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Chapter 8. GROUNDWATER DEPLETION IN SANA'A BASIN

EXECUTIVE SUMMARY

The groundwater in Sana'a Basin has been in depletion since abstraction volumes increased to volumes greater than recharge volumes. Estimates of the depletion were made based on the groundwater level maps in the three aquifers. The specific yield (the volume of water which can be drained from the aquifer by gravity) of the unconfined aquifers was estimated at:

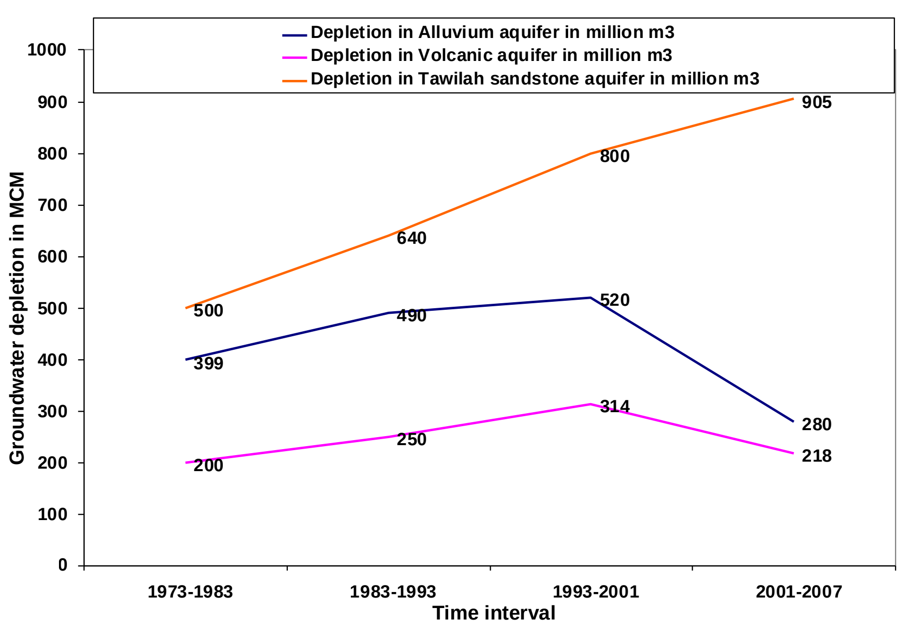
- Alluvium aquifer: 2%, according to the SAWAS groundwater model,
- Volcanic aquifer: 10%, according to the SAWAS groundwater model,
- Sandstone aquifer: 7.1%, determined from porosity of rock samples.

Observation of the groundwater levels shows that the water table has been lowered:

- Alluvium aquifer: maximum of 3.4 m since 1973, or more in eastern areas where the aquifer has dried,
- Volcanic aquifer: maximum of 51.2 m since 1985,
- Sandstone aquifer: maximum of 110 m since 1993.

The depleted volumes (M m^3) calculated for different periods are:

Time period	Depletion in Alluvium aquifer in million m^3	Depletion in Volcanic aquifer in million m^3	Depletion in Tawilah sandstone aquifer in million m^3
1973-1983	399	200	500
1983-1993	490	250	640
1993-2001	520	314	800
2001-2007	280	218	905



GENERAL OUTLINE

Groundwater is a valuable resource, both in Yemen and throughout the world. In the Sana'a Basin, it is the sole source of drinking water for almost the total urban population in Sana'a City and all of the rural population, and it provides over 5.6 million cubic meters per year for drinking needs. Over-exploitation of groundwater resources is the major problem leading to groundwater depletion in the Sana'a Basin, one of the major semi-arid highland basins of Yemen. Consequently, depletion places socioeconomic development in jeopardy. Owing to the lack of institutional arrangements and management instruments, government intervention is not likely to alleviate the crisis. Groundwater depletion, a term often defined as long-term water-level declines caused by sustained groundwater pumping, is a key issue associated with groundwater use. Many areas of the Sana'a Basin are experiencing groundwater depletion.

One of the main tasks of Activity 1 was groundwater depletion mapping. Not all hydrogeological maps are equally important. The groundwater depletion maps are considered very important for identifying the loss of groundwater storage over the last few decades. The main function of the potentiometric maps is to underpin these maps, so they should be designed accordingly, based on historical records of groundwater levels. The groundwater depletion map indicates the loss in quantity of groundwater stored in the aquifer over a certain period. The depletion map is prepared from groundwater level contour maps of both beginning and end of the period. The effective porosity or specific yield is essential in preparing the depletion map. A brief description follows of the procedures for determining effective porosity.

8.1 Determination of effective porosity

In previous studies, trials were made to estimate effective porosity of Quaternary alluvial deposits, Quaternary and Tertiary volcanic rock units and Cretaceous sandstone rock units. Table 8-1 shows the different values of effective porosity with respect to the present aquifer rock unit.

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

Table 8-1 Available effective porosity values from previous studies

Available estimates of applied coefficients	Specific Yield		Storage Coefficient	
	SAWAS model	Naaman model	SAWAS model	Naaman model
Aquifer 1: unconfined - Quaternary Alluvium	0.02	0.01	-	-
Aquifer 2: usually unconfined but probably partly confined - Quaternary Volcanics - Tertiary Volcanics	0.1 0.015	0.2 0.005	- -	- 3.7-7
Aquifer 3: partly confined and partly unconfined - Cretaceous Sandstone	0.08	0.1	2-7	9-4

1 Estimates from SAWAS model obtained from TOR

2 Estimates from Naaman model obtained from Naaman (2004)

In this study, the following values were chosen for the unconfined part of the aquifers:

- specific yield of the alluvium aquifer was chosen as 0.02, according to SAWAS model 1995,
- specific yield of the volcanic aquifer was chosen as 0.1, according to SAWAS model 1995,
- specific yield of the Cretaceous sandstone aquifer unit was derived from tests on the rock samples (see chapter 3 for description of the sampling).

Effective porosity determination on samples from the Cretaceous sandstone was carried out in the Egyptian Petroleum Research Institute Corelab (EPRI CORELAB). Helium porosity under confining pressure technique was used. In this procedure, each sample was weighed and then placed in a sealed sample chamber (matrix cup), using steel disks to minimize void space. The reference cell containing a known volume was pressurized with Helium to 100 psi. The Helium in the reference cell was then allowed to expand into the sample chamber containing the sample. Thus, grain volume of each sample was measured. To measure pore volume, each sample was loaded into a hydrostatic core holder. An effective overburden pressure of 1000 psi was applied to each sample. The Helium was then allowed into the sample under the mentioned confining pressure and pore volume was measured. By knowing the summation of grain volume and pore volume, bulk volume was calculated. Then, dividing pore volume by bulk volume, porosity was calculated (Table 8-2).

In order to simulate the Tawilah sandstone outcropping core samples at depths of 300 m, a high, confining pressure of 1000 psi was used in the procedure. Unfortunately, some of the weathered core samples were affected by this high, confining pressure in such a manner that their determined effective porosity values were unrealistically high (core samples no. 1, 5, 7, 8 and 9). Accordingly, in the mapping of aquifer depletion and storage, an average value of 7.1% is used for effective porosity, which represents the mean value of effective porosity of both Ghiras (core sample no. 2) and Medj-zir (core sample no. 10) formations, representative of the Tawilah sandstone group. This value corresponds well with the value applied by SAWAS.

Table 8-2 Effective porosity, using Helium porosity under confining pressure technique

Sample No.	Formation	Member	Effective porosity%	Grain density gm/cc
1	Ghiras	Thula	19.1	2.64
2	Ghiras	Thula	7.6	2.64
3	Ghiras	Shibam	13.5	2.63
4	Ghiras	Kawkaban	--	--
5	Medj-zir	Zijan	21.3	2.67
6	Medj-zir	Kura	11.4	2.67
7	Medj-zir	Kura	19.1	2.73
8	Medj-zir	Kura	19.6	2.56

Sample No.	Formation	Member	Effective porosity%	Grain density gm/cc
9	Medj-zir	Lahma	17.1	2.66
10	Medj-zir	Lahma	6.6	2.66

Note: Sample no. 4 was not measured as it was so unconsolidated that it could not sustain confining pressure of 1000 psi.

8.2 Procedure for groundwater depletion mapping

The groundwater depletion map indicates the loss in quantity of groundwater stored in the aquifer over a certain period. The depletion map is prepared from groundwater level contour maps of the beginning and the end of the period (Figure 8-1).

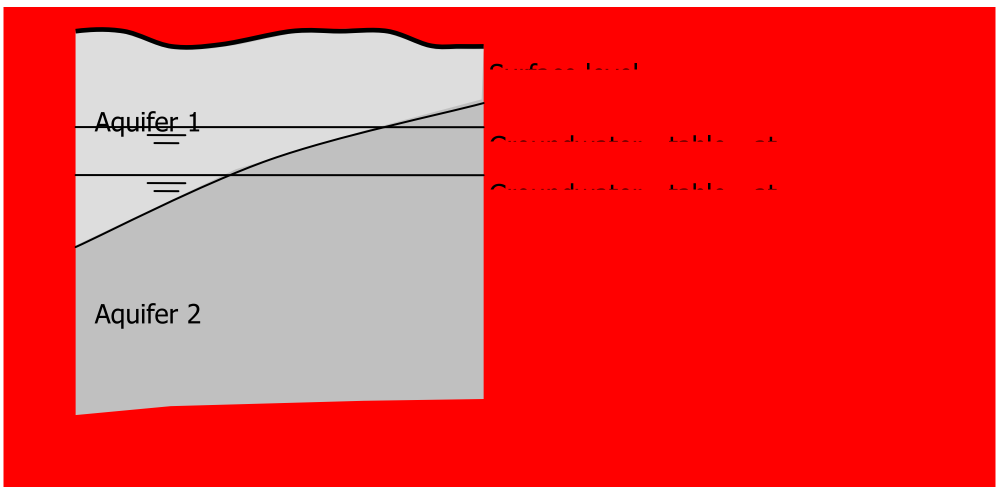


Figure 8-1 Schematic diagram showing methodology of processing depletion maps

The groundwater depletion (D) in any aquifer can be estimated by the following relation:

D = difference in groundwater table * effective porosity

The value applied for effective porosity (or specific yield) depends on the type of aquifer. If the depleted volume is to be calculated for an area where the groundwater table is located in more than one aquifer, then the area of each aquifer should be taken into account.

Groundwater depletion is calculated for the change in the groundwater table. Groundwater depletion applies to unconfined conditions only. Calculation was started with the alluvium aquifer. Calculation was repeated for the aquifer below the alluvium in areas where the alluvium aquifer has dried. The sequence for calculating depletion is:

1- For alluvium aquifer depletion:

- Determine groundwater contours within the extent of the alluvium aquifer for two periods.
- Check elevation of the contours relative to elevation of the bottom of the alluvium aquifer.
- Determine the dry area (small alluvium aquifer areas are neglected).
- Determine groundwater depletion where the alluvium area is not dry.

2- For volcanic aquifer depletion:

- Check where volcanic aquifer is unconfined; this can also be below the alluvium where it is dry.
- Determine contours for unconfined part of this aquifer.
- Determine groundwater depletion.
- Check where volcanic aquifer is dry.

3- For Tawilah sandstone aquifer depletion:

- Check where sandstone aquifer is unconfined; this can also be below the alluvium or volcanic aquifer where it is dry.
- Determine contours for unconfined part of this aquifer.
- Determine groundwater depletion.

Remark: the area of the Tawilah sandstone aquifer not covered by alluvium or volcanics will differ from what is shown above; the aquifer extent of the volcanics will be corrected based on results of the geological fieldwork. The total depletion of groundwater in the Sana’a Basin will be equal to the sum of depletion of the unconfined parts of the alluvium, volcanics and sandstone aquifers. The depletion in the limestone is unknown due to a lack of groundwater level observations.

