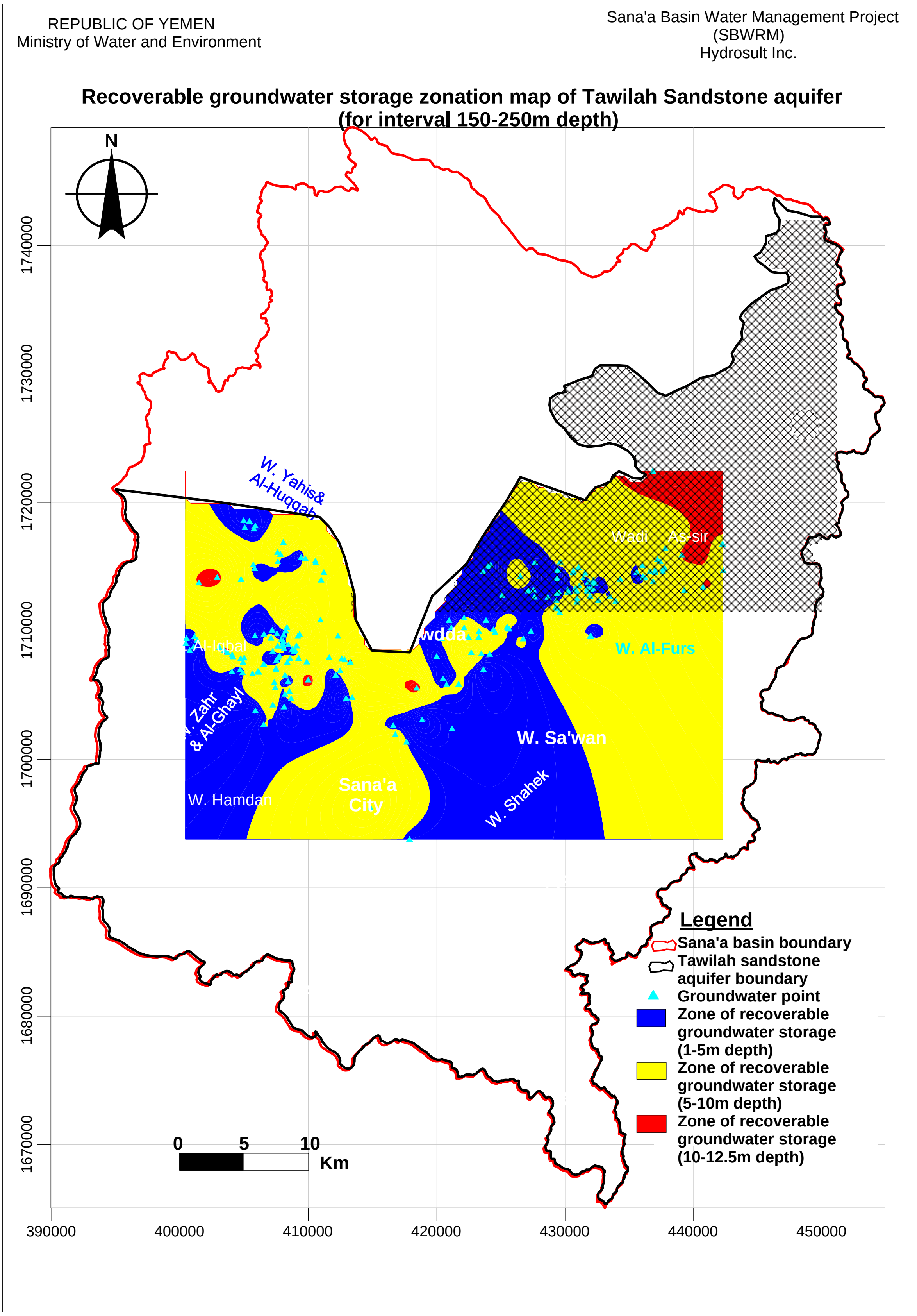

Figure 9-23 Recoverable groundwater storage map of the deep zone of Tawilah sandstone aquifer (m) at 250 m depth

