REPUBLIC OF YEMEN
MINISTRY OF WATER AND ENVIRONMENT
SANA'A BASIN WATER MANAGEMENT PROJECT

(IDA CREDIT 3774-YEM)

Sub-Component 3(d)

ASSESSMENT OF THE WATER RESOURCES OF THE SANA'A BASIN
STRATEGIC OPTIONS FOR THE SUSTAINABLE DEVELOPMENT OF THE BASIN'S WATER RESOURCES.

SUMMARY REPORT

February 2010

FORWARD

Sana'a Basin has been the subject of a number of studies that aimed at generating data and information on the state of the water resources in the basin. In the past three decades groundwater development has been maximized to the detriment of the precarious resource. The project, subject of this report, has been implemented as a component of the larger Sana'a Basin Water Management Project (SBWMP) since 2005, with the key objective of a comprehensive assessment of the basin's water resources.

This report summarizes the thematic activities undertaken under the project, outlines lessons learned and critical technical, institutional and environmental issues that require further attention and presents strategic options to address these issues within a framework of a water resources management policy for the basin.

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ABSTRACT

The Sana'a Basin relies to a large extent on groundwater for both irrigation and domestic and industrial water supply. Until the early 1970s, the domestic water supply of Sana'a City was almost exclusively obtained from private wells dug by hand in the alluvial deposits of the Sana'a Plain, where Sana'a City is located. After the revolution of 1962, economic development and growth of Sana'a resulted in the need for a modern public water supply system.

As a consequence of the rapid population growth of the City of Sana'a - from 80,000 in 1972 to about 1,000,000 in 1995 and the rapid increase of the area's groundwater-based irrigation, the groundwater levels in the Sana'a Plain have experienced a steady decline, from about 30 m below ground surface in the early 1970s, to more than 150 m below ground surface in 1995. This has caused problems with Sana'a water supply.

The main objective of the project to assess the present status of groundwater potential and to establish a reliable data and knowledge base for proper planning and integrated management of available water resources. within the framework a water strategy for the sustainable development of available resources . This was done through four thematic activities, that delivered complementary outputs

Through activity 1 the project quantified the storage volume of the Cretaceous Sandstone and overlying Quaternary Alluvial and volcanic aquifers. Maps and sections were constructed to delineate the aquifers and the amount of historical depletion;, Qualitative and quantitative geological assessment of water storage properties; was also conducted The assessment was based on both historic and current well inventory and investigations data relating to groundwater levels and abstractions, generated by the project,

Activity 2 team conducted an intensive hydrological monitoring and analysis program at three levels: sub-basin level, field level, and basin level, for deriving overall Sana'a Basin water balances. Specific hydrological analyses and evaluations were performed at two points in time during the course of the project. The results were compared and combined with the project's monitoring program results to date, as well as the available historic data, current well inventory data, supplementary study-specific investigations, outputs from the aquifer assessment study satellite imagery and aquifer modeling studies

A new model domain was designed by Activity 3 team The necessary calibration, was undertaken, a number of aquifer maps were constructed to and or adjusted and four scenarios based on the application of water resources technical and institutional corrective measures and regulations were tested Results of Activities 1 and 2 related to aquifer characteristic values and abstraction estimates recharge values water savings through application of improved irrigation systems were used as input to the model The simulation scenarios proved that with proper regulatory measures applied on pumping rates and with the application of improved irrigation methods, the water levels in the aquifers would recover.

Through Activity 4 a system was developed to monitor and record rainfall, wadi flow, evaporation, groundwater level, and recharge rates. Data recording procedures, collection and analysis protocols were established, Groundwater levels would be closely monitored to check pumping regulation and recharge effects including analysis of project impacts through dam and other wadi structures on aquifer recharge and groundwater levels.

A GIS relational database was established by the project . It comprised climatological hydrological and groundwater data. Special forms for data entry were designed. The database is compatible to the NWRA database to allow exchange and transfer of data.

Capacity building and training of the staff on various aspects of hydrogeological assessment, network monitoring and management mathematical modeling , particularly the use of the model

LIST OF ACRONYMS

(CN)	Curve number
(DEM)	Digital elevation model
(EPA)	Environmental protection agency
(GIS)	Geographic Information System pg 5
(IDF)	Intensity duration frequency curves
(IWRM)	Integrated Water Resources Management
(MAI)	Ministry of Agricultural and Irrigation
(NWRA)	National Water Resources Authority
(NWSA)	National Water and Sanitation Authority
(SAR Ratio)	Sodium Absorption Ratio
(SBWMP)	Sana'a Basin Water Management Project
(SCS)	U.S. Soil Conservation Service
(SEI)	Stockholm Environmental Institute
(TDS)	Total Dissolved Solids
(WEAP)	Water Evaluation and Planning Model
(WEC)	Water and Environment Centre

1 INTRODUCTION AND BACKGROUND

1.1 Description of the Project

Sub-component 3d. **Assessment off the Water Resources of the Sana'a Basin** previously entitled "hydrogeological and water resources monitoring and investigations" of the Sana'a Basin Water Management Project (SBWMP) has four activities which have for a purpose the facilitation of the setting up and execution of a comprehensive hydrogeological and water resources monitoring and investigations program in the basin. The Consultant introduced a fifth activity, namely GIS Database, which was instrumental in managing all the data available and generated during the course of the project and established compatibility links to the NWRA database

The expected results of this sub-component are: to provide a better understanding of the water resources availability in quantity and quality and outline the constraints and issues that impact on the quality and quantity of water resources in the basin. The Sub-component would also assess and estimate the impacts of applying water resources saving techniques and aquifer recharge on the availability and usability of water resources. Furthermore it project is expected to enhance the technical capacity of personnel at NWRA and MAI.

These activities are described below:

Activity 1. Aquifer storage investigations and assessment

- Preparatory activities: Review and analysis of existing information (maps, reports, data); Setting up a database; Processing of all data and information reviewed; Identification of main information gaps
- Acquisition of additional field data: Geological field surveys; Laboratory analysis on rock samples; Collecting & interpreting data from exploratory boreholes; Conducting and interpreting pumping tests; Water quality sampling and interpretation;
- Production of outputs: Developing database; Producing maps and cross-sections; Drafting technical notes and final technical report.

Activity 2. Water balance estimation and sub-basin monitoring

- Selecting experimental sub-basins: determination of selection criteria; stepwise selection of sub-basins.
- Defining criteria for the selection of fields to be monitored
- Programming intensive hydrological monitoring and analysis at sample sub-basins and at field level
- Carrying out the monitoring activities programmed.
- Developing a project database with monitoring data and station metadata.
- Estimating water balances at field level, sub-basin level and Sana'a Basin level.
- Executing specific hydrological analyses to achieve a realistic estimation of the impacts of water saving and aquifer recharge investments
- Preparing technical notes and final technical report.

Activity 3. Aquifer modeling studies

- Reviewing data input base model
- Setting up a GIS database with the input data of the model
- Carrying out steady state and unsteady state runs with the base model
- Prepare a technical note on the base model and on options of its improvement
- Refine and update the groundwater model
- Define and carry out scenario calculations

Activity 4. Hydrological monitoring and analysis in Sana'a Basin

- Monitoring rainfall and other meteorological parameters
- Monitoring groundwater levels and surface water discharge
- Monitoring quality of groundwater and surface water
- Preparing guidelines for monitoring of groundwater, surface water, water quality and climatological parameters.

1.2 OBJECTIVES OF THE SUMMARY REPORT

This Summary Report presents a synthesis of the results of the implementation of the sub-component's activities and attempts to highlight the issues, constraints and opportunities related to the water resources situation in the Sana'a basin, as revealed by the implementation of the sub-component. The report also outlines the sources of data, updated and or generated within the framework of the study. The report presents an integrated summary of the results of the study, an insight into the issues and constraints related to the understanding, planning and management of the water resources in the basin, particularly, groundwater, a clearer understanding of the water balance of the basin as well as options for sustainable development of its water resources. The key findings and salient points included in this report would serve as elements for policy formulation regarding the planning, development and management of the Sana'a basin water resources.

2 ACTIVITIES AND OUTPUTS OF THE SUB-COMPONENT 3(D)

2.1 Activity 1 Aquifer storage investigations and assessment

Activities were completed in the field on the reconnaissance and detailed levels and included preparatory activities necessary to review the situation and the availability of data and information and field surveys and analyses to assess the groundwater availability and potential in the basin

The preparatory activities were conducted through desk studies and field reconnaissance surveys and comprised among others: inventory, collection and review of existing reports, information and maps, search and review of supplementary data sources and information. This was coupled with comprehensive analysis and processing of all data and information reviewed and the identification of data reliability and gaps

The detailed field surveys and assessment work included geological field surveys that aimed at defining and assessing the geologic and hydrogeologic characteristics of the Cretaceous Tawilah sandstone , Quaternary alluvium and the Volcanics aquifers. These surveys made it possible to delineate the aquifer geometry and geologic structures in Nihm, Arhab, Hamdan and Bani Hushaish localities. The geological field surveys were extended to the upper catchments of Wadi Surdud, Wadi Al Khared and Wadi Al Ahgur.

Additional data acquisition included geological detailed field surveys, laboratory tests on cores of Tawilah sandstone, collection and interpretation of information from exploratory boreholes and field mapping work. Extensive field geologic surveys were conducted in the entire basin with particular attention to the Hamdan, Bani Husheish and Nihm areas where the sandstone outcrops reflect intensive tectonic activities .All this new information was documented in the form of technical reports and maps that were produced by the project.

These surveys allowed a better understanding of the structural geology and its lithological variations in the stratigraphic sequence of the area under investigation. In addition they provided better information through the mapping of the the main groundwater aquifers in the Sana'a basin. The mapping clarified the geometry of these units (upper, lower and lateral boundaries), especially for the two distinct groundwater reservoirs (a) Quaternary Sediments; (b) Cretaceous Sandstone (Tawilah Sandstone). Together, they represent by far the largest part of groundwater storage in the Sana'a Basin.

Special attention was paid to the sandstone areas around NWSA's NW and NE well fields, whereby the consultant's hydrogeology team delineated the geological and hydrogeological setting of NWSA NW and NE well fields and verified the contact between the two aquifers, measured the water levels in the data logger stations representing the two well fields and validated and updated the old monitoring network jointly with NWRA Sana'a branch counterparts.

Furthermore the Activity 1 team Identified Sandstone effective porosity, which is needed to estimate the volumes of stored groundwater that can be drained by gravity and assessed the sandstone thickness under the entire basin as has been revealed from subsurface geological cross-sections and the fence diagram. The recoverable storage from the three aquifers was assessed and mapped.

An important activity that was completed under this activity was the determination of the depletion rates in the three aquifers and mapping the depleted areas. To that effect aquifer depletion maps were constructed.

Different regional and local hydrogeological cross-sections were constructed, and the hydrogeological units were verified. In the study of these cross-sections in combination with available well lithology data, the following aspects were defined and checked:

- The outcropping of the different water-bearing formations.
- The fault line directions and the effect on the formations.
- The distribution of the thickness of each formation.
- The hydraulic interaction (laterally and vertically) between the different water f ormations.