Total depletion of groundwater in the Sana’a Basin will be equal to the sum of depletion of the unconfined parts of the alluvium, volcanics and sandstone. Depletion in the limestone is unknown due to a lack of groundwater level observations, as it is beyond the scope of this study.

8.3 Groundwater depletion maps of the unconfined alluvium aquifer

The alluvium aquifer is considered the most depleted aquifer in Sana’a Basin. This may be attributed to the low value of recharge rate from rainfall and lateral subsurface flow from adjacent aquifers, as well as the high abstraction rate from the large number of hand-dug wells penetrating this aquifer. The number of wells penetrating this aquifer was 206 during the seventies (Italconsult, 1973), while it reached 6,725 dug wells and 305 deep wells by 2001 (WEC 2001). Initially, the water level records were checked against the bottom level of the alluvium aquifer to delineate the dried areas of 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 (see chapter 6). These areas were defined in the base map to blank out from the total area of the aquifer before construction of depletion maps. The dried areas in the alluvium aquifer reached 80.7 km^2 since pre-development until now (1973-2007). The specific yield value of 0.02 was used in calculating the quantity of groundwater depletion (SAWAS model, 1995). Based on the six water table maps developed for the alluvium aquifer during the years 1973, 1983, 1993, 2001, Feb. 2007 and Sep. 2007, four depletion maps were constructed to shed light on the depletion phenomenon in the alluvium aquifer in Sana’a Basin (Figures 8-3, 8-5, 8-7 and 8-9). The maps indicate the following:

From 1973, pre-development time, until 1985, it is noted that the depleted area covers the eastern wadis, particularly in the southern part (Figure 8-2). The total depleted area reached 367 km^2 (40% of the total area of the alluvium aquifer). During this interval, the greatest groundwater level decline reached 2.5 m. The deepest increment of decline, from 1.5 m to 2.5 m depth, covered an area of about 5.8 km^2 and represented 2% of the depleted area. The shallowest increment of decline, from 0 m to 0.5 m depth, covered an area of 332 km^2 in the southern part of the alluvium aquifer, representing 90% of the depleted area. The estimated depleted groundwater during this time interval reached 231.55 million cubic meters (Table 8-3 and Figure 8-3). Figure 8-2 shows the linear relationship between the depleted surface area and the groundwater depletion quantity in million cubic meters. The linear relationship may reflect the effect of aquifer homogeneity more than spatial distribution in operational wells. Assuming that the depleted area equals zero, the relationship indicates that groundwater abstraction was around 10 million cubic meters.

During the years 1985-2007, depletion of the alluvium aquifer sharply increased and covered an area of 371.5 km^2 (41% of the aquifer surface area), with an increase of about 5 km^2. During this interval, the greatest groundwater level decline reached 3 m. The deepest increment of decline, from 2 m to 3 m depth, covered an area of 12.2 km^2, representing 3% of the depleted area. The shallowest increment of decline, from 0 m to 1 m, covered an area of 320.8 km^2 in the southern part of the alluvium aquifer, representing 88% of the depleted area. The estimated quantity of depleted groundwater during this time interval reached 371.5 million cubic meters (Table 8-3 and Figure 8-4). The depletion shown in the spatial distribution map (Figure 8-5) may be attributed to the low rate of recharge from the western and eastern wadis, as well as the rapid increase in number of drilled wells. Figure 8-4 shows the linear relationship between the depleted surface area and the quantity of groundwater depletion in million cubic meters (M m^3). The linear relationship may reflect the complete correlation between the quantity of groundwater depletion and the area of depletion. This may be attributed to the constant increase in operational wells during this time period.

Table 8-3 Depleted area and groundwater depletion volume of the alluvium aquifer during 1973-1985

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1973-1985	Red	5.8	-1.5	-2.5	1	14.5
	Cyan	8.3	-1	-1.5	0.5	12.45
	Yellow	21.1	-0.5	-1	0.5	21.1
	Blue	332	0.00	-0.5	0.5	183.5
Total water storage in million m^3						231.55

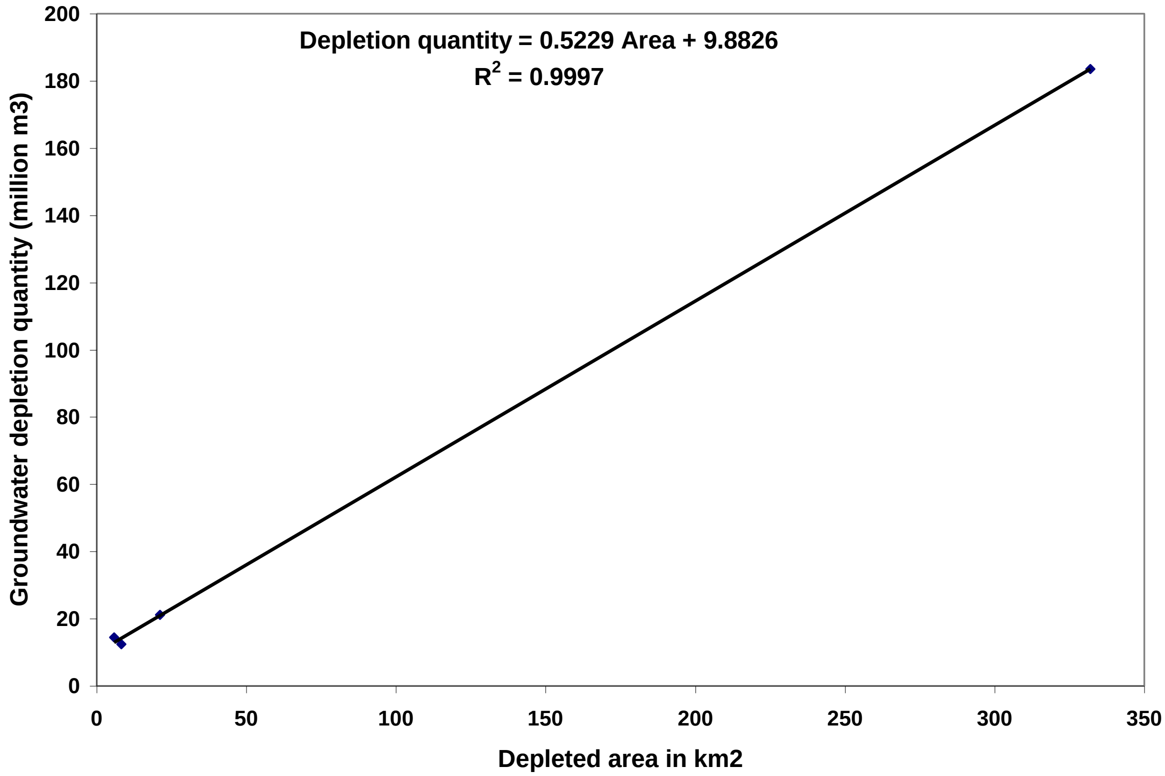


Figure 8-2 Relationship between depleted area and groundwater depletion quantity in the alluvium aquifer in Sana'a Basin during the interval 1973-1985

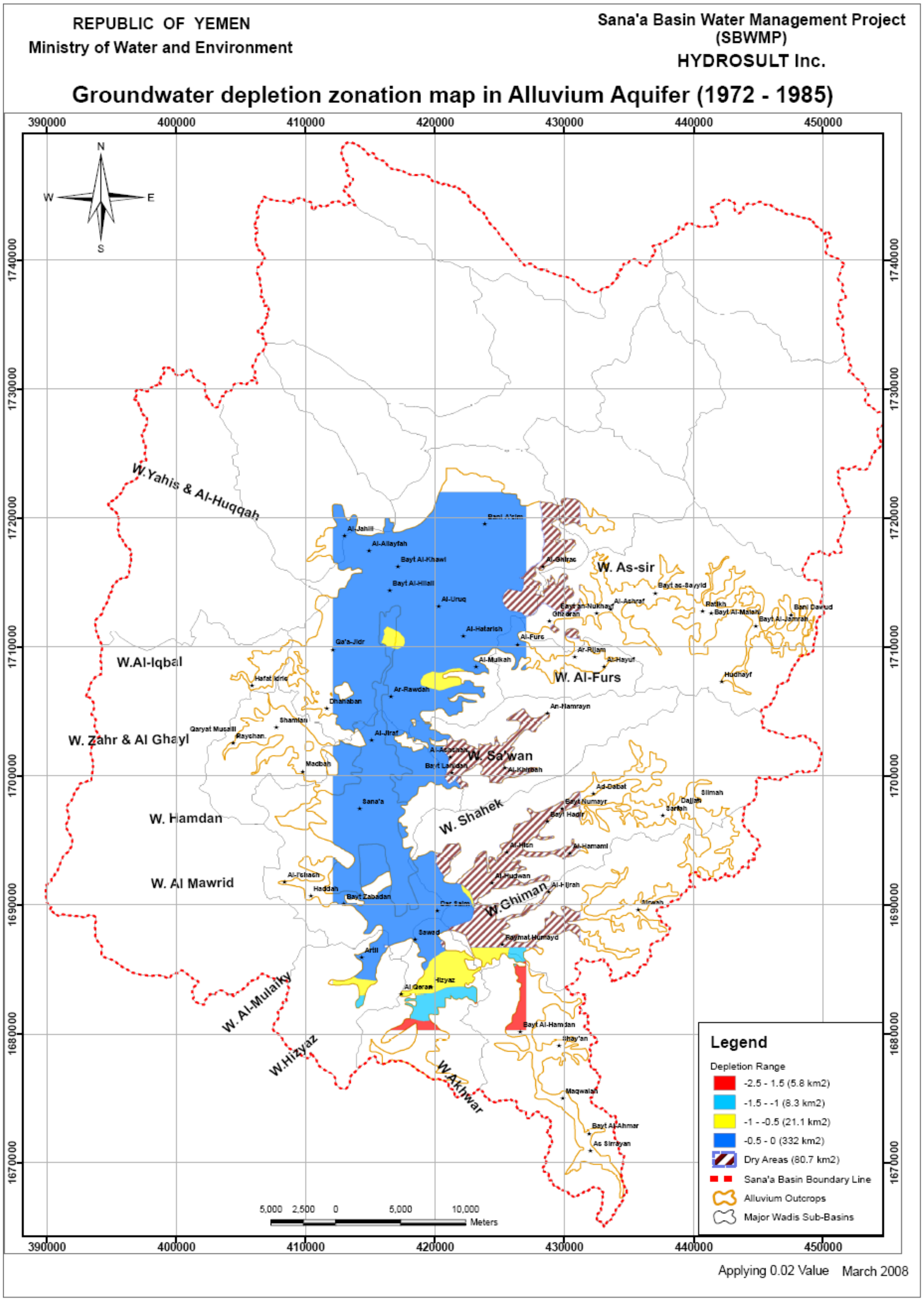


Figure 8-3 Groundwater depletion map in the alluvium aquifer during 1973-1985

Table 8-4 Depleted area and groundwater depletion volume of the alluvium aquifer during 1985-2007

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1985-2007	Red	12.2	-2	-3	1	12.2
	Yellow	38.5	-1	-2	1	38.5
	Blue	320.8	0.00	-1	1	320.8
Total water storage in million m^3						371.5