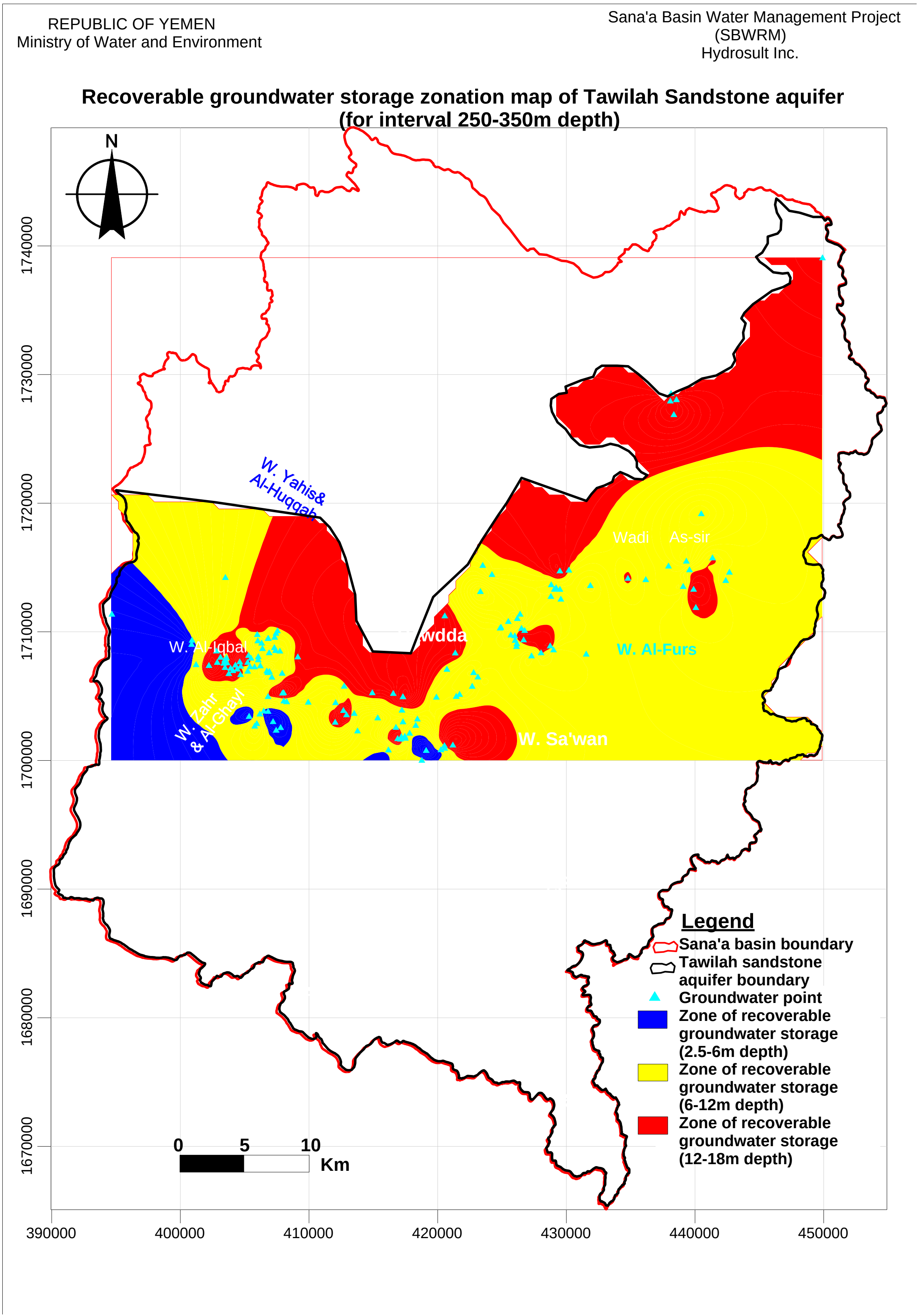

Figure 9-24 Recoverable groundwater storage map of the deep zone of Tawilah sandstone aquifer (m) at 350 m depth