The following section summarizes the reports and maps produced within this Activity:

Technical note 1: Included the following: Review of existing reports and maps, Review of geological and stratigraphical sequence of Sana'a Basin; Review of hydrogeological studies of the Sana'a Basin; Review of previous well inventory surveys, annual drawdown and aquifer geometry; Review of previous hydrogeological cross-sections; Review of supplementary data

Technical note 2: Included the following; Processing and interpretation of data; Processing and Interpretation of all data previously collected

Technical note 3: Identification of main information gaps and field work plan; Gaps related to delineation of the aquifers; Gaps related to capacity of the aquifers

Technical note 4: Geologic field activity in Nihm area; Delineation of Tawilah sandstone aquifer geometry and geologic structures in Nihm area

Technical note 5: Geologic field activity in Bani Husheish area; Delineation of aquifer geometry of both Tawilah sandstone and Alluvium aquifers, as well as geologic structures in Bani Husheish area.

First quarterly report: Inventory and review of the previous reports, maps and supplementary data; Finalization of identification of the principle information gaps; Writing and submission of technical note about the principle information gaps; Proposed a field work plan to be followed to fill the information gaps identified; Geological field work carried out in Nihm and Bani Husheish areas December 9-27, 2006

Second quarterly report: Introduction; Geological field survey; Hydrogeologic aspects

Aquifer tests; Conclusions and recommendations

Technical note 6: Geological field work carried out in upper Wadi Surdud catchment

Delineation of Tawilah sandstone aquifer geometry and geologic structure in Upper Wadi Surdud catchment

Third quarterly report: Delineation of aquifer boundaries in the basin; Delineation of western and eastern NWSA well fields; Collection of sandstone core samples; New pumping test activity; Groundwater depletion data; Capacity building.

Maps: Some of the key maps produced by the Consultant are: Lineation orientation maps, limits and delination of the aquifers, hydraulic properties of the aquifers (T and S) , maps delineating the bottom and lower surfaces of the aquifers, depletion maps for the various aquifers, recoverable volume maps for the three aquifers, A large number of geological cross sections for correlation purposes as well as fence diagrams. Reassessment of previous pumping tests and reassessment of aquifers hydraulic parameters groundwater quality distribution maps for the various aquifers.

2.1.1 Outputs of Activity 1

2.1.1.1 Groundwater Occurrence

The Cretaceous Sandstone is the main aquifer in the region, It has low regional permeability but, locally, higher permeabilities are found in weathered and fractured zones. It is heavily exploited to the northeast and northwest of Sana'a, where it either outcrops or occurs beneath an unconsolidated cover of up to 50 m thickness. Depths to water in the main area of abstraction were about 30 to 40 m in the early 1970s but have declined by 2-4 m/yr since. In the south of the Basin, the Sandstone is confined beneath several hundred meters of Tertiary Volcanics. Some of the key problems identified by the work of Activity 1 relation to the Cretaceous Sandstone aquifer are:

- Its lateral boundaries especially across the western basin boundary extend into the zones of Wadi Ahjar
- Nature of the northern boundary is dominated by faults, dikes and lava outpourings , thus producing barriers to groundwater movement
- The sandstone has been removed completely by erosion in the zone between Rawda and the structurally controlled limestone outcrops further north
- In the southern part, the sandstone is hidden under thick volcanic covers and subjected to block faulting

The basalt flows and started sequences of the Tertiary Volcanics act as aquicludes, except where fractured or where primary permeability occurs in sediments between flows. The mixed basalt and rhyolite flows at the top of the sequence are more highly fractured and contain perched aquifers which supply dug wells and feed high-level springs. The upper layers of the Volcanics are highly weathered and relatively permeable where they underlie the unconsolidated Quaternary deposits in the south of the Basin. Here, they are exploited together with the unconsolidated aquifer by dug and drilled wells.

The Quaternary Basalts are highly permeable due to fracturing and the presence of clastic deposits between flows. Where the Formation is saturated, it provides an unconfined aquifer. Water levels are deep, ranging from 60 to 130 m, depending on the elevation. Wells are generally limited to the southern edge of the outcrop where water levels are less than 100 m deep. In **the rest of the area, surface water is stored in cisterns to provide water for domestic purposes.**

The unconsolidated Quaternary deposits provide a poorly permeable aquifer which has been heavily exploited in the Sana'a Basin due to its proximity to the urban area. The aquifer is regionally unconfined but locally semi-confined. Due to the fine-grained nature of the deposits in the plain, recharge is expected to be mainly indirect, into coarse-grained material along wadis and at the base of the hills.

The Amran Limestone is generally considered to be a poor aquifer although supplies can be obtained from zones of secondary permeability. Karst features, however, are poorly developed. The depth-to-water is over 100m in the plateau area in the northwest of the Basin. In the northeast, in valleys leading to the Wadi al Kharid, the depth-to-water is less than 35 m and groundwater is abstracted mainly by means of dug wells. The Unnamed Formation is believed to act as an aquiclude, although its regional permeability may be similar to the Amran Limestone.

2.1.1.2 Aquifer Delineation

A consistent and complete set of maps representing the delineation of the different water-bearing formations was constructed. These are namely:

- Bottom Contour Elevation Map of the Quaternary Alluvial Formations covering an area of approximately 605km^2 (outcropping). The maximum bottom level is located at the south of the Basin and has an elevation of 2,428 m.a.s.l., and the minimum is in the north at an elevation of 1,920 m.a.s.l.;
- Thickness Contour Map of the Quaternary Alluvial Formations
- Top Contour Elevation Map of the Quaternary and Tertiary Volcanic Group-, covering an area of approximately 2,260 square kilometers.

- Bottom -Contour elevation of the Volcanic formation, at 1,660 m.a.s.l (in the south), and 2,514 m.a.s.l in the north-east of the Basin;.
- Thickness Contour Map of the Quaternary and Tertiary Volcanic Group maximum thickness of approximately 660 m in the south of the basin;.
- Top Contour Elevation Map of the Tawila Sandstone Group –covering an area of 2,330 km^2 and outcropping area of 315 square kilometers;.
- Bottom Contour -Elevation Map of the Tawila Sandstone Group with a maximum elevation of 2,387 m.a.s.l. in the west of the Basin;.
- Thickness Contour Map of the Tawila Sandstone Group with a maximum thickness of 850 m, located at the south of the Basin;.
- Top Contour Elevation Map of the Amran Limestone Group covering the whole Basin, with an area of approximately 3,240 km^2 and outcropping over 440 km^2.

2.1.1.3 Aquifers storage capacity

The storage capacity of the three main aquifers was determined using parameters derived from new pump tests conducted by the Consultant re-analyzed pumping tests. To that effect the consultant has used the following data for each of the tested aquifers

- alluvial aquifer: 14 constant discharge and 2 multi-step tests;
- volcanic aquifer: 2 constant discharge and 2 multi-step tests; also 20 tests on record were re-analyzed;
- sandstone aquifer: 3 constant discharge and 4 recovery tests; also 45 tests on record were re-analyzed.

The following table 1 illustrates the parameters estimated for each aquifer:

Table 1 Aquifer Properties

	Number of wells	hydraulic conductivity (m/d)			
		Min	avg	max	Method
Alluvium	14	0.09	1.75	12.23	Papadopulos and Cooper
Volcanic	22	0.0004	0.09	0.42	Cooper – Jacob (old tests)
Sandstone	81	0.5	7.3		Cooper – Jacob (old tests
	Number of wells	transmissivity (m^2/d)			
		Min	avg	max	Method
Alluvium	14	9	511	3,618	Papadopulos and Cooper
Volcanic	22	0.34	47	200	Cooper – Jacob (new tests)
Sandstone	4	23.5	81.5	148	Cooper – Jacob (new tests)
	81	6	170	3770	Cooper – Jacob (old tests)
	Number of wells	specific yield			
		Min	avg	max	Method
Alluvium	14	0.0004	0.0096	0.078	Papadopulos and Cooper
	Number of wells	storage coefficient			
		Min	avg	max	Method
Sandstone	4	0.41×10^{-4}	4.1×10^{-4}	9.6×10^{-4}	Cooper – Jacob (new tests)
	81	1.5×10^{-4}	2.2×10^{-3}	9.4×10^{-3}	Cooper – Jacob (old tests)

The tests in the alluvium indicated unconfined conditions, with a wide range of conductivity values, whereby the higher values are found in the northern (thicker) part of the aquifer. Low specific yields of this aquifer indicate the effect of clays and silts within the alluvial deposits.

The tests in the volcanic aquifer reflect low regional conductivity and high localized conductivity, the latter is found in parts of the aquifer that have been weathered and or fractured. This results in a large range of hydraulic conductivity values.

The tests in the Tawilah sandstone also reflect the effect of fracturing. The assessment of hydrodynamic characteristics of alluvium, Tawilah sandstone and volcanic aquifers from new pumping tests and data from past pumping tests on record reflects the following:

The statistical study of hydrodynamic characteristics indicates that the Tawilah sandstone aquifer is highly anisotropic and heterogeneous in relation to the structural events that affect this aquifer. The range of transmissivity is very wide for the same formation. This may be attributed to the degree of fracturing that affects the aquifer. No correlation was found between different hydrodynamic parameters of the Tawilah sandstone aquifer; such as depth versus transmissivity or thickness of aquifer versus transmissivity;

Analysis of pumping test curves from the Tawilah sandstone aquifer shows that there is a lateral recharge effect. This recharge comes from the same aquifer, but from a long distance. In the Ghatrane area, the geological structure constitutes a boundary effect and limits the hydraulic relationship between wells in the Tawilah sandstone aquifer. In the Bani Hushaish area, the effect of geologic structure, such as dykes, is pronounced in the pumping tests.

The storage coefficient indicates that the Tawilah sandstone aquifer is under confined conditions (S varies between 10^{-4} and 10^{-3}) in the area around the Sana'a Plain and in Bani Hushaish. Groundwater in the shallow zone of the Tawilah sandstone aquifer is generally stored under unconfined conditions (water-table) although the overlying poorly permeable alluvium or silt-clay layers interbedded with the Tawilah sandstone may impart some degree of confinement to the aquifer. Where the sandstone is overlain by a considerable thickness of alluvium, confined to semi-confined conditions prevail with storage coefficients of the order of 10^{-4}.

The annual recharge to groundwater in the Sana'a Basin is estimated at 51.2 Mm^3 while the annual discharge is estimated at:

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

2.1.1.4 Groundwater Quality

The results of the groundwater quality sampling campaign in Sana'a Basin are presented in the form of tables, maps, diagrams and statistics in chapter 7. The water quality of the different aquifers is a witness to the hydraulic connectivity of these aquifers. In the alluvium aquifer the groundwater is of mixed origins of mineralization, where rain water and subsurface flow from neighboring aquifers are the main sources of salt contribution. The groundwater salinity of the alluvium aquifer ranges between fresh and slightly brackish. The TDS (Total Dissolved Solids) ranges between 85 and 2,950 ppm. Close to 66% of the water points have TDS less than 1,000 ppm, 26 % range between 1,000-2,000 ppm, and only 8% are reported to have TDS in excess of 2,000 ppm.

The groundwater salinity increases towards the north, reflecting the increase in aquifer thickness and groundwater use in this direction. It is observed, that the higher salinities are mainly recorded in dug wells of the Wadi El Ghayl downstream area. The possible source of contamination of the alluvium aquifer in the Arhab area, are the marine salts from the underlying fractured limestone aquifer.

In the volcanic aquifer, the groundwater is of mixed origins of mineralization, where rain water and fossil water are the main sources of salt contribution. The groundwater salinity of the volcanic aquifer ranges between fresh and brackish. The TDS varies from 217 ppm to 2,010 ppm with a mean value of 670 ppm. The groundwater salinity increases towards the north. A large part of the aquifer area has a TDS value below 400 ppm and in the western part of the basin the TDS value is much lower: 100-200 ppm. **The high TDS values in the north-east may be attributed to groundwater originating from the Tawilah sandstone aquifer.**

In the Tawilah sandstone aquifer the groundwater of both the shallow and deep zones is of mixed origins of mineralization. The feeding recharge source is rainwater for the shallow zone, and during pluvial times, for the deep zone. Subsurface flow is the source of possible contamination from adjacent aquifers.