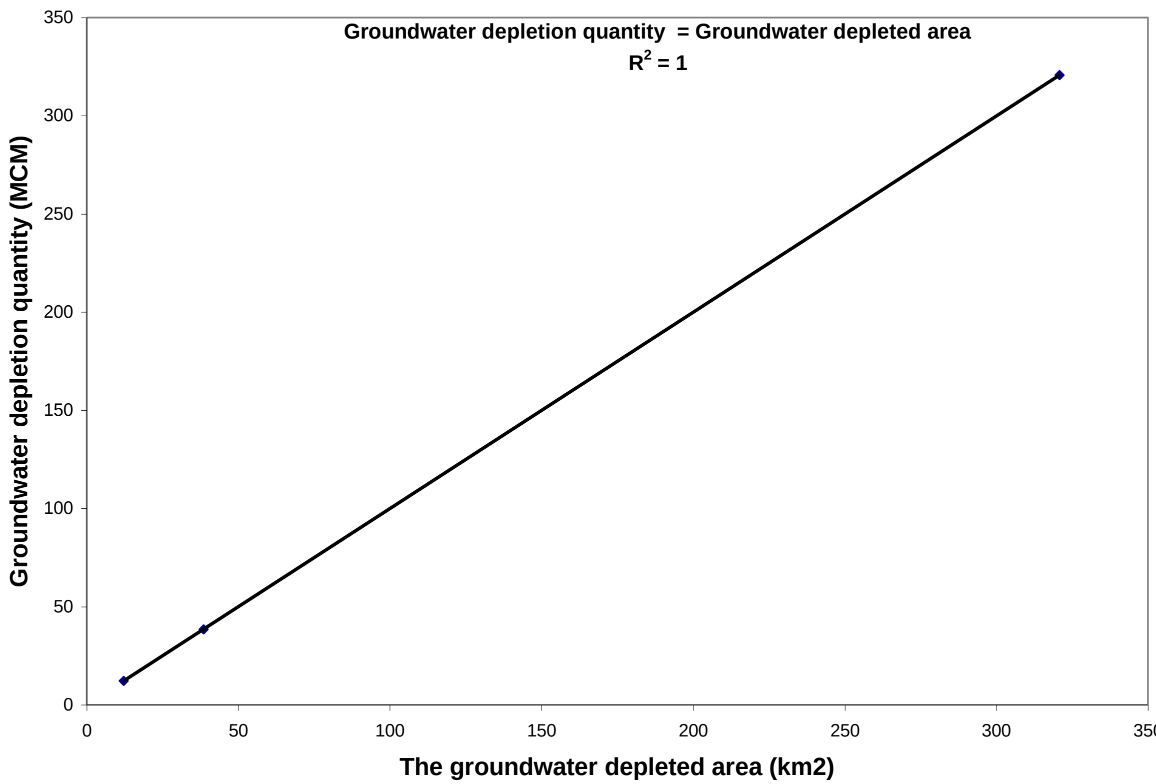


Figure 8-4 Relationship between depleted area and groundwater depletion quantity in the alluvium aquifer in Sana'a Basin during the interval 1985-2007

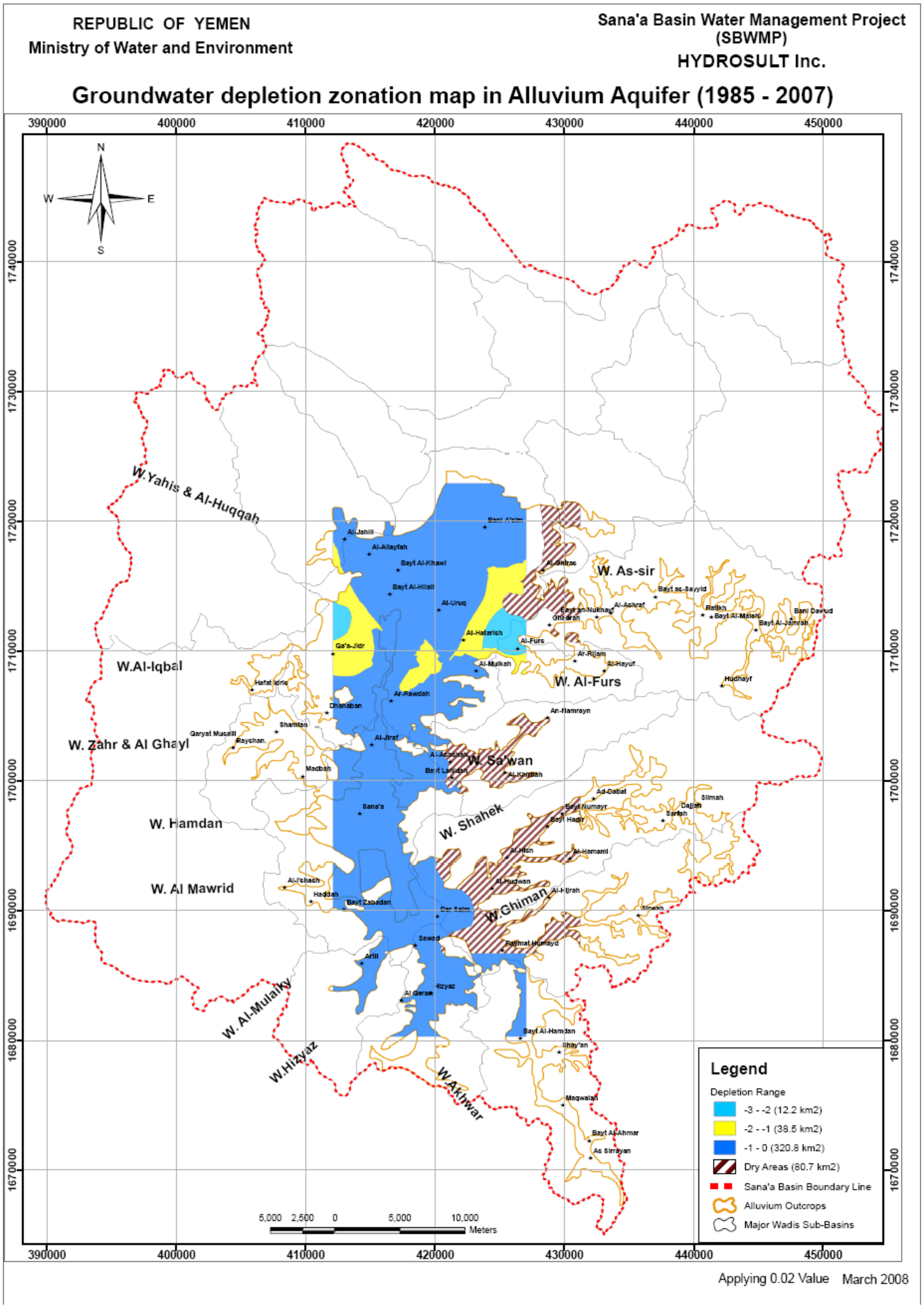


Figure 8-5 Groundwater depletion map in the alluvium aquifer during 1985-2007

During the interval 1993-2007, the depleted area increased. The alluvium aquifer depletion problem was critical as indicated by the increasing blue colored areas characterized by groundwater decline of 0.5 m in the northern part of the aquifer, particularly at Bayt Al Khawi (Figure 8-7). This explains the great number of dry hand-dug wells in this aquifer, stated in the well inventory of WEC 2001. The total depleted area covered 487.5 km^2, which represents 52% of the aquifer surface area. During this interval, the greatest groundwater level decline reached 2.8 m. The deepest increment of decline, from 1.5 m to 2.8 m depth, covered an area of about 15 km^2 and represented 4% of the depleted area. The shallowest increment of decline, from 0 m to 0.5 m in depth, covered an area of 374.5 km^2 in the southern part of the alluvium aquifer and represented 92% of the depleted area. The estimated depleted groundwater quantity in this time interval reached 240.2 million cubic meters (Table 8-5 and Figure 8-7).

Table 8-5 Depleted area and groundwater depletion volume of the alluvium aquifer during 1993-2007

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1993-2007	Red	15	-1.5	-2.8	0.3	4.5
	Cyan	46.4	-1	-1.5	0.5	23.2
	Yellow	51.5	-0.5	-1	0.5	25.75
	Blue	374.5	0.00	-0.5	0.5	186.75
Total water storage in million m^3						240.2

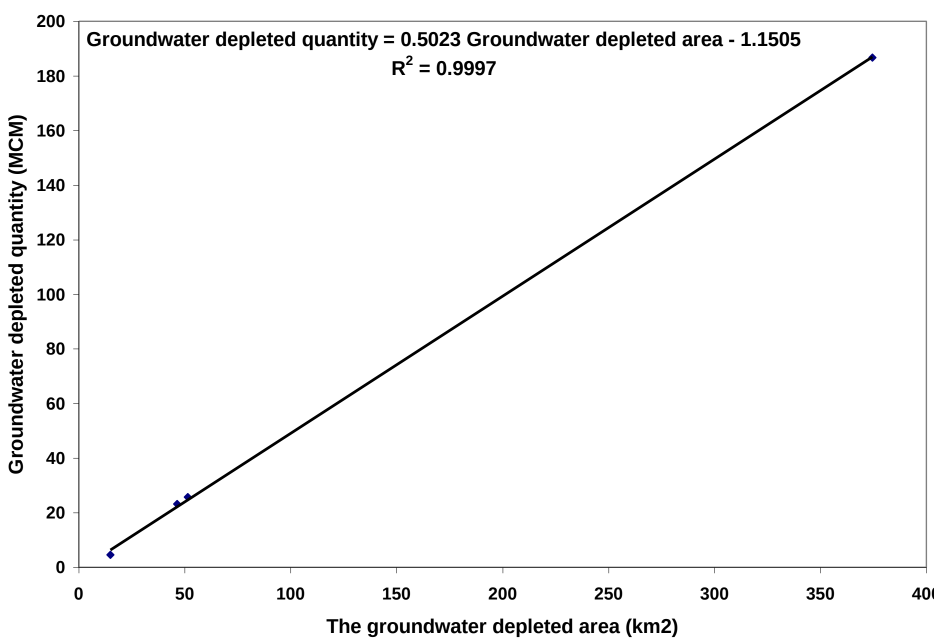


Figure 8-6 Relationship between depleted area and groundwater depletion quantity in the alluvium aquifer in Sana'a Basin during the interval 1993-2007

Notably, the relationship between quantity of groundwater depleted in M m^3 and the depleted area shows that, during this interval, the dried areas appeared. This means that the alluvium aquifer has been greatly depleted during the last decade.