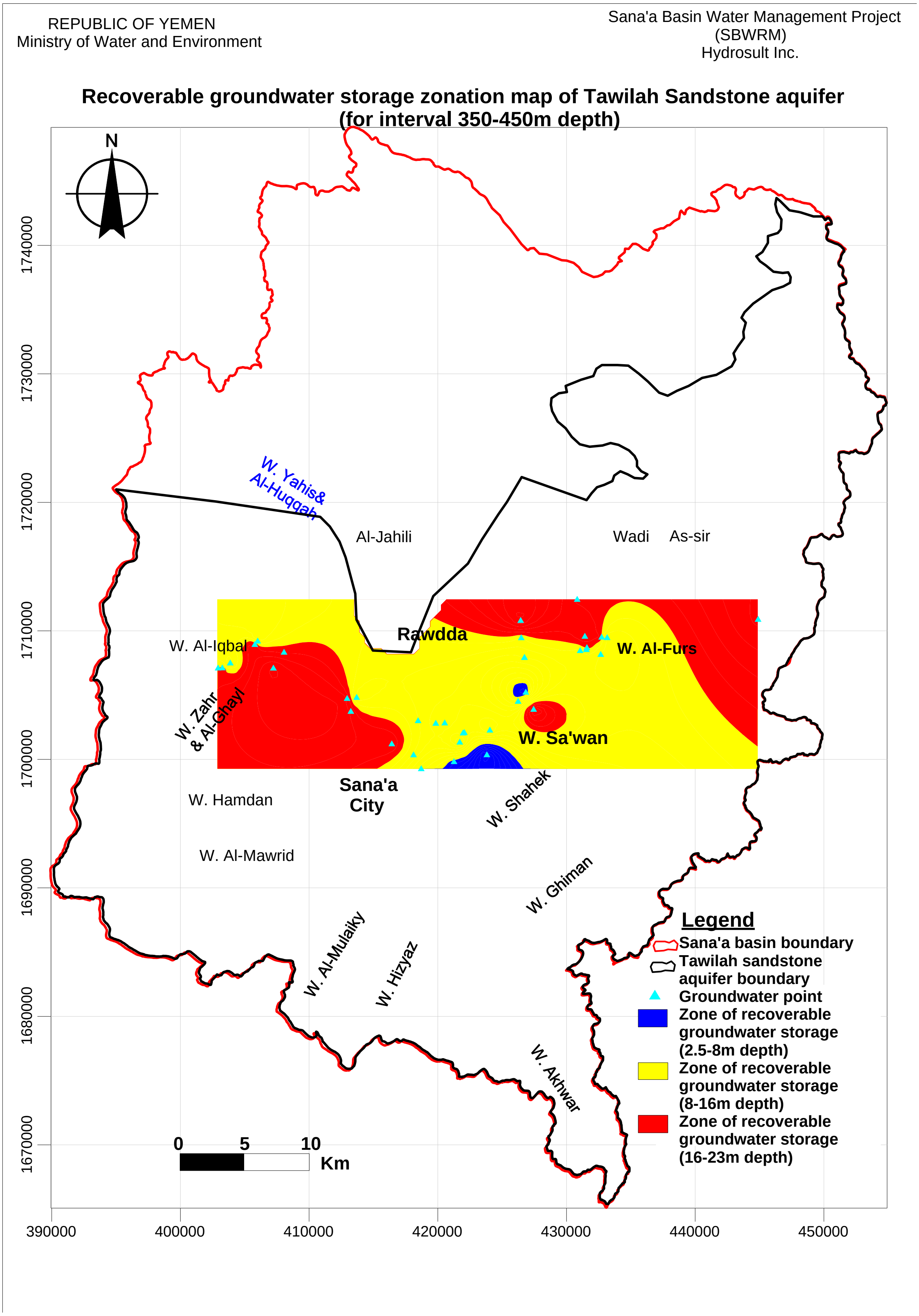

Figure 9-25 Recoverable groundwater storage map of the deep zone of Tawilah sandstone aquifer (m) at 450 m depth

Table 9-8 Recoverable groundwater storage volume of the deep zone of Tawilah sandstone aquifer in Sana'a basin

Storage interval	Area color	Surface area (km^2)	Range of storage From	Range of storage To	Average storage depth (m)	Storage volume in million m^3
70-150	Red	1	12	18	15	15
	Yellow	320	6	12	9	2880
	Blue	350	2.5	6	4.25	1487.5
Total recoverable groundwater storage in million m^3						4382.5

Storage interval	Area color	Surface area (km^2)	Range of storage From	Range of storage To	Average storage depth (m)	Storage volume in million m^3
150-250	Red	200	10	12.5	11.25	2250
	Yellow	600	5	10	12.5	7500
	Blue	410	1	5	3	1230
Total recoverable groundwater storage in million m^3						10980

Storage interval	Area color	Surface area (km^2)	Range of storage From	Range of storage To	Average storage depth (m)	Storage volume in million m^3
250-350	Red	400	12	18	15	6000
	Yellow	600	6	12	9	6300
	Blue	100	2.5	6	4.25	425
Total recoverable groundwater storage in million m^3						12725

Storage interval	Area color	Surface area (km^2)	Range of storage From	Range of storage To	Average storage depth (m)	Storage volume in million m^3
350-450	Red	200	16	23	19.5	3900
	Yellow	350	8	16	12	4200
	Blue	50	2.5	8	5.25	262.5
Total recoverable groundwater storage in million m^3						8362.5