The groundwater salinity of the sandstone aquifer is generally fresh with brackish water only in a few samples from the unconfined zone. The TDS varies from 193 ppm to 1,872 ppm with a mean value of about 600 ppm. About 70% of the aquifer area has a value of TDS between 200 and 400 ppm. Relatively high values of TDS exist in the east in the range of 500 ppm and 1,200 ppm. The groundwater salinity is highest in the north east where the aquifer is in contact with the Amran limestone.

The groundwater in the limestone aquifer was sampled from 29 wells even though this aquifer beyond the scope of the study. The groundwater salinity is close to 400 ppm in about 75% of the aquifer area. The TDS dramatically increases in the south-west and reaches a value of about 1,800 ppm with a maximum of 2,200 ppm. The desirable level of TDS in Yemen is 650 ppm while the maximum permissible value is 1,500 ppm. The permissible value is exceeded in about 10% of the wells in the alluvium and sandstone aquifers, and is exceeded in about 20% of the wells in the volcanic aquifers.

The groundwater in Sana'a Basin is generally hard to very hard water causing problems when used for domestic purposes. The water is suitable for livestock purposes according the TDS levels. The suitability for irrigation was verified using the SAR-ratio. The groundwater in the Sana'a Basin is generally suitable for all soils.

2.1.1.5 Groundwater Depletion

Over exploitation of groundwater resources beyond the recharge level is the major factor leading to aquifer depletion. Observations and analyses of available water levels have concluded that water table has dropped in all unconfined aquifers over the past three decades Estimates of the depletion were made based on the groundwater level maps in the three aquifers.

Observation of the groundwater levels in the alluvium aquifer shows that the water table has generally dropped by 3.4 m since 1973, and even more in the eastern parts of the basin, where the aquifer has dried up, while in the volcanic aquifer the water table has dropped by 51.2 meters since 1985. The water level in the Tawila sandstone aquifer has dropped by 141 meters since 1993, as shown in Table 3 below

Table 2 Groundwater Depletion

Time period	Groundwater depletion volume in million m^3			
	Alluvium aquifer		Volcanic aquifer	Tawilah sandstone aquifer
	With dried areas	Without dried areas		
1972-1983	186.5	---	---	---
1983-1993	---	---	11408	---
1993-2001	---	618.8	---	149.71
2001-2007	---	478.64	---	---
1972-2007	470.54	550.83	---	---
1983-2007	371.5	---	17057	---
1993-2007	240.2	313.15	---	101.6

2.1.1.6 Recoverable Groundwater Storage (NOTE- THIS SECTION MAY BE MODIFIED BASED ON THE COMMENTS BY SBWMP AND THE CORRECTIONS UNDERWAY BY Dr.GAD, THE REGIONAL HYDROGEOLOGIST OF CHAPTER 9)

The recoverable groundwater storage volumes of the deep zones of the Tawilah sandstone aquifer in Sana'a Basin were computed and are illustrated in Table 2 below: and Figure 1 (A,B,C,D) in Annex I.

Table 3 Recoverable groundwater storage

Storage Interval	Area colour	Surface area (km^2)	Range of storage		Average storage depth (m)	Storage volume in million m^3
			From	To		
70-150	Red	1	12	18	15	15
	Yellow	320	6	12	9	2,880
	Blue	350	2.5	6	4.25	1,487.5
Total recoverable groundwater storage in million m^3						4,382.5

Storage Interval	Area colour	Surface area (km^2)	Range of storage		Average storage depth (m)	Storage volume in million m^3
			From	To		
150-250	Red	200	10	12.5	11.25	2,250
	Yellow	600	5	10	12.5	7,500
	Blue	410	1	5	3	1,230
Total recoverable groundwater storage in million m^3						10,980

Storage Interval	Area colour	Surface area (km^2)	Range of storage		Average storage depth (m)	Storage volume in million m^3
			From	To		
250-350	Red	400	12	18	15	6,000
	Yellow	600	6	12	9	6,300
	Blue	100	2.5	6	4.25	425
Total recoverable groundwater storage in million m^3						12,725

Storage Interval	Area colour	Surface area (km^2)	Range of storage		Average storage depth (m)	Storage volume in million m^3
			From	To		
350-450	Red	200	16	23	19.5	3,900
	Yellow	350	8	16	12	4,200
	Blue	50	2.5	8	5.25	262.5
Total recoverable groundwater storage in million m^3						8,362.5

2.2 Activity 2 Water balance estimation and sub-basin monitoring

A key objective of Activity 2 was to collect and update hydrological information on rainfall, evapotranspiration, surface water and groundwater for **improvement of the estimation of the water balance of the Sana'a Basin and its sub-basins**. Another specific objective of the Activity 2 was to implement specific monitoring activities in selected experimental sub-basins to study the effect on water resource availability and depletion by **measures concerning water recharge and irrigation methods**.

The following major activities were completed during the course of implementation:

- Selection of 4 experimental sub basins and data collection and monitoring.
- Field water balance study at 3-farms, two modern irrigation farms (Ghadran and Al Hinami) and one traditional farm (Luluah).
- Reservoir monitoring and water balance at six reservoirs.
- Sub basin water balance for the 22 sub basins in Sana'a basin.
- Overall comprehensive water balance modeling using Water Evaluation and Planning (WEAP) model.
- In addition to the data collection and monitoring conducted under this study, a lot of data, information and knowledge from previous studies such as WEC, (2004) SAWAS, (1996) WRAY, (1995) HWC, (1992) GAF, (2007) are used as inputs to this study.
- Water balance is evaluated under average (long term), Year 2007, and Year 2008 situation.

Reports and Technical notes prepared

Technical Note1: covering the procedure of sub-basin selection and the sub-basin monitoring program including field-level observations. The note describes the procedure applied to select four representative sub-basins.It also specifies the information of the sub-basins considered, derived from readily available data and from fieldwork.

Technical note on interim results of sub-basin monitoring activities including field-level observations and water balance estimation.

The note included:

- a description of the locations and records of the monitoring stations;
- a preliminary overview of the field observations;
- a preliminary water balance of each sub-basin.

The technical note also presented a water balance based on the data collected.

Maps: Maps Covering the entire Sana'a Basin and presenting information in a grid and/or by sub-basin. (Detailed maps (scale 1:100,000 or smaller), prepared in GIS format), namely: Groundwater recharge map, showing the average annual recharge potential, where recharge is classified as high, medium and low, and groundwater abstraction map, showing the average abstraction of groundwater for agricultural and domestic use as well as groundwater development map, showing the rate of groundwater development.

2.2.1 Outputs Of Activity 2

The key outputs resulting from the implementation of Activity 2 are described below:

2.2.1.1 Identification and Selection of Experimental Sub-basins

The criteria and the process to select four experimental sub basins in Sana'a basin are described in Technical Note 1 and in the Activity 2 Report. The four experimental sub basins are:

- Wadi Zahr & Al Ghay (Methbel watershed)
- Wadi as Sirr
- Wadi Khalaqa and
- Wadi Sa'Wan

The sub-basin were selected with the notion: if hydrological monitoring is successfully conducted it will be possible to derive parameters for computation of Sana'a basin water balance. Figure 3

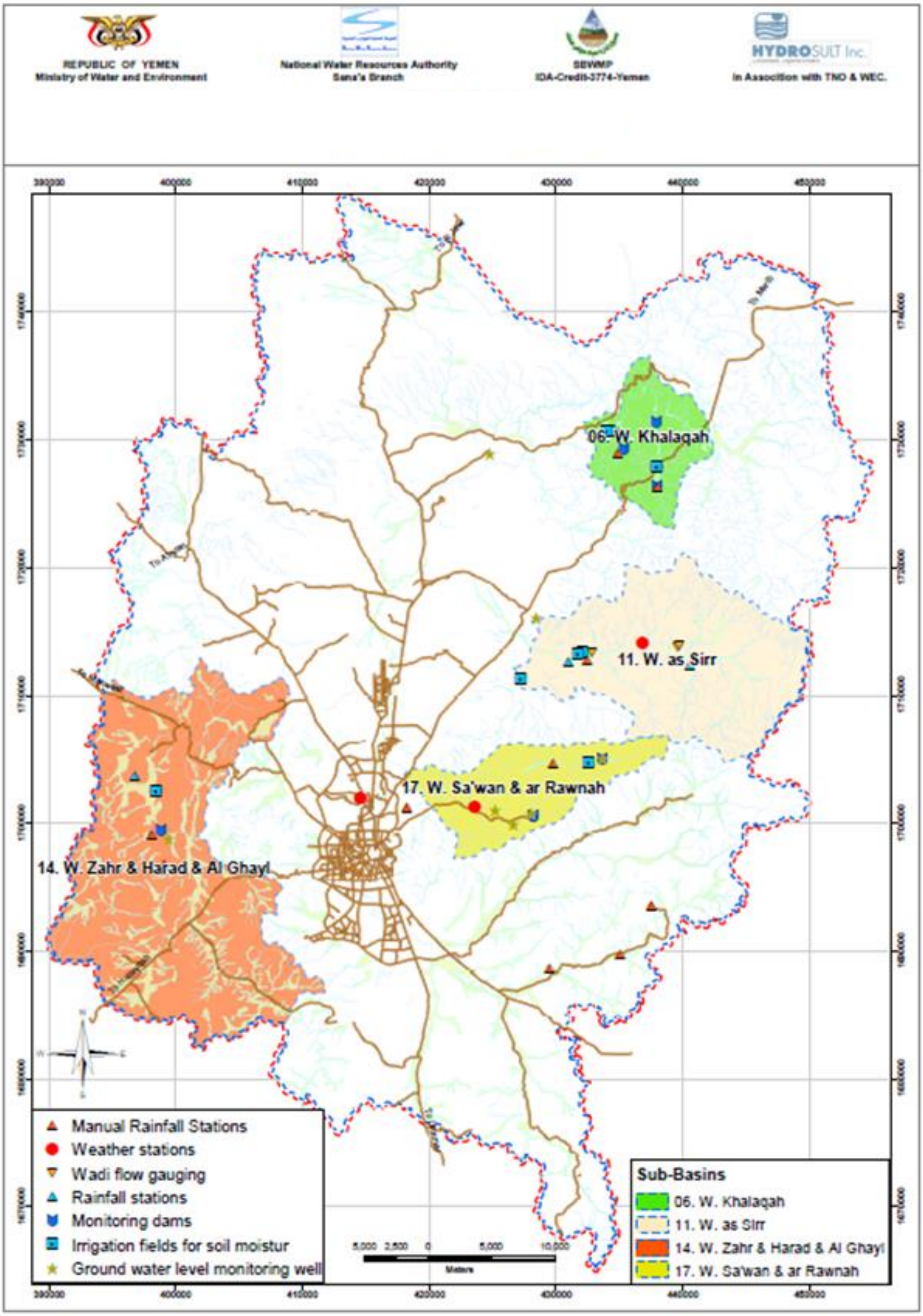


Figure 2 Experimental sub-basins and hydro meteorological stations

2.2.1.2 Hydrological Monitoring in the Experimental Sub-basins

A major objective of Activity 2 was to collect hydrological information in the four sub-basins to be subsequently used to determine Sana'a basin and sub-basins water balance. The monitored hydrological elements were:

- Rainfall
- Weather
- Wadi runoff
- Groundwater level
- Reservoir water level
- Soil moisture and
- Irrigation water abstraction

2.2.1.3 Field Water Balance

The field water balance study was conducted in three farms (Ghadran, Al Hinami, and Luluah). New irrigation water saving techniques were implemented in Ghadran and Al Hinami farms. Both farms are located in Wadi as Sirr sub-basin respectively. Surface irrigation method (furrow) was used in Luluah farm which is located in Wadi Zahr sub-basin.