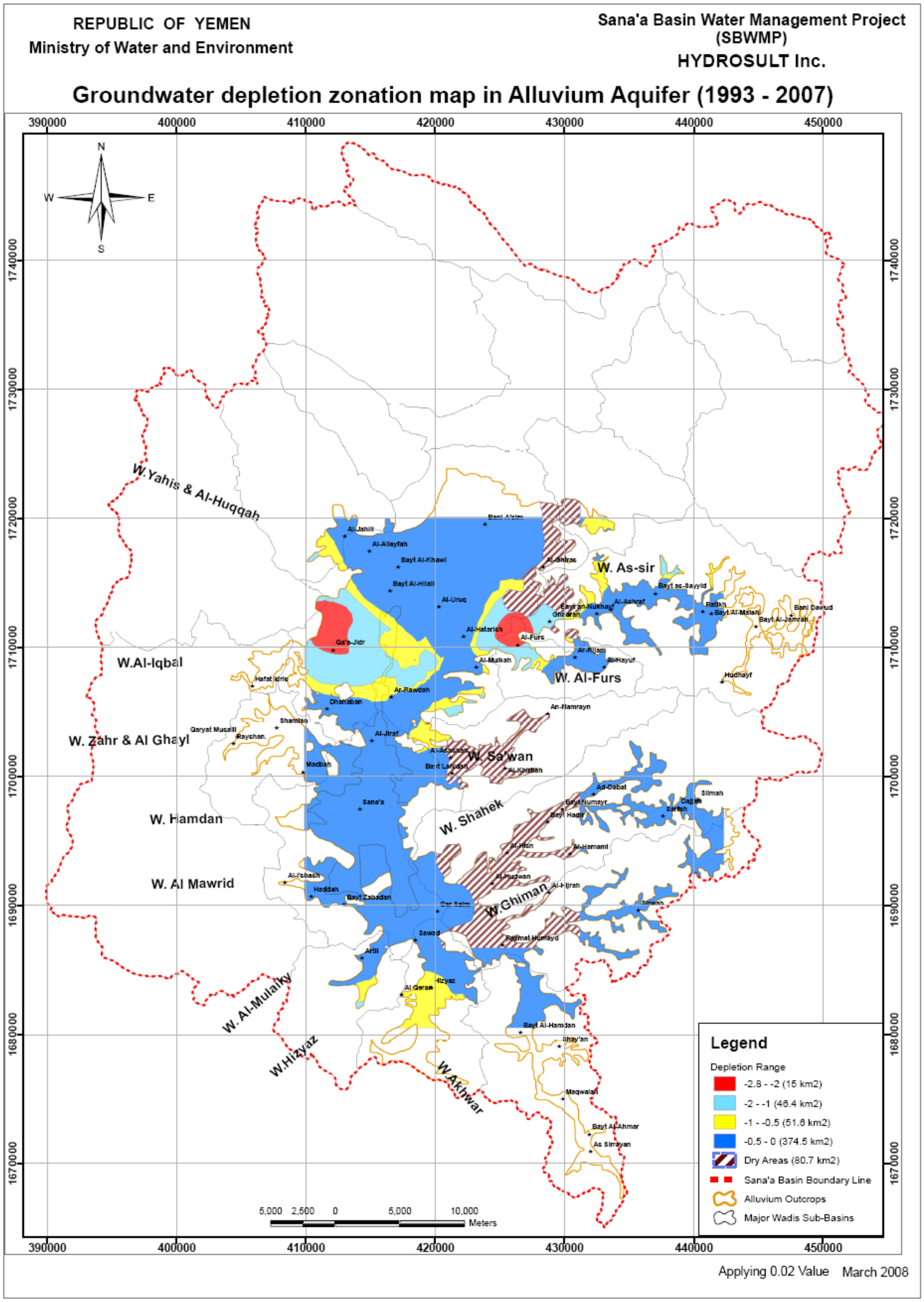


Figure 8-7 Groundwater depletion map in the alluvium aquifer during 1993-2007

From pre-development time until now (the period of 1972-2007, Figure 8-9), the depleted area from the alluvium aquifer reached 471.8 km^2, which represents 52% of the total surface area of the alluvium aquifer. Moreover, the yellow-colored areas (with groundwater level decline from 1 to 2 m) appeared in the central part of the northern area of the aquifer, while the critical red-colored areas were only present in southern parts of the aquifer. This may be attributed to the low rate of recharge in the southern aquifer areas, as well as over-pumping in the northern part.

During this interval, the greatest groundwater level decline reached 3.4 m. The deepest increment of decline, from 3 m to 3.4 m in depth, covered an area of about 2.1 km^2, representing 1% of the depleted area. The shallowest increment of decline, from 0 m to 1 m, covered an area of 334 km^2 in the southern part of the alluvium aquifer, representing 70% of the depleted area. The estimated depleted groundwater quantity in this time interval reached 240.2 million cubic meters (Table 8-6 and Figure 8-8).

Table 8-6 Depleted area and groundwater depletion volume of the alluvium aquifer during 1973-2007

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1973-2007	Red	2.1	-3	-3.4	0.4	0.84
	Cyan	35.7	-2	-3	1	35.7
	Yellow	100	-1	-2	1	100
	Blue	334	0.00	-1	1	334
Total water storage in million m^3						470.54

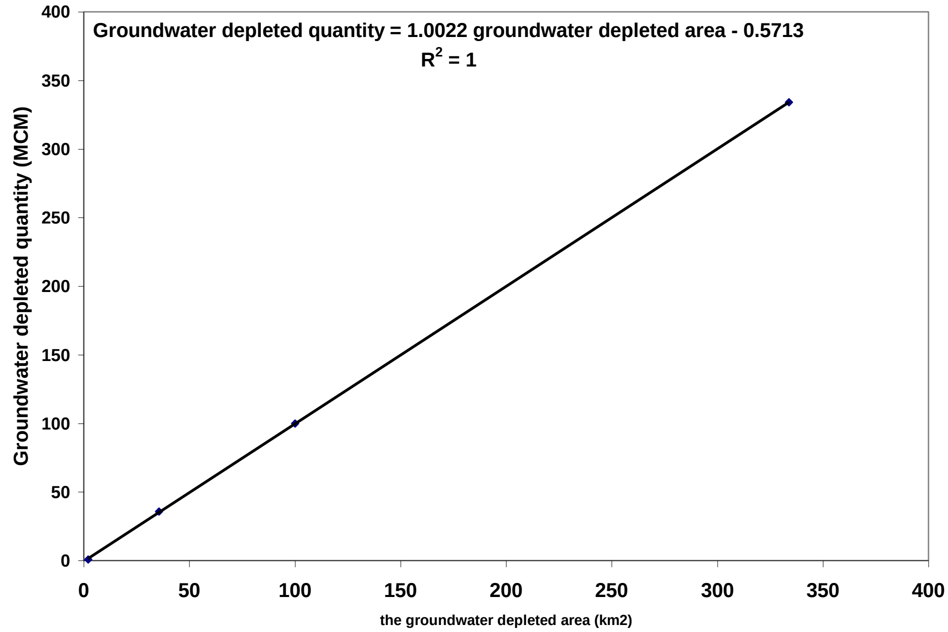


Figure 8-8 Relationship between depleted area and the groundwater depletion quantity in the alluvium aquifer in Sana'a Basin during the interval 1973-2007

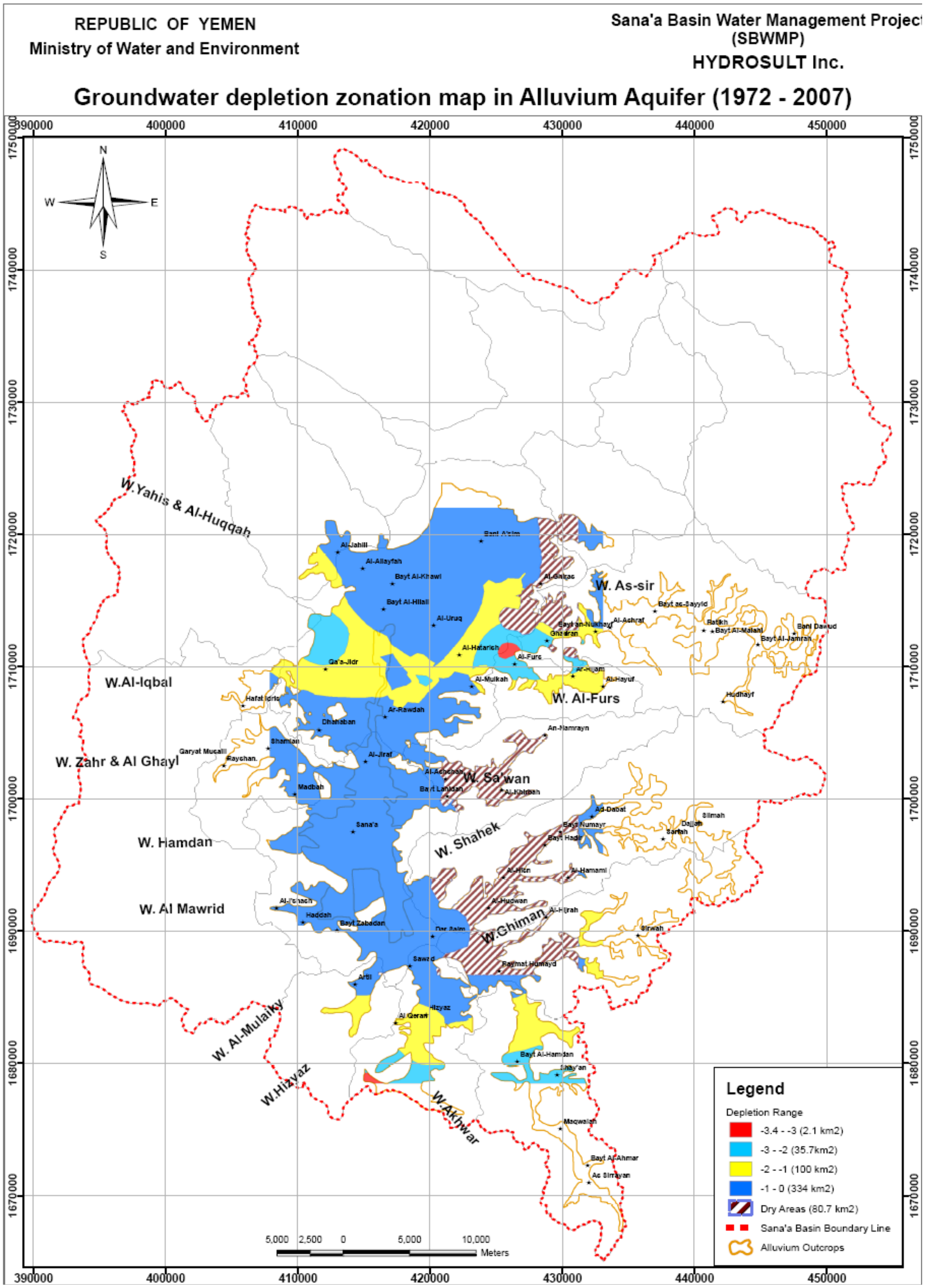


Figure 8-9 Groundwater depletion map of the alluvium aquifer during 1973-2007

In general, during the interval 1993-2007 (Figure 8-7), due to the concentration of wells between Bani A'sim and Al-Ghiras with heavy uncontrolled pumping, the red-colored depleted areas with groundwater decline of more than 3 m appeared in these locations, while the blue-colored areas, with groundwater decline less than 1 m, decreased to one quarter of their extent during the previous time period. During the interval 2001-2007, the red-colored depleted areas with groundwater decline more than 3 m moved towards the south in the outlet of Wadi As-sir and Wadi Al Furs while the blue-colored areas with groundwater decline less than 5 m spread in the central part of the northern area of the aquifer and their extent tripled. Also, the critical situation of Bani A'sim was abated. The total depleted area in this time interval reached 28 km^2 (3% of the total aquifer area).

Notably, the relationship between the quantity of groundwater depletion in M m^3 and the depleted area indicates that, during this interval, the dried areas decreased, since the absolute value of the relationship decreased from 1.5 to 5 for the interval 1973-2007 with respect to the interval 1993-2007. This indicates that the recent control on drilling wells in the alluvium aquifer abated the critical situation. In addition, the dried area capacity of the alluvium aquifer (80.7 km^2) can be artificially recharged by 240 M m^3 of reused waste water. The side effect of this option is the increase in the quantity of groundwater depletion. A scenario for re-converting the dried areas into wet areas was proposed and the resulting depletion was predicted. The results were tabulated in Table 8-7. Figure 8-10 indicates that the injection of groundwater into the alluvium aquifer negatively affects the groundwater quantity. So, artificial recharge of the alluvium aquifer by reused waste water may be not suitable.