The water balance study indicated that in the two farms equipped with water saving techniques, efficiency of irrigation water application is equal to 100%. No water loss by deep percolation was observed. In Luluah farm, irrigation water application efficiency is about 56%.

2.2.1.4 Reservoir Runoff and water balance

Reservoir water balance for six dams (Al-Hayathem ,Arisha, Khalaqa, Methbel, Mekhtan, and Mussaibih) including groundwater recharge are estimated based on measured reservoir water level using staff gauges, direct measurements of water releases (for irrigation and domestic water use), and evaporation estimation using GAF (2007) data. Summary of the water balance is provided in table 3.

Table 3 Summary of the water balance for six reservoirs (year 2007-2008)

Elements	Dams					
	Al-Hayathem	Arisha	Khalaqa	Methbel	Mekhtan	Mussaibih
Dam catchment area (km^2)	27.4*	6.5	5.5	32.6	5.6	3.6
Reservoir area geology	Limestone	Sandstone	Sandstone (foundation cutoff wall provided)	Tertiary volcanic	Volcanic	Volcanic (foundation cutoff wall provided)
Total balance days	238	189	513	105	513	602
Annual rainfall (mm)	192	221	221	192	221	221
Total measured volume of runoff; balance period (m3)	439380	197448	203822	9864	122210	44344
Reservoir Evaporation (m3)	65561	4000	48712	1272	47845	19275
Release (m3)	88373	122959	65400	1775	11863	2757
Recharge (m3)	285447	70489	89710	6817	62502	22832
Average reservoir pool area (m2)	52698	3925	16762	1512	15846	6547
Mean recharge (mm/day)	19	79	9	36	6	5

* Excluding Khalaqa catchment

Table 3 indicates that the reservoirs have different groundwater recharge rate depending on the geological formation of the reservoir area. Recharge in limestone and sandstone are is higher than in volcanic area.

2.2.1.5 Ground Water Recharge

Recharge in the 22 sub-basins of Sana'a basin was calculated at 53.4Mm^3 derived from two components: direct recharge from rainfall, and wadi bed recharge. Results indicated that recharge from direct rainfall is a rare phenomenon occurring only during intensive rainfalls where the soil field capacity is exceeded by the amount of water percolating. The mean annual value of direct recharge from rainfall is only 3.9 Mm^3, while the major recharge to the Sana'a basin estimated at 49.5 Mm^3 occurs from surface runoff in wadi beds, representing 8% of the annual rainfall. It should be indicated here that evapotranspiration consumes 92% of the 199 mm annual rainfall. Table 3

Table 4 Summary of Rainfall-Runoff-Recharge calculation

No	Sub Basin	Rainfall Station	Rainfall	Runoff	Recharge			Catchment Area (WEC, 2004)	Runoff	Recharge		
					Rainfall	Runoff	Total			Rainfall	Runoff	Total
			mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	Km^2	Mm^3	Mm^3	Mm^3	Mm^3
1	Wadi al Mashamini	Astan-a	171	12.4	0.0	9.3	9.3	76.5	1.0	0.0	0.7	0.7
2	Wadi al Madini	Samnah-a	150	12.6	0.0	9.5	9.5	211.5	2.7	0.0	2.0	2.0
3	Wadi al Kharid	Samnah-a	150	14.6	0.0	11.0	11.0	136.7	2.0	0.0	1.5	1.5
4	Wadi al Ma'adi	Maadia-a	189	21.5	0.0	16.1	16.1	111.5	2.4	0.0	1.8	1.8
5	Wadi A'sir	Birbasla	231	40.8	0.8	30.6	31.4	210.2	8.6	0.2	6.4	6.6
6	Wadi Khalaqa	Birbasla	231	24.1	2.9	18.1	20.9	75.9	1.8	0.2	1.4	1.6
7	Wadi Qasabah	Samnah-a	150	11.7	0.0	8.8	8.7	64.6	0.8	0.0	0.6	0.6
8	Wadi al Huqqah	Darwan	194	19.5	0.0	14.7	14.6	120.7	2.4	0.0	1.8	1.8
9	Wadi Bani Hwat	Sana'a Air Port	170	11.3	0.0	8.5	8.5	322.4	3.6	0.0	2.7	2.7
10	Wadi Thumah	Samnah-a	150	14.1	0.0	10.6	10.6	77.6	1.1	0.0	0.8	0.8
11	Wadi as Sirr	Sana'a Air Port	170	17.5	0.0	13.1	13.1	219.1	3.8	0.0	2.9	2.9

No	Sub Basin	Rainfall Station	Rainfall	Runoff	Recharge			Catchment Area (WEC, 2004)	Runoff	Recharge		
					Rainfall	Runoff	Total			Rainfall	Runoff	Total
			mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	Km^2	Mm^3	Mm^3	Mm^3	Mm^3
12	Wadi al Furs	Sana'a Air Port	170	20.3	0.0	15.2	15.2	45.8	0.9	0.0	0.7	0.7
13	Wadi al Iqbal	Darwan	194	17.6	0.3	13.2	13.5	204.4	3.6	0.1	2.7	2.8
14	Wadi Zahr & al Ghay	Mind	279	15.8	4.8	11.9	16.6	364.8	5.8	1.7	4.3	6.1
15	Wadi Hamdan	NWRA-A. CAMA	228	24.2	0.0	18.2	18.2	63.7	1.5	0.0	1.2	1.2
16	Wadi al Mawrid	Darsalm. NWRA'A. CAMA	202	35.6	0.0	26.7	26.7	179.6	6.4	0.0	4.8	4.8
17	Wadi Sa'Wan	Shoub	245	30.9	0.3	23.2	23.5	95.4	3.0	0.0	2.2	2.2
18	Wadi Shahik	Adabat	197	29.6	2.4	22.2	24.6	236.9	7.0	0.6	5.3	5.8
19	Wadi Ghayman	Adabat. Darsalm	173	16.4	1.5	12.3	13.8	143.8	2.4	0.2	1.8	2.0
20	Wadi al Mulakhy	Wallan	248	17.7	3.1	13.3	16.4	69.8	1.2	0.2	0.9	1.1
21	Wadi Hizyaz	Wallan	248	21.5	3.3	16.1	19.4	80.5	1.7	0.3	1.3	1.6
22	Wadi Akhwar	Wallan	248	19.3	2.8	14.5	17.3	125.4	2.4	0.4	1.8	2.2
A Averaage			199	20.0	1.0	15.3	16.3	3236.8	66.0	3.9	49.5	53.4

2.2.1.6 Water savings from improved irrigation system

Irrigation is the largest water consumer in Sana'a basin (221 Mm^3 for 18953 ha -GAF 2007). In the case of Lulah Farm with the traditional system of irrigation, the irrigation efficiency is about 56%, whereas at the farms, where modern irrigation systems are practiced, such as Al Hinami and Ghadran, the irrigation efficiency is nearly 100 %, in terms of water application. Therefore, irrigation water savings of about 40% could be achieved by modernizing the traditional farms. Moreover, if all existing traditionally irrigated areas are converted to modern farms, the annual total irrigation water demand would be reduced to 133 Mm^3 from the present demand of 221 Mm^3. The total annual water balance of Sana'a basin would then be improved from -192.7 Mm^3 to -114.2 Mm^3. Table 5 shows Comparison of average annual water balance with traditional and modern irrigation systems.

Table 5 Comparison of average annual water balance with traditional and modern irrigation systems

Sub-basin	Water Balance (Mm^3) Traditional System	Water Balance (Mm^3) Modern System
1	-0.04	0.0
2	-2.36	-0.5
3	-1.51	-0.3
4	0.00	0.0
5	-0.18	-0.1
6	-0.77	-0.2
7	-2.57	-1.5
8	-13.24	-7.0
9	-52.20	-32.5
10	-0.52	0.0
11	-24.59	-13.6
12	-9.49	-5.7
13	-19.32	-10.7
14	-7.46	-0.9
15	-2.90	-2.1
16	-34.00	-30.4
17	-10.26	-5.9
18	-3.64	-0.2
19	-2.87	-0.6
20	-2.83	-1.4
21	-1.57	-0.5
22	-0.40	-0.1
	-192.7	-114.2

Though there will be a larg improvement in water use efficiency in the modern irrigation system, the overall water balance of Sana'a basin will continue to decline. Generally, the water resources of Sana'a basin cannot sustain irrigation development from ground water resources. The existing water demand of most of the sub-basins could be managed to a certain extent through the introduction of modern irrigation techniques, however, sub-basins 8,9,11,12,13,16, and 17 cannot sustain their existing water demand.

2.2.1.7 Sana'a Basin and Sub-basins Water Balance

The Sana'a basin and sub-basins water balance was computed using the WEAP model of the Stockholm Environmental Institute (SEI) for the average long term mean annual rainfall in Sana'a basin and for years 2007 and 2008 conditions.

Long term water balance

A. Water Supply Demand

The total domestic and non domestic water demand including 20% system losses in Sana'a basin is estimated for the year 2010 at 58.4 Mm^3. Using the forecast from the 2004 census, the 2010 Sana'a basin population will be about 2.9 Million. This volume is larger than the groundwater recharge volume estimated at about 53.4 Mm^3/year (as illustrated in Table 4).

Two sub basins; Wadi al Mawrid (16) and Bani Huwat (9) are the largest consumers. The water demand in Wadi al Mawrid in which Sana'a City is located is about half of the total Sana'a basin water supply demand. This is a challenge for water management and water right issues and is a source of conflict between water users (urban and rural water users) as people living in the rural areas in other sub basins may prefer the water for irrigation use.

B. Irrigation water demand

The total annual irrigation water demand is 221.1 Mm^3 . This is equivalent to an annual demand of 11668 m^3/ha. Wadi Bani Huwat and Wadi as Sirr are the largest consumers.

C. Rainfall

The mean annual rainfall estimated by arithmetic mean by the WEAP Model was found to be **662.9 Mm^3.**

D. Catchment Runoff

The total average annual runoff generated in the 22 sub-basins of Sana'a basin is **66 Mm^3** most of which is infiltrated in the Wadi bed to recharge the ground water. Figure 4 illustrates the distribution of the mean annual runoff in the basin.

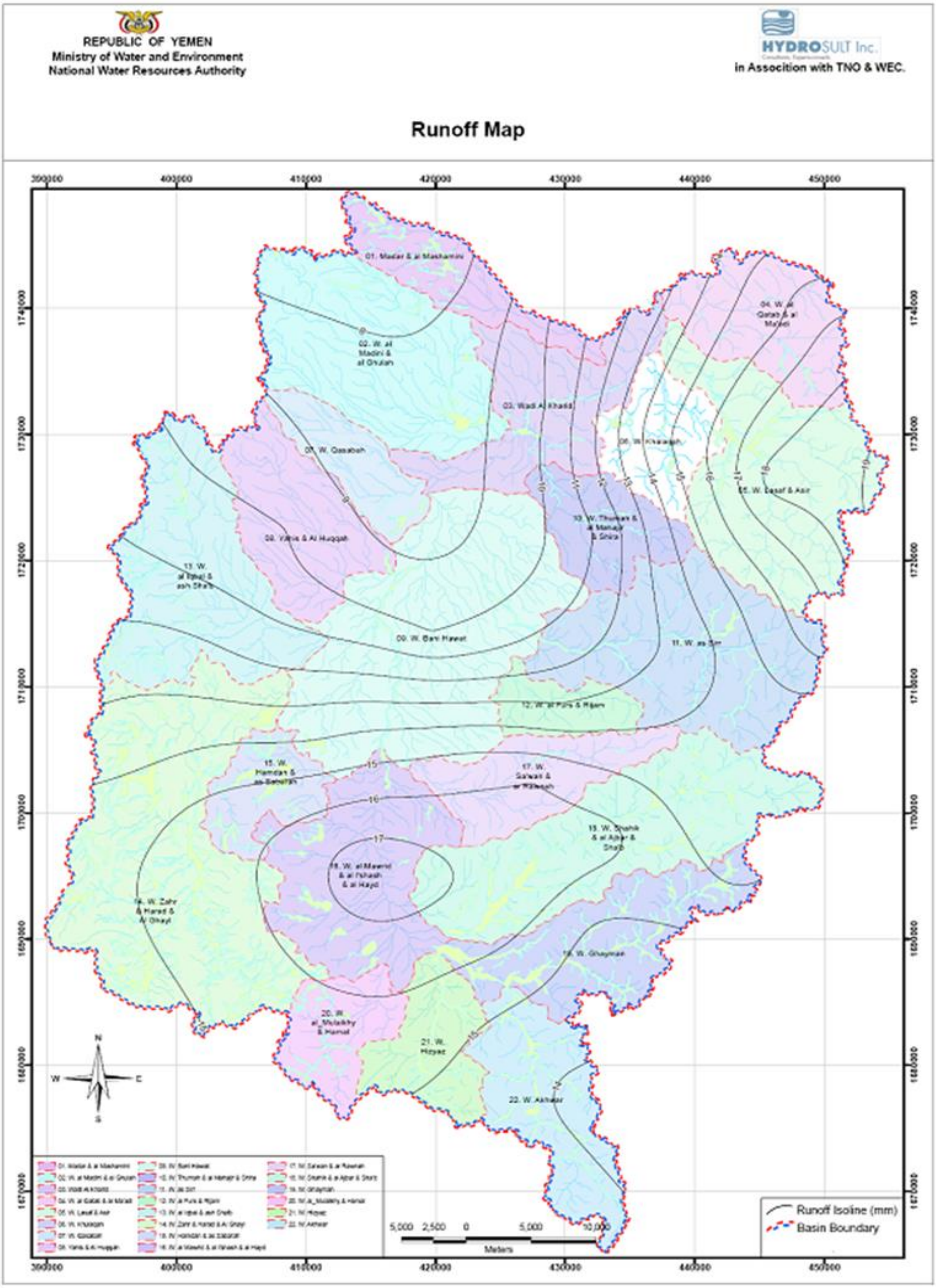


Figure 3 Mean Annual Runoff Map

E. Reservoirs Inflow

The total annual reservoir inflow is about **8.8 Mm^3** which is about **12%** of the total runoff generated in the basin.

F. Recharge

The average ground water recharge in Sana'a basin is shown in Table 6. Recharge is estimated from reservoir, catchment runoff, direct rainfall and return flow from demand sites.

Table 6 Average groundwater recharge (all sources) Mm^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Reservoir	0.1	0.3	0.9	1.6	0.6	0.2	0.4	1.2	0.1	0.1	0.1	0.1	5.5
Direct rainfall and Wadi Runoff	4.8	5.9	7.5	11.7	5.9	1.1	1.7	5.8	1.9	0.6	1.2	3.0	51.2
Return flow	1.9	2.2	2.5	3.6	2.9	1.1	1.0	2.6	1.2	0.6	0.7	1.2	21.3
Total	6.8	8.3	10.9	16.9	9.3	2.4	3.0	9.6	3.2	1.3	2.0	4.3	78.1

The ground water recharge from wadi runoff and rainfall according to the WEAP model is estimated at 51.2 Mm$^{3.}$ Subtracting the direct rainfall part of 3.9 Mm^3 (as estimated in section 2.2.1.5) brings the Wadi runoff contribution to 48.3 Mm^3. Therefore, the percentage of recharge from the total Wadi runoff of 66 Mm^3 is 73%. The present result is in good agreement to WRAY 1995 estimate that 20-30% of Wadi runoff will be lost to evapotranspiration through spate irrigation and the remaining will contribute to ground water recharge as basin outflow is almost negligible.

The ground water recharge from all sources namely direct rainfall, wadi runoff, reservoirs and return flow from demand sites including Sanaa's waste water treatment plant, is about 78.1 Mm^3.

G. Water Balance

The total annual water resources delivered from groundwater, diverted surface water (spate irrigation), and reservoirs (direct abstraction and from shallow well recharge) is 86.8 Mm^3. Figure 5 shows the sub-basin water balance map.

Table 7, below, illustrates the unmet demand or supply delivered from non-replenishable ground water sources (mining) was estimated at **192.7Mm^3**.

Table 7 Unmet demand at sub-basin level or water delivered from Ground Water (mining) Mm3

Sub basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
11	0.59	0.60	1.27	1.30	2.91	3.73	3.52	2.83	2.27	1.64	0.80	0.68	22.1
12	0.30	0.34	0.55	0.54	0.99	1.23	1.16	0.96	0.79	0.59	0.34	0.30	8.1
13	0.84	0.97	1.44	1.18	1.46	2.01	1.90	1.40	1.53	1.49	1.11	0.95	16.3
14	0.20	0.15	0.49	0.00	0.00	1.11	0.93	0.29	0.41	0.87	0.68	0.53	5.7
16	2.50	2.30	2.75	2.39	3.02	3.44	3.24	2.79	3.11	3.12	2.70	2.55	33.9
17	0.25	0.12	0.37	0.53	1.13	1.49	1.39	0.87	0.77	0.62	0.21	0.16	7.9
18	0.00	0.00	0.00	0.00	0.00	0.88	1.16	0.00	0.16	0.60	0.30	0.03	3.1
19	0.02	0.01	0.11	0.00	0.00	0.69	0.62	0.06	0.30	0.36	0.21	0.12	2.5
8	0.53	0.64	1.01	0.89	1.19	1.62	1.37	1.06	1.27	1.12	0.77	0.65	12.1
9	1.67	1.71	3.35	0.77	7.07	8.73	7.14	6.44	6.27	4.88	2.34	1.92	52.3
All others	1.63	1.40	1.28	0.70	1.50	4.17	4.15	2.35	3.68	3.60	2.73	1.44	28.6
Sum	8.53	8.24	12.62	8.31	19.27	29.11	26.58	19.03	20.56	18.89	12.20	9.34	192.7

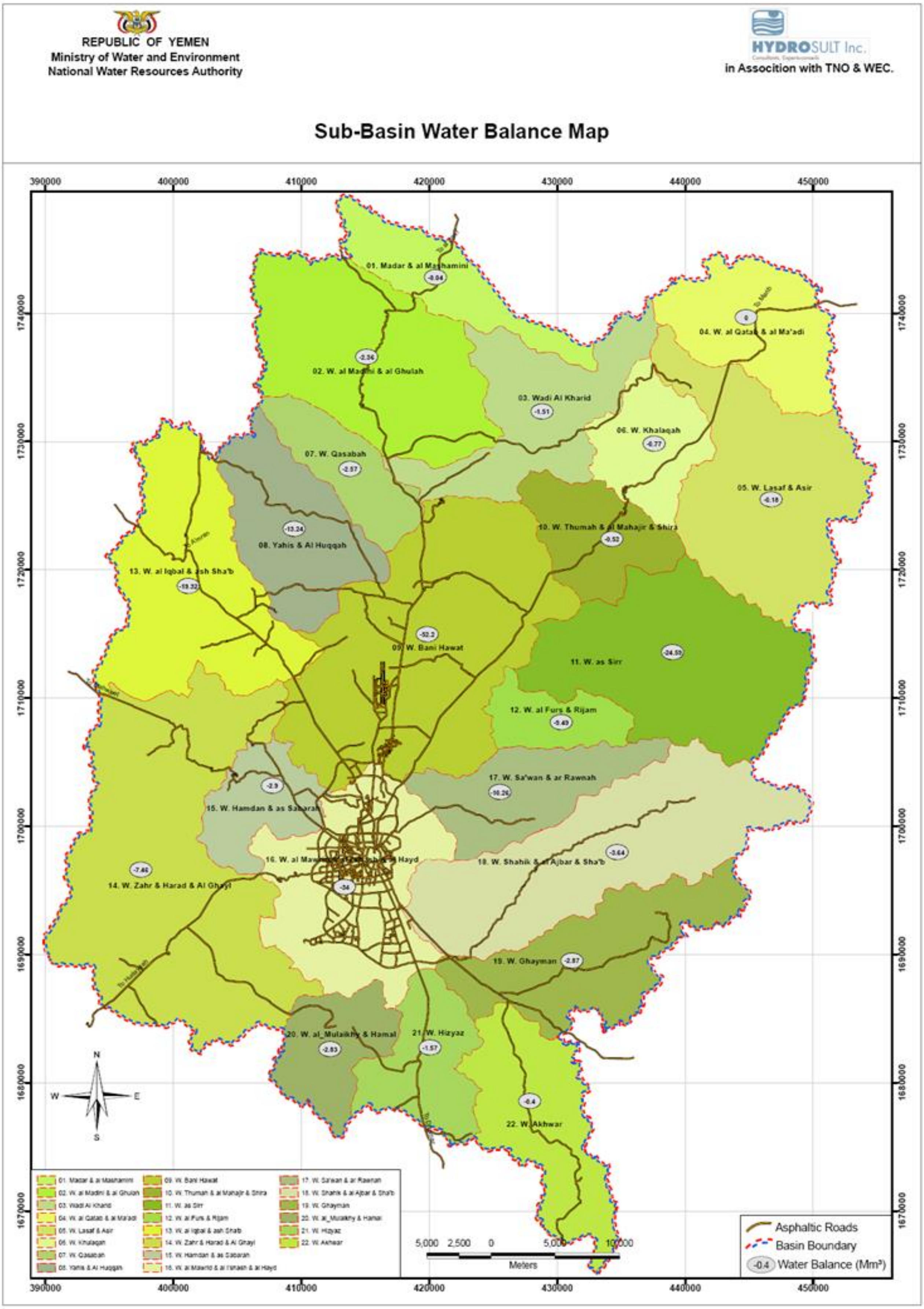


Figure 4 Sub-basin Water Balance Map

Water balances for the year 2007

A. Rainfall

The total rainfall received in the basin in year 2007 based on WEC records is about 649 Mm^3 compared to the average of 663 Mm^3.

B. Catchment Runoff/Infiltration

The total annual runoff generated using WEC stations rainfall record in 2007 is about 67.7 Mm^3 , which is less than the average annual runoff of 75.4 Mm^3

C. Reservoir Inflow

The total reservoir inflow in Sana'a basin in Year 2007 is 4.6 Mm^3 compared to the average 8.8 Mm^3.