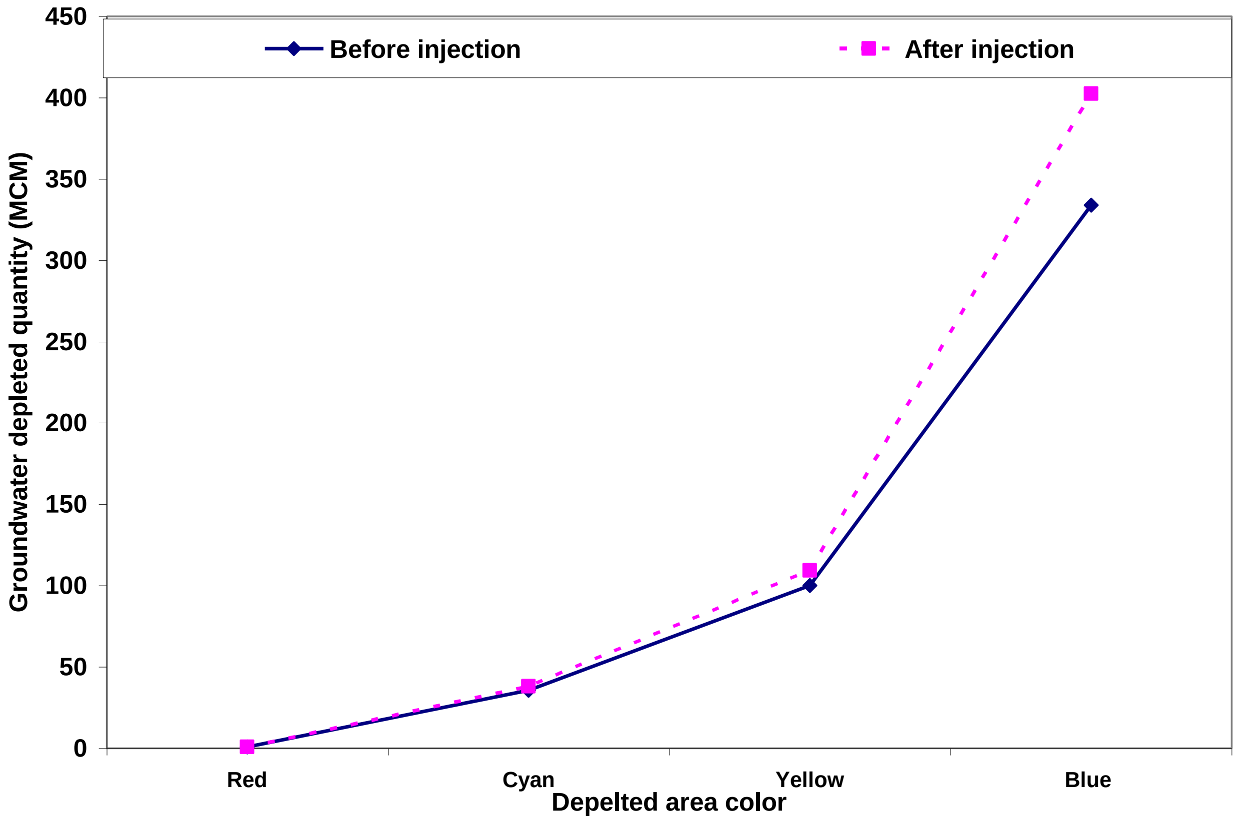


Figure 8-10 Graph showing the effect of artificial recharge on the depletion problem in the alluvium aquifer in Sana'a Basin

Table 8-7 Depleted area and groundwater depletion volume of the alluvium aquifer without dried areas

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1972-2007	Red	2.06	-3.00	-3.37	0.30	0.75
	Cyan	38.16	-2.00	-3.00	1.00	38.16
	Yellow	109.37	-1.00	-2.00	1.00	109.37
	Blue	402.55	0.00	-1.00	1.00	402.54
Total water depletion in million m3						550.83

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1993-2007	Red	15.05	-2.00	-2.80	0.80	11.97
	Cyan	53.00	-1.00	-2.00	1.00	53.00
	Yellow	58.72	-0.50	-1.00	0.50	29.36
	Blue	437.64	0.00	-0.50	0.50	218.82
Total water depletion in million m^3						313.15

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
2001-2007	Red	0.83	-3.00	-3.20	0.20	0.17
	Cyan	22.50	-2.00	-3.00	1.00	22.50
	Yellow	91.95	-1.00	-2.00	1.00	91.95
	Blue	364.02	0.00	-1.00	1.00	364.02
Total water depletion in million m^3						478.64

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1993-2001	Red	24.90	-7.00	-9.94	2.94	73.09
	Cyan	27.54	-5.00	-7.00	2.00	55.09
	Yellow	71.94	-2.00	-5.00	3.00	215.83
	Blue	137.39	0.00	-2.00	2.00	274.79
Total water depletion in million m^3						618.80

8.4 Groundwater depletion maps of the unconfined volcanic aquifer

The volcanic aquifer is considered as the least depleted aquifer in Sana'a Basin. This may be attributed to the low abstraction rate from the operational hand dug wells (3,510), dug/bore wells (126) and drilled wells (1,951). There are a total of 5,587 wells which penetrate this aquifer (WEC 2001). Initially, the dried areas of the alluvium aquifer (80.7 km^2) are considered as part of the underlying volcanic aquifer in estimating the quantity of groundwater depletion from the volcanic aquifer. The area of the volcanic aquifer corresponding to the rest of the alluvium aquifer area was masked to prevent error resulting from duplication in estimation of the volcanic aquifer depletion areas. An effective porosity of 0.01 was applied for the volcanic aquifer (SAWAS 1995). Based on the three watertable maps developed for the volcanic aquifer during 1985, 1995 and 2007, depletion maps were constructed to shed light on the depletion phenomenon in the volcanic aquifer in Sana'a Basin during the intervals 1985-2007 and 1985-1995 (Figure 8-11& 8-14). The maps indicate the following.

From 1973, pre-development time, until1983, there is no data to construct the depletion map of the volcanic aquifer. Available groundwater levels enable the construction of the groundwater depletion map of the volcanic aquifer during the interval 1985-2007 (Figure 8-11). It is noted from the map that the depleted area covers the western side only due to the lack of data during this interval. The total depleted area reached 1,267.8 km^2 (38% of the total area of volcanic aquifer). During this time interval, the greatest groundwater level decline reached 51.2 m. The deepest increment of decline, from 35 m to 51.2 m in depth, covered an area of about 78 km^2 and represented 6% of the depleted area. The shallowest increment of decline, from 0 m to 15 m, covered an area of 779 km^2 in the southern part of the volcanic aquifer and represented 61% of the total depleted area. The estimated depleted groundwater quantity in this interval reached 17,056.6 million cubic meters (Table 8-8 and Figure 8-12). Figure 8-12 shows the linear relationship between the depleted surface area and the groundwater depletion quantity in million cubic meters. The linear relationship indicates a strong correlation between the two variables. However, the negative sign of the absolute term means that the groundwater depletion before the year 1985 was 541 M m^3.

Table 8-8 Depleted area and groundwater depletion volume of the volcanic aquifer during 1985-2007

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1985-2007	Red	78	-35	-51.2	16.2	1263.6
	Cyan	81.2	-25	-35	10	812
	Yellow	329.6	-15	-25	10	3296
	Blue	779	0.00	-15	15	11685
Total water storage in million m^3						17056.6

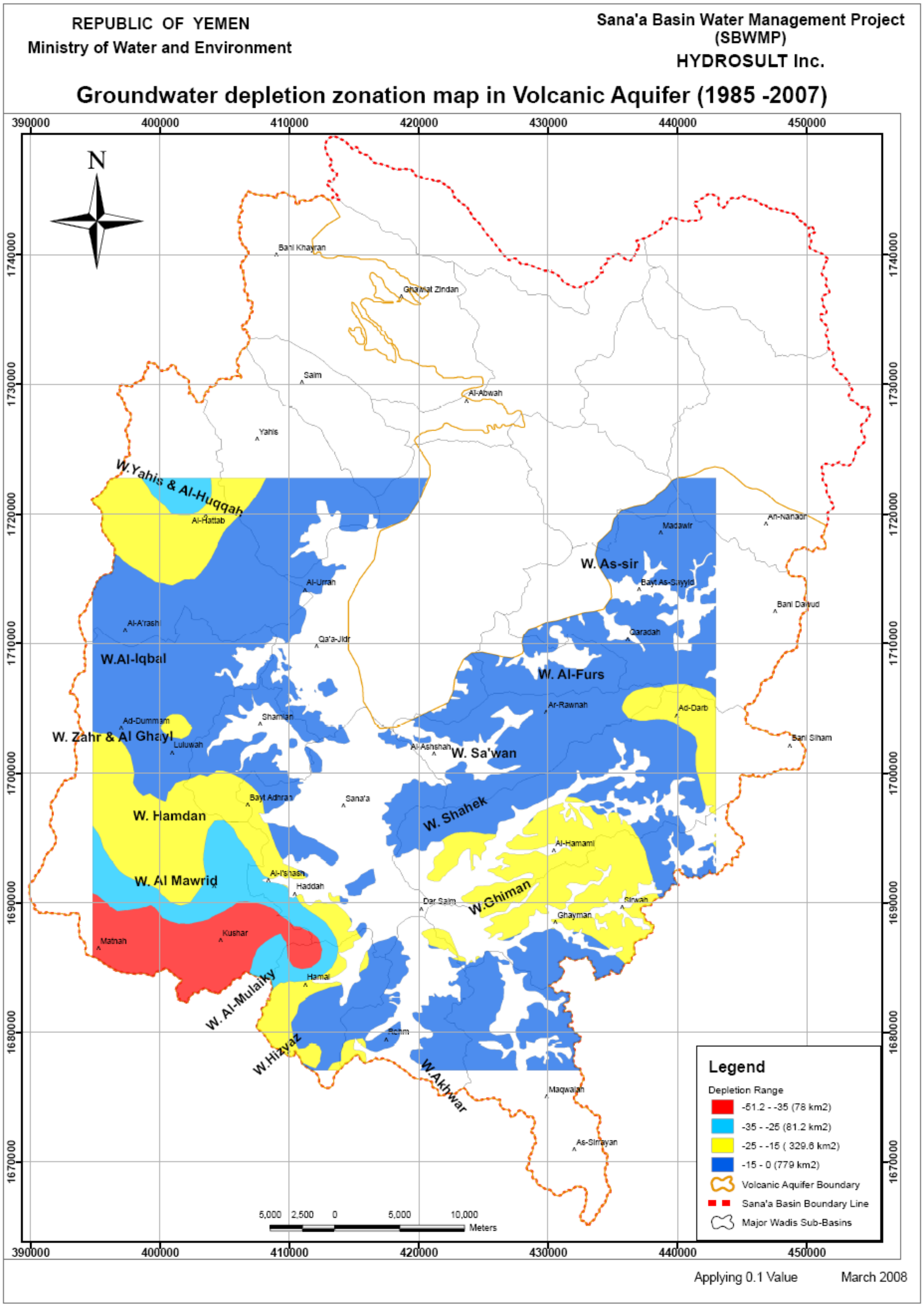


Figure 8-11 Groundwater depletion map in the volcanic aquifer during 1985-2007

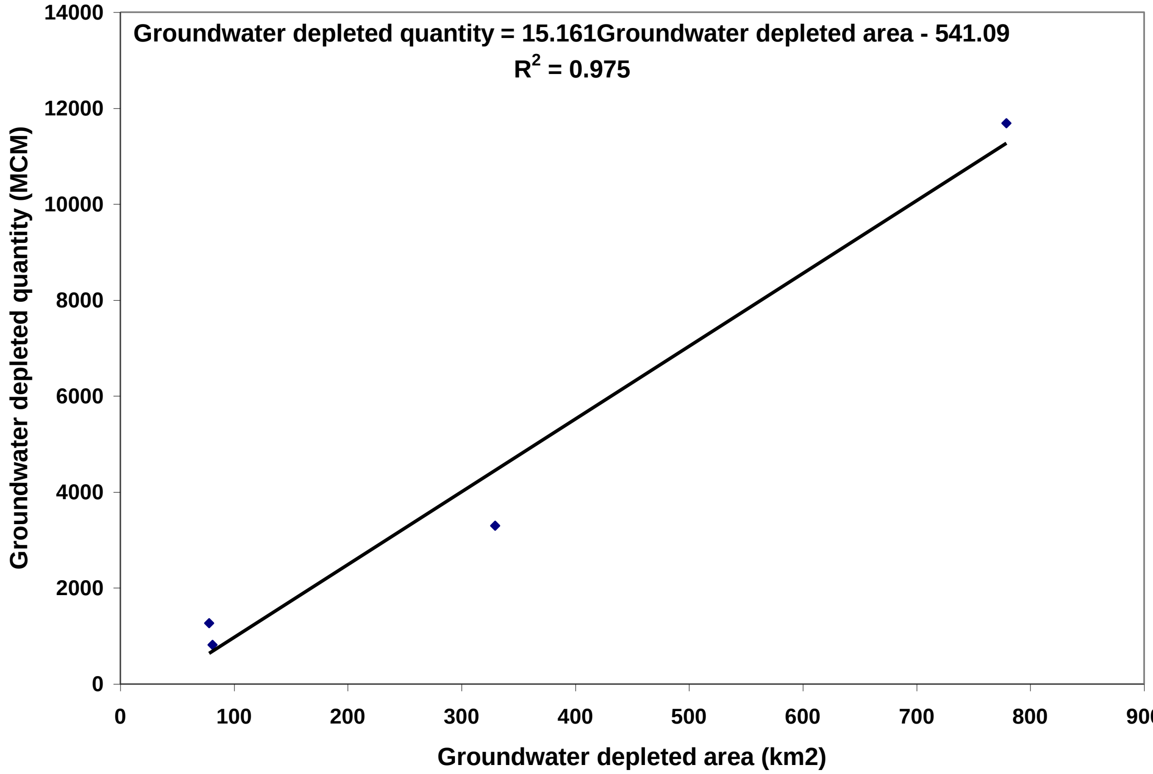


Figure 8-12 Graph showing relationship between depleted areas and groundwater depleted quantity in the volcanic aquifer in Sana'a Basin (1985-2007)