D. Recharge

The ground water recharges from all sources that is direct rainfall, wadi runoff, and reservoir and return flow from irrigation. The total amount is 67.8 Mm^3 most of which will come from Wadi Runoff (Table 8)

Table 8 Groundwater recharge in Year 2007 (All sources), Mm^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Reservoir	0.0	0.1	0.5	0.6	0.5	0.5	0.1	1.3	1.2	0.0	0.0	0.0	4.6
Direct rainfall and Wadi runoff	3.9	7.7	7.4	5.1	4.1	0.8	6.6	7.7	1.1	0.0	0.0	0.0	44.4
Return flow	1.5	2.3	2.6	2.4	2.2	0.8	2.7	3.0	1.0	0.1	0.1	0.1	18.7
Total	5.4	10.1	10.5	8.1	6.7	2.1	9.3	12.0	3.3	0.2	0.1	0.1	67.8

E. Water Balance

The total water demand in Sana'a basin for year 2007 is 271.4 Mm^3 (Table 9)

Table 9 The total water demand in 2007, Mm^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
14.6	16.0	21.9	22.7	30.4	33.6	30.2	28.5	25.4	20.7	14.2	13.2	271.4

Water supply delivered, that is the total annual water resources delivered from ground water, surface water, and reservoirs is 75.4 Mm^3 instead of 86.8 Mm^3 for average rainfall condition (Table 10)

Table 10 Water supply delivered from replenishable water sources, Mm^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
5.5	9.1	10.4	9.3	8.8	3.6	10.5	12.2	4.5	0.6	0.3	0.3	75.4

F. Unmet demand

The unmet demand from the natural recharge and surface water resources, or the water withdrawn (mined) from the aquifer for the year 2007 is estimated at 196.4 Mm^3 , which is higher than the average of 192.7 Mm^3.

Water Balance for the year 2008

A. Rainfall

In the Year 2008 rainfall data was collected from 17 stations including the 4 WEC stations. The total rainfall received in the basin in year 2008 based on the 17 stations records is about 409 Mm^3 compared to the average of 663 Mm^3. Hence Year 2008 is relatively a dry year compared to the average.

B. Catchment Runoff/Infiltration

The total annual runoff including infiltration to the groundwater in 2008 is about 47.2 Mm^3 , which is much less than the average annual runoff of 75.4 Mm^3

C. Reservoir Inflow

The total reservoir inflow in Sana'a basin in Year 2008 is 3.3 Mm^3 which is less than the average of 8.8 Mm^3

D. Recharge

The ground water recharge from all sources (direct rainfall, wadi runoff, reservoir and return flow from irrigation) is estimated at 49.8 Mm^3 , most of which is through Wadi Runoff (Table 11).

Table 6 Groundwater recharge in Year 2008 (All sources), Mm^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Direct rainfall and Wadi runoff	3.9	2.8	0.7	0.0	6.0	1.6	1.0	0.8	0.2	4.8	7.1	5.0	33.8
Reservoir	0.0	0.1	0.1	0.0	0.0	0.9	0.1	0.1	0.1	0.0	0.7	0.2	2.1
Return flow	1.5	1.1	0.3	0.0	2.5	1.0	0.7	0.4	0.1	1.9	2.3	1.8	13.8
Total	5.4	4.0	1.0	0.1	8.5	3.5	1.7	1.3	0.3	6.7	10.1	7.0	49.8

E. Water Balance

The total annual water demand in Sana'a basin for the 2008 is estimated at 276.6 Mm^3 (Table 12).

Table 7 Annual total water demand in year 2008, Mm^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
15.1	16.4	22.4	23.1	30.8	34.0	30.7	28.9	25.8	21.2	14.6	13.7	276.6

Water supply delivered from ground water, surface water, and reservoirs is 50.5 Mm^3 instead of 86.8 Mm^3 for average rainfall condition (table 13).

Table 8 Water supply delivered from replenishable water sources. Mm^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
5.5	4.2	1.2	0.1	9.2	4.2	2.1	1.5	0.4	6.9	8.7	6.6	50.5

F. Unmet demand

The year 2008 water demand from the aquifer is estimated at 229 Mm^3 , which is higher than the average of 192.7 Mm^3 (Table 14).

Table 14 Year 2008

Table 9 2008 Modeled Unmet Demand or Water abstracted from Aquifer (Mm^3)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9.6	12.2	21.2	23.0	21.7	29.9	28.5	27.4	25.4	14.3	6.0	7.1	226.3

2.3 ACTIVITY 3 — AQUIFER MODELING STUDIES

The following is a summary of the work completed under this Activity:

Model Design

A Conceptual Model was designed according to the actual Groundwater Dynamic Flow System in the Sana'a Basin. Also, the governing Partial Parabolic Differential Equation was defined, including the Vertical Conductivity Flow between the aquifers. The available well data compiled from the previous studies, were based on different geographic projection systems.In order to correct this situation, this data and information were transformed to a unified geographic coordination system (X,Y,Z), by applying the digital elevation model (DEM) map system .Such information was based on the outputs of Activities 1 and 4.

The processing and interpretation of field hydrogeological surveys and different studies were completed by activity1 and as a result of this activity, the different contour maps for the top, bottom, thickness, and boundaries of each of the following main aquifers were prepared:

- Quaternary Alluvium,
- Tertiary and Quaternary Volcanic Group,
- Cretaceous Tawilah Sandstone.

These maps were essential for the actual simulation of the delineation of the water bearing formations.

The groundwater dynamic flow system was determined for the; one layered aquifer, two layered aquifer, and the three layered aquifers. This information was represented in a distribution map, where the flow system constitutes one hydraulically connected system.

The conceptual model was designed according to the actual groundwater flow in the basin. The model is simulated by two layered aquifers, where the horizontal flow and the vertical conductivity flow between the simulated layers was considered. Such concept gave actual simulation for the dynamic flow system of the basin. The prevailing hydrological conditions, including the Constant Head Boundary, the General Head Boundary, Permeable Boundary, Closed Boundary, and Recharge Boundary were defined, edited and imported to the New Model.

Data Preparation

The available hydrogeological well data were filtered and their validity checked. These data were imported to the New Model. The Head Observation points for each simulated layer were checked and imported also to the New Model in MODFLOW format.

The flow properties for each aquifer were defined from the output of the pumping test analyses. Activity 1 carried out new pumping tests in some locations in the Basin. The past and present pumping test data were re-analyzed, and general values for the Hydraulic Parameters were determined. The results of the pumping test analyses and the output of the calibration runs for the old Sana'a Model (Naaman, 2004) were checked and selected values were considered as initial values for the New Model.

Total groundwater abstraction values were compiled after filtering the available data collected by the Consultant's teams for Activities 1 and 2, including the WEC survey data.

Complete information about the pumped wells was prepared in Visual MODFLOW Form, including the coordinates, screen ID, absolute level of top and bottom of the screen, starting time, stop time, and pumping rate in cubic meters per day. These data were documented in a database and stored in soft copy (excel Form) and in hard copy.

The observation wells data were also compiled from the different studies carried out since 1972. These data were compiled in Visual MODFLOW format, including the X and Y co-ordinates, Screen ID (number of aquifers penetrated by the well screen), Screen Elevation, Observed Data and corresponding Observed Head Value. All these data, were documented in the Database attached to the Sana'a Basin Modeling studies in software (excel sheets) and in hard copy. GIS modules were provided for data automation, mapping, viewing spatially varying information layers, and spatial analysis of information layers.

Pumping Intensity distribution maps (pumped water per square meter for each grid cell) were constructed and documented in soft (PDF and SHP files format) and hard copy for different periods. These maps are presented in a special album attached to the Modeling Studies documents.

Calibration of the Model

The Model Run setting was determined, including the Layer Type and Numeric Engine for solving the Flow equations. The re-wetting setting was introduced to allow for rewetting of the "dry" cells if the head dropped below the bottom elevation of the grid cell during iterations within the simulation runs.

Seven Budget Zones were edited; four zones are located in the first simulated layer and three are located in the second simulated layer. These zones were defined to obtain complete water balance components for each water flow system zone and for each aquifer formations.

Steady State Calibrated Runs were carried out for the base year 1972. Output of the Calibrated Run was presented, including Calibrated Conductivity Values for the First and Second Simulated Layers. Calibrated Values for Water Balance Components are presented for each of the seven defined user zones.

Details of flow rates were determined, both inflow to and outflow from each Zone to other Zones, whether laterally or vertically. Also, flows from or to Constant Heads, Wells, Drains, Recharge, and General Head Boundaries, were determined. The Calibrated and Observed Scatter Graph, and the Calibration Residuals Histogram were presented. Finally, the Calculated Head Contour Map was submitted.

Adaptive time stepping was designed whereby the initial time step size, the minimum and maximum time step size, the time step multiplier, and a time step reduction factor for each stress period were defined.

Visual MODFLOW automatically merges all the different time period data defined for each pumping well and boundary conditions into the uniform stress period format required by the MODFLOW.

Running the Model

The simulated layers were subdivided in 7 flow budget zones; 3 zones in the first simulated layer and 4 zones in the second. Such distribution gave the complete water balance components for each aquifer formations. The steady state calibration run gave the areal distribution for the conductivity (Kx, Ky, Kz) for each simulated layer, and for each cell.

The transient run was carried out for the defined period, and each period covering the corresponding time steps. The specific yield and storage coefficient (the storage coefficient equals to the specific storage multiplied by the formation thickness), were defined as a result of transient state calibration. Selected hydrographs from the different studies were applied to get the goodness of fit of measured heads with the calculated.

Calibration residual histogram and the scatter graph of calculated head versus observed head including the residual values (max., min., mean, and absolute mean), were presented. Such graphs gave the confidence interval, and the accuracy of the calibration results. For each model run, the adaptive time stepping was designed to give the initial time step size, a minimum and maximum time step size, a time step multiplier, and a time reduction factor for each stress period. Thus, provides improved and control of simulation output.

All the applied input model data were stored in GIS-database. Thus, providing GIS-functionalities to enable the updating of the spatial input data.

Calibrated Values for Water Balance Components for the present status were computed for each of the seven User Budget Zones defined. The variation of groundwater levels during the last three decades is demonstrated in graphs representing the drop of the water level in each of the user-defined zones.

The Computed Groundwater Contour Elevation Map was generated. The Drawdown Contour Map was created, and the over-exploitation areas were determined.

2.3.1 Outputs of Activity 3

Aquifer modeling and simulation studies were carried out, and different new information was obtained whether prepared or introduced during the achievement of these studies. This new information was established during the different phases of implementation; model design, model input, running the model, and model results evaluation.