During the interval 1985-1995, the depletion map of the volcanic aquifer (Figure 8-14) shows that the total depleted area reached 822.4 km^2 (32% of the total area of the volcanic aquifer). During this interval, the greatest groundwater level decline reached 50 m. The deepest increment of decline, from 35 m to 50 m depth, covered an area of about 35.5 km^2 , representing 4% of the depleted area. The shallowest increment of decline, from 0 m to 15 m depth, covered an area of 601.3 km^2 in the southern part of the volcanic aquifer, representing 73% of the total depleted area. The estimated depleted groundwater quantity during this time interval reached 11,408 million cubic meters (Table 8-9 and Figure 8-12). Figure 8-12 shows the linear relationship between the depleted surface area and the quantity of groundwater depletion in million cubic meters. The linear relationship indicates a strong correlation between the two variables. However, the positive sign of the absolute term means that the groundwater depletion increased with time. Assuming that the depleted area equals zero, the groundwater depletion quantity reached 390 M m^3 before the year 1985.

Table 8-9 Depleted area and groundwater depletion volume of the volcanic aquifer during 1985-1995

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1985-1995	Red	35.5	-35	-50	15	532.5
	Cyan	77.3	-25	-35	10	773

	Yellow	108.3	-15	-25	10	1083
	Blue	601.3	0.00	-15	15	9019.5
Total water storage in million m^3						11408

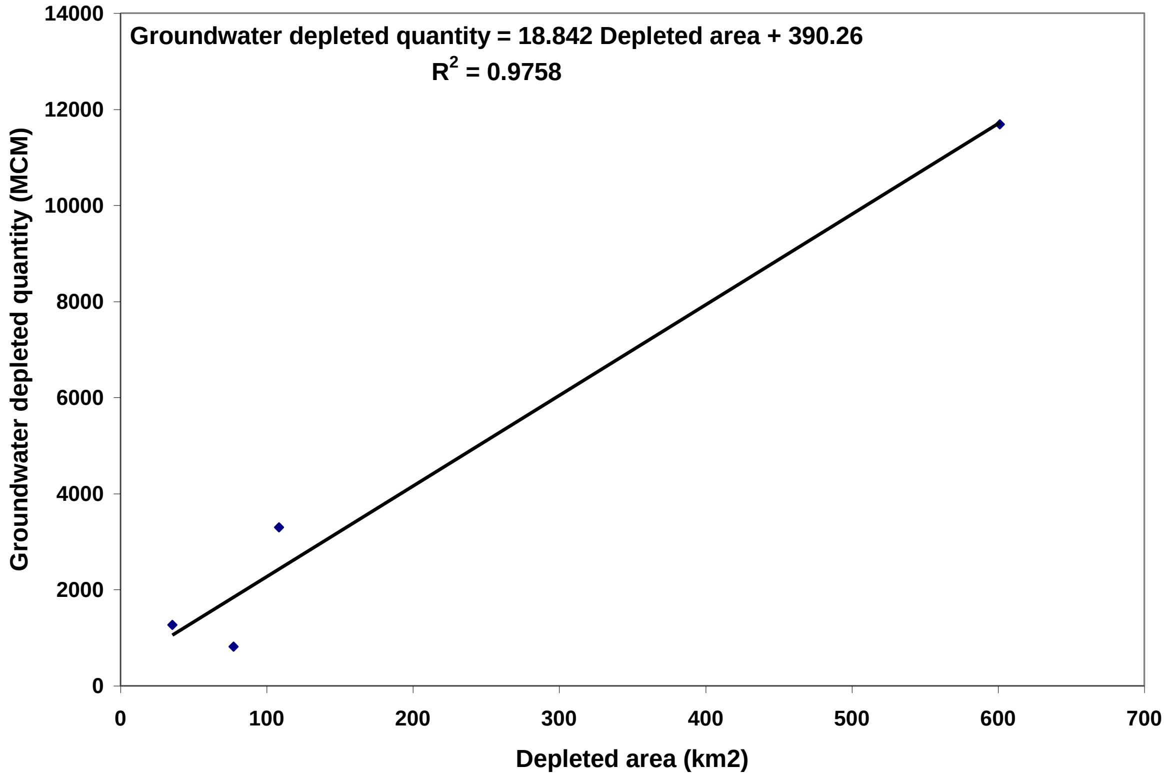


Figure 8-13 Relationship between depleted areas and groundwater depleted quantity in the volcanic aquifer in Sana'a Basin during the interval 1985-1993

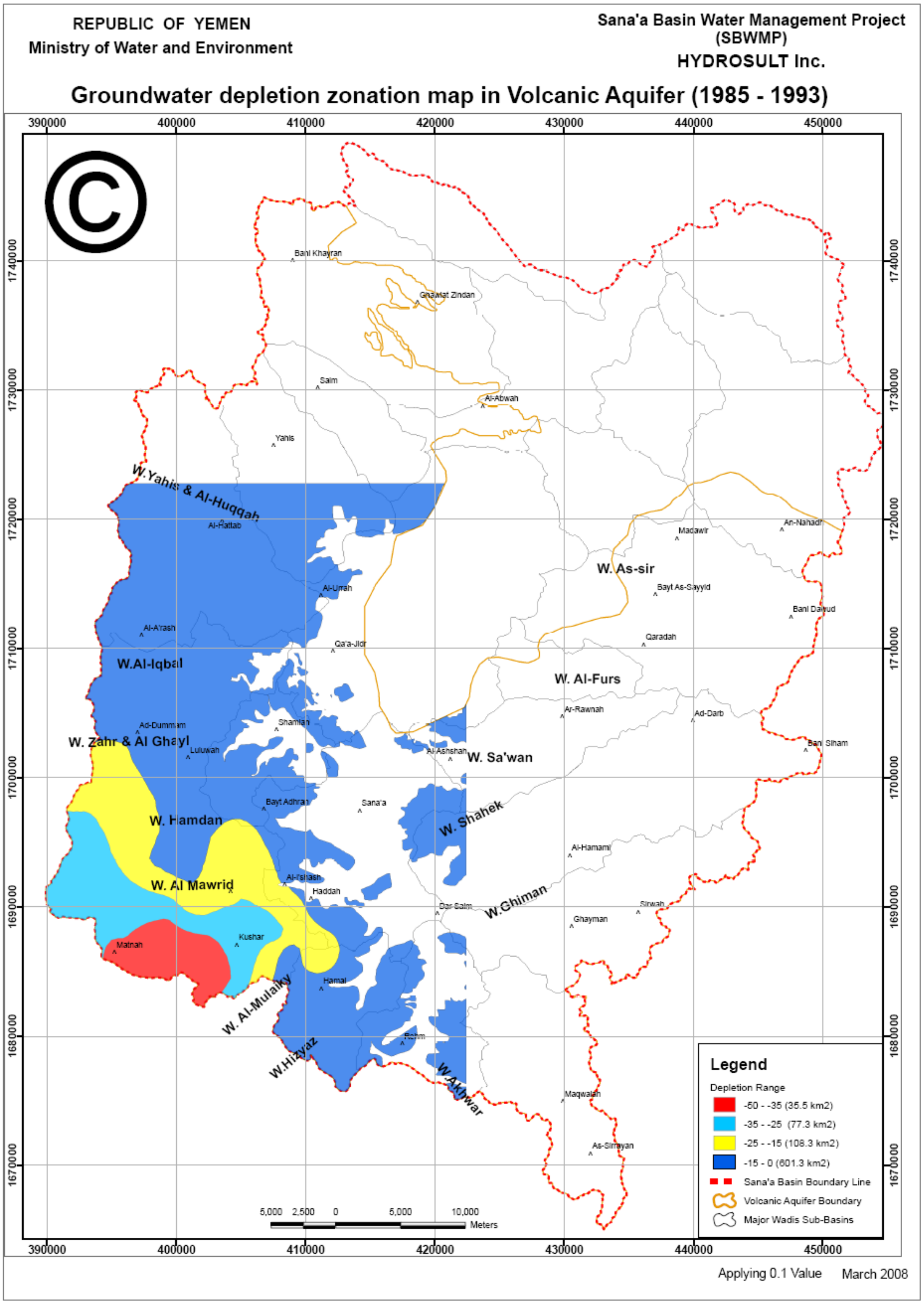


Figure 8-14 Groundwater depletion map of the volcanic aquifer during 1985-1993

8.5 Groundwater depletion maps of unconfined outcrops of the Tawilah sandstone aquifer

Due to lack of groundwater level data in the Tawilah sandstone aquifer as a result of scarcity of good observation wells and the fact that most wells penetrating this aquifer are productive, depletion mapping of unconfined outcrops was based essentially on the available data surveyed during the current project in the eastern outcrops of this aquifer. Also, the southern part of the Tawilah sandstone aquifer has no hydrogeological data since it is buried under thick cover of the Tertiary volcanic group. Due to lack of records, a trial was made to check the depletion mapping in certain periods before and after the masking process mentioned in the previous paragraph (Figure 8-16 & 8-17).

The estimated depletion areas in the case of an unmasked map (Figure 8-16) were 137.4 km^2 for depletion depth of 2 m, 71.9 km^2 for depletion depth between 2 and 5 m, 27.5 km^2 for depletion depth from 5 to 7 m and 24.9 km^2 for depletion depth between 7 and 9.9 m depths (areas with blue, yellow, cyan and red colors respectively), while, after masking the aquifer outcrops, the areas of depletion became 24.1 km^2 for depletion depth of 2 m, 9.7 km^2 for depletion depth of 2 m to 5 m and 0.1 km^2 for depletion depth from 5 m to 7 m respectively (Figure 8-17). The depletion depth between 7 m and 9.9 m has disappeared from the masked map. From the above mentioned trial, it was noted that the masking process is essential for obtaining an accurate estimation of groundwater depletion values.

Two depletion maps were plotted, using an average value of effective porosity of 0.07, based on processed data available covering the periods 1993-2001 and 1993-2007 (Figures 8-16 and 8-17). The maps indicate the following:xxx

During the interval 1993-2001 (Figure 8-17), depletion of the outcropping area of Tawilah sandstone is critical. The largest groundwater level decline reached 100 m which corresponds to a depletion depth of 7 m. This may be attributed to over-pumping in the northeast NWSA well fields and continuous drilling of wells. The total depleted areas of groundwater of Tawilah sandstone aquifer during the period 1993-2001 reached 34 km^2 (77.5 M m^3). The locally depleted areas, from 0 m to 2 m depth, cover 24.1 km^2, representing 71% of the total depleted area. The deepest increment of decline, from 5 m to 7 m depth (corresponding to 100 m decline in groundwater surface), represents 0.3% of the total depleted area (Table 8-10).

Table 8-10 Depleted area and groundwater depletion volume of the Tawilah sandstone aquifer during 1993-2001

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1993-2001	Red	--	--	--	--	--
	Cyan	0.1	-5	-7	2	0.2
	Yellow	9.7	-2	-5	3	29.1
	Blue	24.1	0.00	-2	2	48.2
Total water storage in million m^3						77.5

The regression line between groundwater depletion quantity and depleted area in the Tawilah sandstone aquifer during the interval 1993-2001 (Figure 8-18) exhibits a strong relationship between them. This may be attributed to the fracture density characteristic of this part of the aquifer (see lineaments density map in chapter 10). In addition, assuming a zero value of variable x (the depleted area) the result is 3.8 M m^3 as storage in this aquifer outcrop.

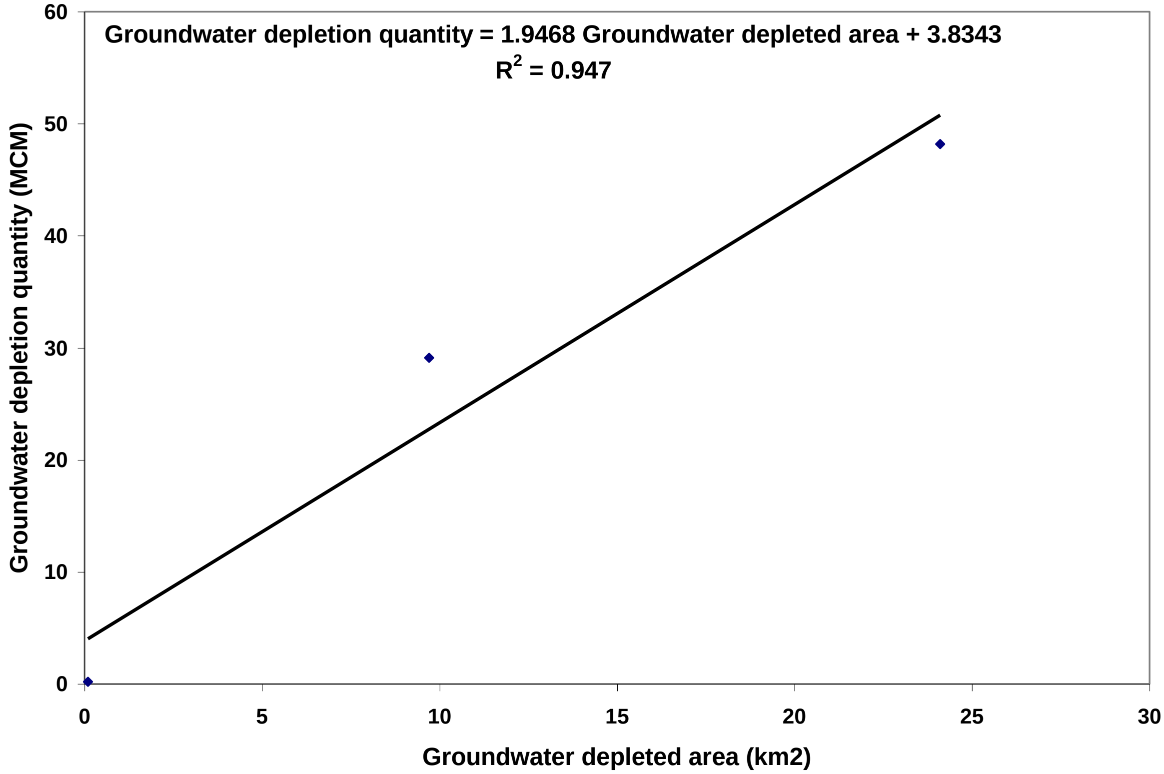


Figure 8-15 Relationship between depleted areas and groundwater depleted quantity in the Tawilah sandstone aquifer in Sana'a Basin during the interval 1993-2001

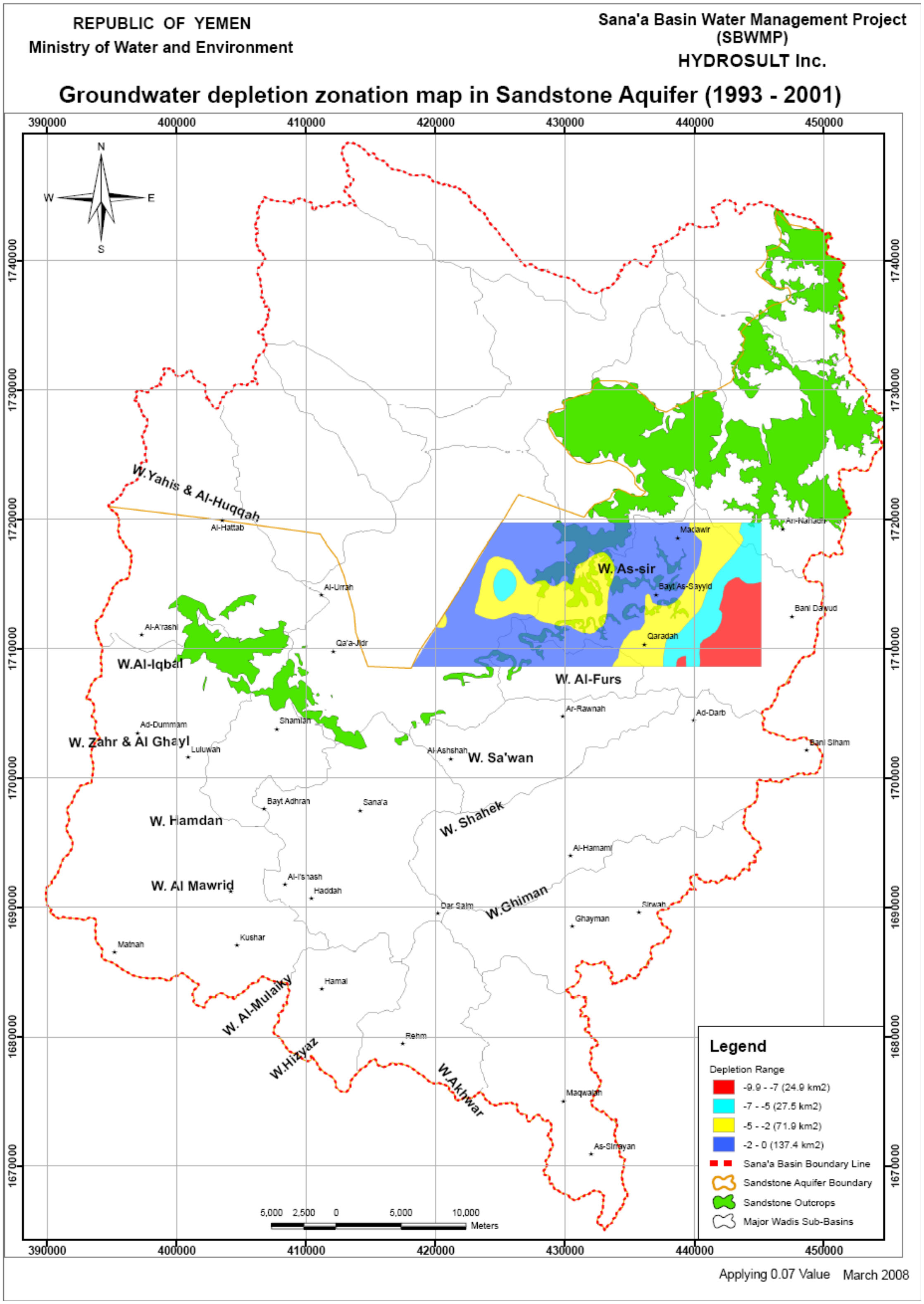


Figure 8-16 Non-masked groundwater depletion map of the Tawilah sandstone aquifer during 1993-2001

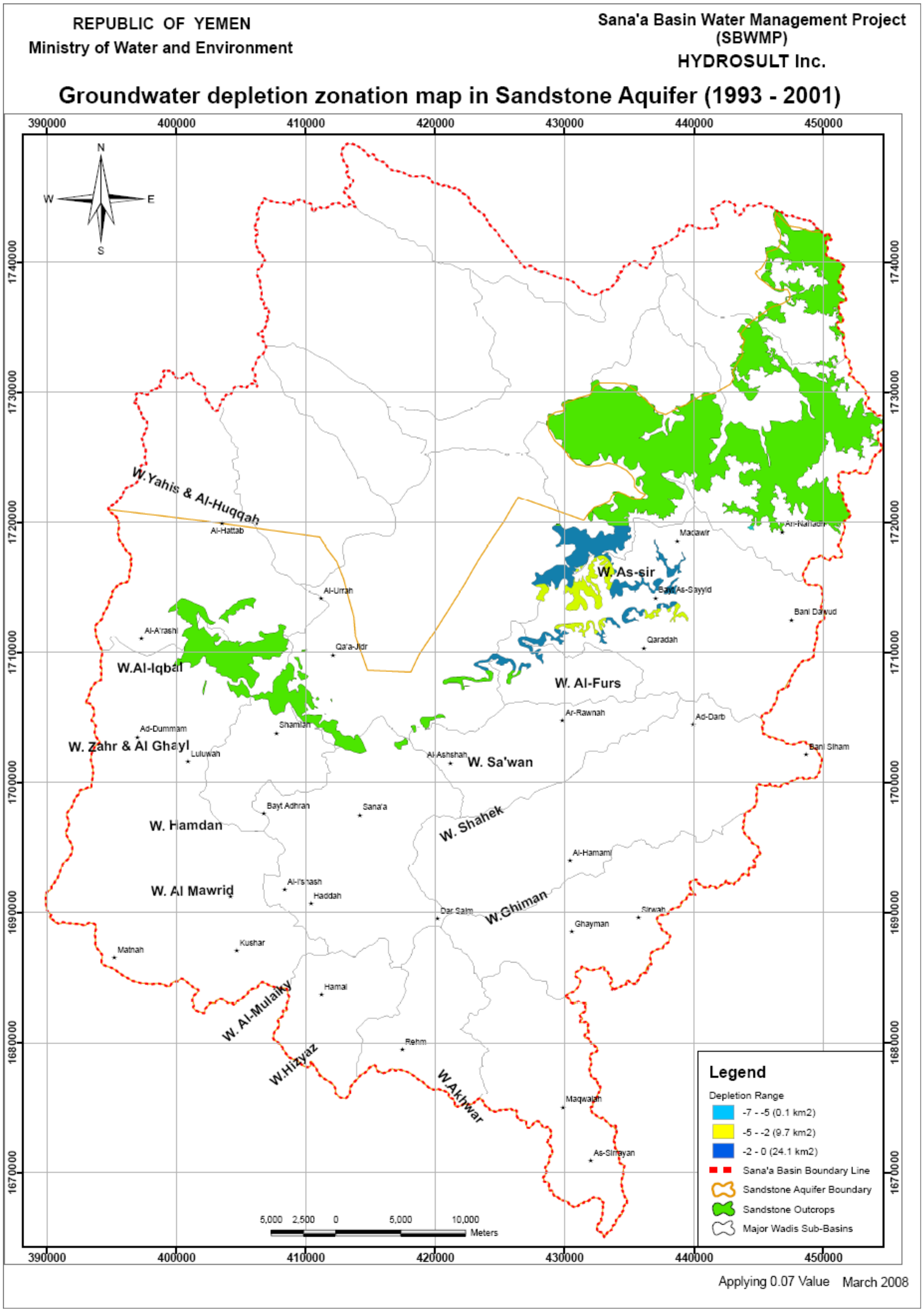


Figure 8-17 Masked groundwater depletion map of the Tawilah sandstone aquifer during 1993-2001

xxxFrom 1973, pre-development time, until 1993, there is no data available to construct the depletion map of the Tawilah sandstone aquifer. Available groundwater level data enable construction of the groundwater depletion map of the Tawilah sandstone aquifer during the interval 1993-2007 (Figure 8-19). It is noted from the figure that the depleted area covers the eastern side only due to lack of data for the western side during this interval. The total depleted area reached 34 km^2 (22% of the total area of the outcrops of the Tawilah sandstone aquifer). During this interval, the greatest groundwater level decline reached 110 m and covered an area of about 0.1 km^2 of the depleted area (0.3% of the depleted area). The lowest decline reached 43 m and covered an area of 33.6 km^2 in the southern part of the outcrops of the Tawilah sandstone aquifer (99% of the total depleted area). The estimated depleted groundwater quantity in this interval reached 101.6 million cubic meters (Table 8-11 and Figure 8-18). Figure 8-18 indicates the linear relationship between depleted surface area and groundwater depletion quantity in million cubic meters. The linear relationship indicates a strong correlation between the two variables. The negative sign of the absolute term means that groundwater depletion before the year 1993 was 5% of the total depletion throughout this interval.