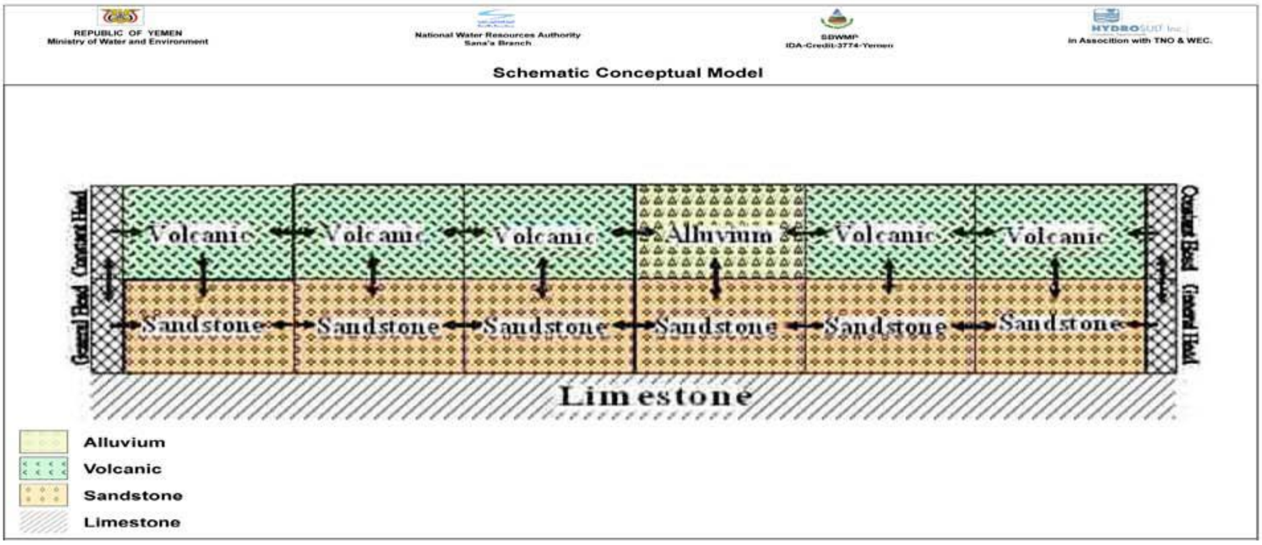
2.3.1.1 Model Design

A New Model Domain was created including the Grid Network and Grid Layers. The fine grid network was designed to reflect the density of the available data, and meanwhile to stress on the over-pumped areas. The Layers' Surface Elevation Maps, including the Ground Surface Elevation Contour Map aquifer delineation maps were edited and imported to the new Model Domain.

The study area was discretized into 63columns and 70 rows with cell size ranging from 750x750 meters in the centre to 1500x1500 meters outwards. Such network is quite accurate as it corresponds to the current density of updated data, Naaman model on the other hand was discretized into 37x37 cells only with cell widths ranging from 1 km in the center to 4km near the boundaries.

Aquifer delineations were simulated with very high accuracy, and Groundwater Dynamic Flow system was determined for the different aquifers considering the interaction of the hydraulic connection. The conceptual model was defined, and the hydraulic boundary conditions according to the hydro-geological conditions were identified. The conceptual model is illustrated below.

The recharge and abstraction rates were estimated according to the updated surveys, and studies. The available input water level data were verified by applying different methods including the projection of the data by applying GIS technique for different time layers.



2.3.1.2 Model Output

Four simulations of groundwater development Scenarios were identified and the model was run for each scenario to simulate a number of **potential future aquifer use for** groundwater development and groundwater management.

The first Scenario represents the present status based on the year 2005 and is based on maintaining status-quo and not introducing any management measures. A simulation of this situation at the year 2020 was made whereby the predicted water balance components for 2020 were computed for the continued present rate of pumping, under the same present rate of groundwater recharge.

The second Scenario simulates the effect of water augmentation i.e. the increase of groundwater recharge considering the on-going NWRA activities related to recharge improvement and the government strategies to increase recharge.

The third Scenario aims at maximum sustainability by reducing consumption of water resources and increasing the ground water potential, based on the water resources management action plan for Sana'a Basin prepared by JICA, 2007.

The fourth Scenario is the combination of Scenarios 2, and 3. And simulates the effect of water resources management (JICA, 2007), and the ongoing government plan for increasing recharge in some selected sub-basins.

The output from each Scenario as well as the detailed water balance components for each budget zone outlining the over-exploitation areas were defined for both simulated layers. The predicted groundwater level and values of the contour head were computed and plotted for each model run for each of the proposed scenarios. In addition, the calibrated flow balance graph for each model run was prepared, showing the discrepancy value with respect to the total inflow and the total outflow.

The complete predicted water balance components for the different runs for each of the seven defined budget zones, for the present status and for each of the proposed four scenarios were presented. The components included: Details of flow rates for both lateral and vertical (leakage) inflow to and outflow from each zone to its adjacent zone, flows from or to Constant Head or General Head Boundary, Wells Drains and Recharge. Such information is very valuable for evaluating groundwater potential.

The pumping intensity for the present status is shown in figure 5, where the high intensity areas range from 0.5 t0 2.0 meters/year. Such intensity exceeds the mean annual recharge. Thus, a continuous drawdown was recorded in the middle of the Northern part of the modeled area. The proposed management strategy, suggests to decrease the pumping rate at the high intensity pumping rate locations to a reasonable rate. The values and the rates of such decrease in each location were established based on the values of the recharge rate and the hydraulic parameters, as defined by the outputs of the calibration run of the model at each location. The results are illustrated in Figure 6

The complete data of the different rates of intensity of pumped water and the corresponding data of the pumped wells located in each cell, were stored in a GIS database to be used in any evaluation of any applied management strategy.

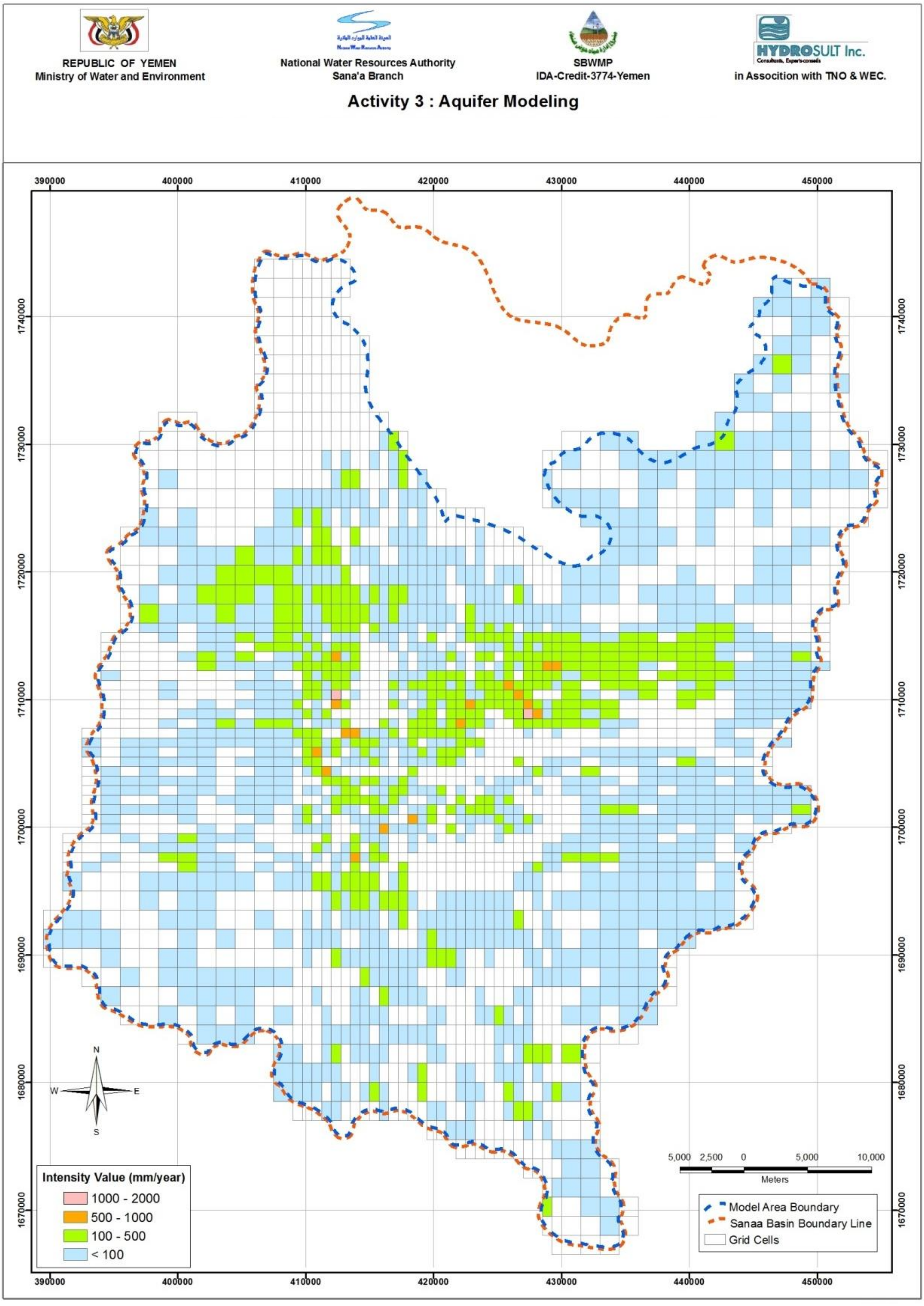


Figure 5 The Intensity of pumped water for the present status

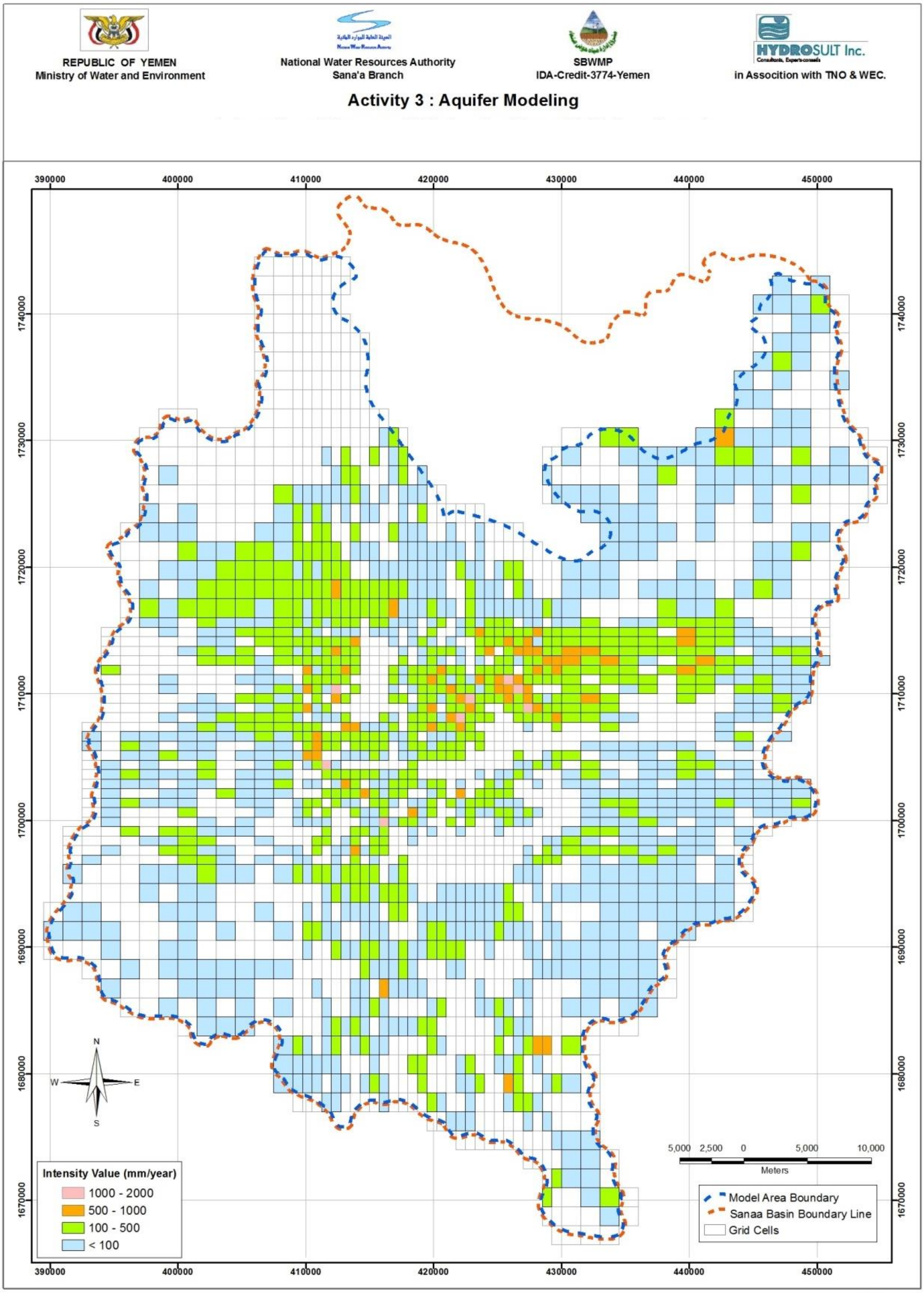


Figure 6 The proposed intensity of pumped water for the year 2020

The predicted outputs and the results for each Scenario were evaluated. And the inter-related results for each Scenario with respect to the other were analyzed . These outputs gave complete idea of the expected relative severity of the groundwater position. Table 15

The expected over-exploitation zones for each run for each of the two simulated layers were determined and by applying the GIS shape file, the area of each zone was defined and plotted on predicted overexploitation maps. Figures 7 and 8 (in Annex I), show the predicted overexploitation areas in 2020 for both simulated layers for Scenario 1 representing the continuation of the present status. Figure 9 shows the overexploitation areas in the year 2020 formed in the first simulated area when adopting Scenario 4. It should be noted that the overexploitation areas, which have been formulated in the second simulated layer when applying scenario 1, have been recovered due to the effect of applying Scenario 4.