Table 8-11 Depleted area and groundwater depletion volume of the sandstone aquifer during 1993-2007

Depletion interval	Area color	Surface area (km^2)	Range of depletion		Depletion depth (m)	Depleted water in million m^3
			From	To		
1993-2007	Red	--	--	--	--	--
	Cyan	0.1	-6	-8	2	0.2
	Yellow	0.2	-3	-6	3	0.6
	Blue	33.6	0.0	-3	3	100.8
Total water storage in million m^3						101.6

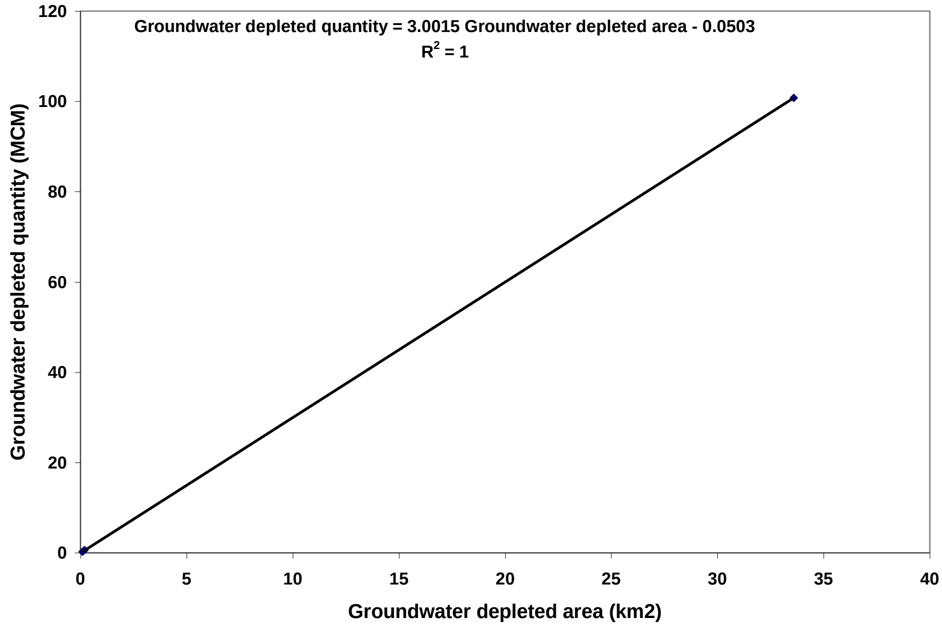


Figure 8-18 Relationship between depleted area and groundwater depleted quantity in the Tawilah sandstone aquifer in Sana'a Basin during the interval 1993-2007

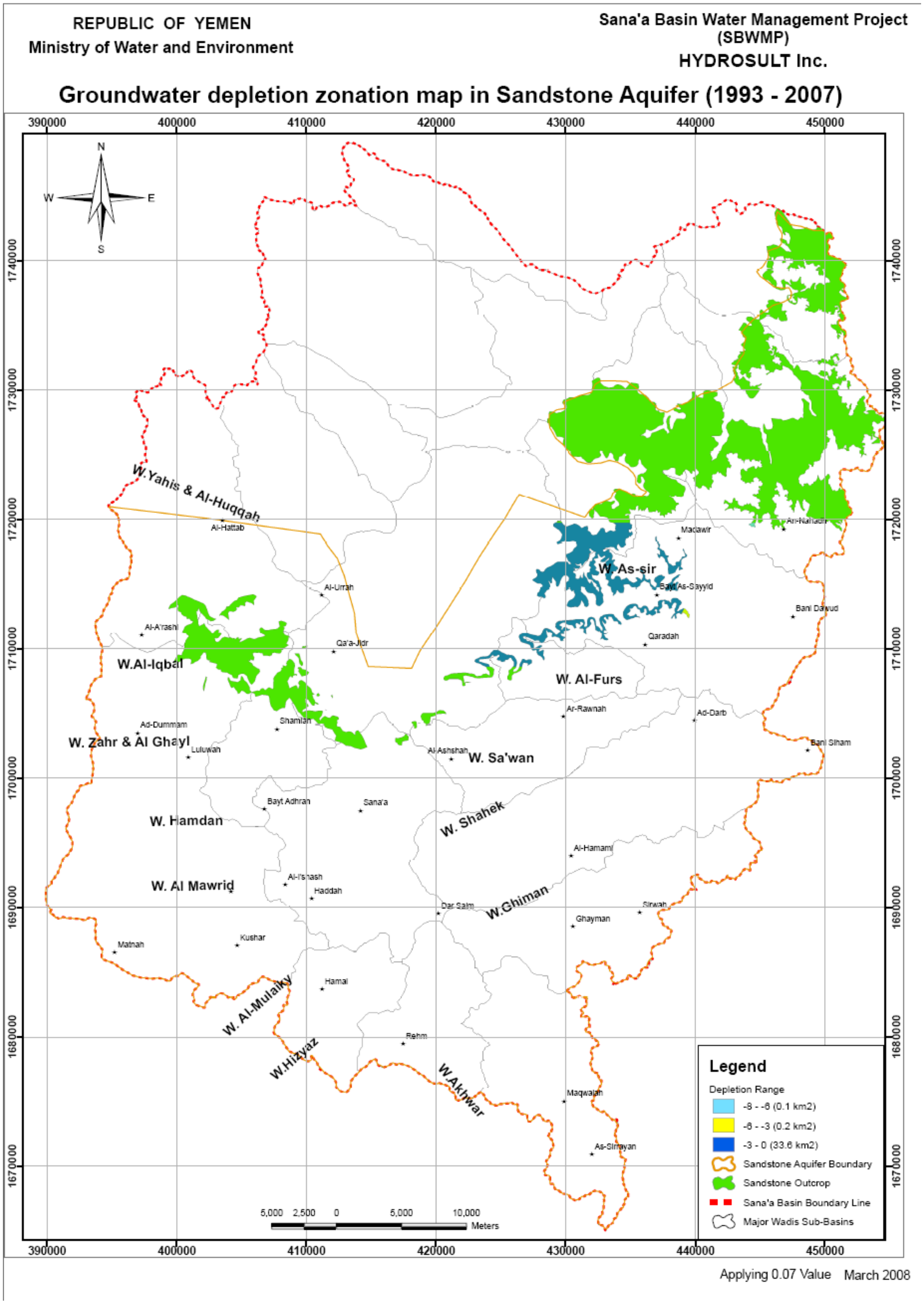


Figure 8-19 Masked groundwater depletion map of the Tawilah sandstone aquifer during 1993-2007

8.6 Groundwater depletion of the aquifers studied inside Sana'a Basin

The general trend of groundwater depletion in the three aquifers studied inside Sana'a Basin is constructed from the results presented (Table 8-12 and Figure 8-20).

Table 8-12 Groundwater depletion volume of the aquifers studied inside Sana'a Basin

Time period	Depletion in Alluvium aquifer in million m^3	Depletion in Volcanic aquifer in million m^3	Depletion in Tawilah sandstone aquifer in million m^3
1973-1983	399	200	500
1983-1993	490	250	640
1993-2001	520	314	800
2001-2007	280	218	905

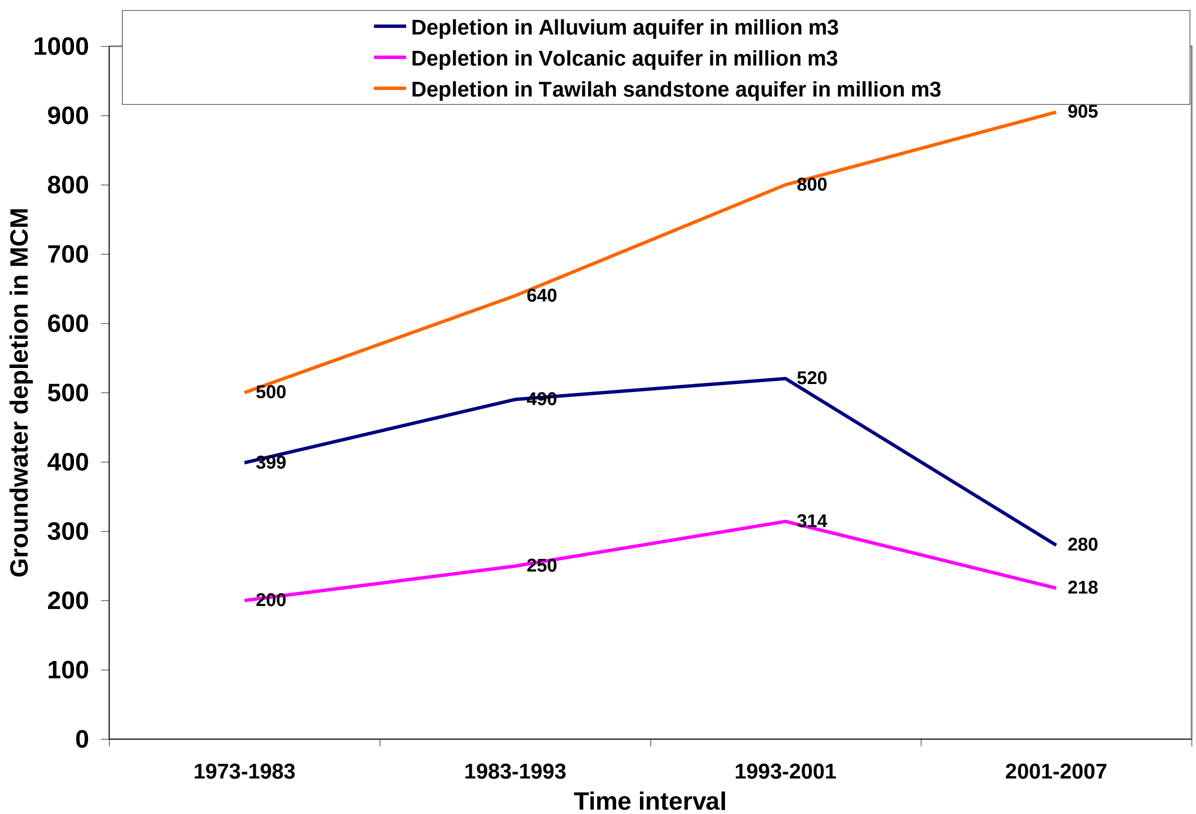


Figure 8-20 Graph showing general trend of groundwater depletion volume in aquifers studied inside Sana'a Basin