Table 15 illustrates the simulated results of the four scenarios considering scenario 1 as the base situation i.e. status quo. Application of the three other scenarios reduces the areas of over exploitation and thus would improve in the groundwater potential in the basin. The highest advantage would be effected by applying Scenario 4, whereby the over-exploited area would be reduced in size from 360 km2 to 46 km2 in so far as the first simulated layer is concerned and completely recovered in the simulated layer 2.

Table 10 Evaluation of the results of the proposed scenarios

Table Scenarios	**Predicted Over-Exploitation Areas Km. Sq**		**Percent of water Potential Improvement (%)**	
	1st Simulating Layer	**2nd Simulating Layer**	**1st Simulating Layer**	**2nd Simulating Layer**
Scenario 1	360 (fig. 6)	104 (fig. 7)	---	---
Scenario 2	318	97	11.7	5
Scenario 3	59	---	83.6	100
Scenario 4	46 (fig. 8)	---	87.2	100

The model was run as one complex hydraulic unsteady state system with hydraulic interaction between the two simulated layers to simulate the situation under scenario 1.The predicted groundwater elevation and predicted equipotential head contour map for the year 2020 in the first and second simulated layers respectively were constructed. Figures 9 & 10 (in Annex I) illustrate the effect of maintaining the prevailing hydrological conditions (Scenario 1). As illustrated there would be a drop in groundwater level in the case of maintaining the present status of pumping under the present rate of groundwater recharge till the year 2020.

Figures 11 & 12 (in Annex I) illustrate the results of applying scenario 4. As illustrated there is a rise in the groundwater levels in both simulated layers due to the implementation of this scenario for the year 2020, mainly due to the management of pumping rate.

In order to evaluate the actual response of applying scenario 4 with respect to the continuation of the present status scenario 1, the recoverable groundwater contour map was constructed for the first simulated layer, as shown in figure 13 (in Annex I). This map demonstrates the recovered values of more than 240 meters which are located in the over-exploitation areas. In these areas most of the aquifers, particularly the alluvial aquifer had become dry In most of the Eastern and Western parts of the Volcanic aquifer, the recoverable value ranges between 40 to 120 meters.

A recoverable equipotential head contour map was constructed for the second simulated layer under scenario 4 covering mainly the Tawilah Sandstone aquifer depicts that the recoverable values range from 30 to more than 180 meters, with maximum recoverable values at the centre of the modeled area.

In addition to the above the following outputs were achieved:

- A complete **GIS database** was prepared, and the all input data and output results were worked out with complete interaction with MODFLOW system, and presented in special album.
- On Job Condensed **Training Course** has been held at Sana'a Basin Office NWRA for four days. The course was attended by ten specialists from NWRA.
- A number of maps related to the aquifers geometry and delineation, predicted water levels and head, as indicated in this section.

Activity 4 Hydrological monitoring and analysis in Sana'a Basin

The general objective of Activity 4 was to further develop and support the collection of the required hydrological information on rainfall, evapotranspiration, surface water and groundwater for the execution of the water management activities in the Sana'a Basin and its sub-basins.. The initiative aimed to improve the monitoring and data processing skills at NWRA and MAI to support the continuation of monitoring in the future.

The outputs of Activity 4 aimed at providing an organizational basis and to increase the awareness and capacity for the execution of a regular and stable monitoring program. The monitoring exercise provided the data for the analysis of the water resources development which would support the execution of the water resources management planning in the Sana'a Basin. Without a regular and continuous monitoring program it would be difficult to know, understand and predict the condition of the water resources.

Reports and Technical Notes Prepared

- **Technical note on 1-the Inventory of current monitoring practices and the Proposal for execution of monitoring.**

The technical note covered the status of basin-wide monitoring of:

- rainfall and other meteorological data
- groundwater levels
- surface water runoff
- Groundwater - and surface water quality. The inventory used data from the existing databases (at NWRA, NWSA, MAI and others) and will use reports from previous studies.

The contents of the note also served as guidelines for data collection.

- **Technical note 2 on water quality**

The technical note covered the review of the Basin-wide monitoring of groundwater- and surface water quality and contained guidelines for groundwater quality measuring.

- **Monitoring program of the Sana'a Basin.**

A monitoring program was prepared based on the premise of hydrological monitoring by NWRA The SBWMP was to provide additional monitoring equipment. Monitoring staff and transport

- **Technical note on interim results of monitoring activities.**

The collected data combined with the historical provided information on the conditions of the groundwater and surface water resources and on the effects of measures implemented during the project.

- **Final report on Activity 4**

This included all results of the monitoring program. The technical report also specified the required monitoring program and incorporated all relevant information contained in the technical notes. The Final report would also serve as a handbook for the required hydrological monitoring.

2.4.2 Outputs of Activity 4

2.4.2.1 Water Quality Monitoring

A literature review for the water quality studies within the entire Sana'a Basin was undertaken. This was followed by data collection and analysis of reliable water quality data from previous studies.

Comparisons were drawn between hydro-chemical maps that were developed by the project using the 1986 data and the new hydro-chemical maps from 2007 data. The comparison showed significant deterioration of some water quality parameters, while positive changes have been observed in other parameters. Interpretations for all of these comparisons are presented in the report of Activity 4

Results of the intensive water quality sampling and assessment study in the area around treated wastewater passages, showed that the groundwater in the vicinity of the treated wastewater passage is not significantly impacted by the proximity, On the other hand, microbiological analysis showed that some wells in the region were significantly polluted with microbiological organisms.

Designs for a water-quality monitoring network for the entire basin were prepared by the project. For the purpose of finalizing the selection of locations for the water quality monitoring network, the 1986 hydro-chemical maps, 2007 hydro-chemical maps and vulnerability maps were integrated. From this integration, critical locations, where it is essential to install water quality monitoring stations, were determined.Thus, a finalized network of monitoring stations throughout the Basin was developed according to three general priorities for the selected locations, based upon the weight of each location.

In addition, the water quality index approach was applied to study the suitability of the water for different intended uses. Maps were developed for the suitability of water quality in Sana'a Basin: for drinking, irrigation and livestock use, and water type maps were also developed for the different aquifers within the Sana'a Basin.

Locations for surface water monitoring stations throughout the basin were selected and conseqently verified on the ground by field visits to the different proposed locations to assure their suitability

An analysis of the digital elevation model for the basin and delineation of the basin and sub-basin's streamlines through watershed management models allowed the Consultant to determine the basin outlet location through stream delineation. Sub-basin and sub-sub-basin boundaries were then determined using GIS software and the DEM map. In addition, IDF curves and design storms were developed for the basin as a whole. Design storms were used to model different storm intensities and evaluate their impact on the hydrograph of each stream and its outlet.

Land-use maps, surface roughness details and soil maps were used in the watershed management calculations to derive the hydrographs for different locations. Consequently the delineated stream system was converted into a semi-two-dimensional river basin network. This allowed a river network simulation for the streamlines within the entire basin to be performed.

Finally, the water depths at different critical locations within the Sana'a Basin were determined. From this intensive activity, a database of stream hydraulic characteristics was developed for the entire basin.

Furthermore, location of sagging points where surface runoff water is most likely to accumulate to a reasonable measurable depth were determined and 14 surface runoff monitoring stations locations were determined, as well as three monitoring stations along treated wastewater passages.

2.4.2.2 Rainfall Monitoring

The literature review revealed that about 24 rainfall stations have been installed in the area of Sana'a Basin since 1970, through various projects. Of these stations, 15 were installed at different locations within the basin area while 9 others were installed outside Sana'a Basin boundary at a close distance from the basin's boundary. Review of the reliability of these stations showed that none has continuous records for the whole of the 36 years. Some of these stations recorded rainfall over a two-year period, others recorded for five-year period and, in most of the stations, the longest recording period was seven years.

The review showed that the longest recorded period from a single station was 22 years, at Al-Salf station. In the north-eastern part of the basin, the rain intensity reaches 170 mm/year while, in the south-western part, it reaches 330 mm/year. In addition, the nature of the spatial distribution of rainfall over the basin varies drastically from one location to another. Thus, the need for a robust rainfall monitoring network for the entire basin, which has an area of 3200 km2, is indispensable to generate reliable information on rainfall and weather in the Sana'a Basin. Furthermore, data was collected and analyzed to develop a storm pattern for Sana'a Basin.

The data collection procedure was also evaluated, and it was concluded that the system is capable of controlling the data collection time intervals from monthly data points to one-minute time steps.

Preliminary data analysis showed that the data collection system should be re-adjusted to 5-minute time steps since the type of storm resembles the semi-arid-type storms that require smaller time step to typify them. Starting from the upcoming rain season, which starts in March 2007, rainfall data will be collected on a 5-minutes time step basis. However, the total number of existing rainfall stations is eight, while the total number of meteorological stations was only two.

Preliminary rainfall analysis was performed on the available data from 1972 to 2005 in order to determine the new rainfall and meteorological stations' locations,. Other analyses were performed, such as variogram analysis, krigging analysis and residual-error analysis. From the statistical analysis, it was concluded that the total number of rainfall stations within the entire basin should be in the range of 30 to 44 rainfall stations. To that effect, 35 new rainfall stations and 8 meteorological stations are proposed to present the new designed monitoring network within Sana'a Basin.

The following selection criteria are considered for the new stations:

- draw lessons from the residual errors in the existing rainfall station analyses;
- consider the location of the existing meteorological and rainfall stations;
- the elevations of the new stations should be extended to the highest and lowest elevations within the basin, thus the relationship between the ground elevation and rainfall intensity can be developed;
- distribution of the stations in the different sub-basins.
- Field visits to the proposed locations were performed to assign the final location for the new stations

2.4.2.3 Groundwater Monitoring

Developing a monitoring network for the groundwater level began by performing intensive field visits to the entire basin. The selection of new monitoring wells locations was performed through precise scanning of the entire basin and follows the aquifers formation. Accordingly, the survey team was looking for any suitable boreholes or dug wells for water level monitoring. Figure 16 presents the schematization of the methodology used for this task. Thus, the entire basin has been divided into four major aquifers; limestone, sandstone, volcanic and alluvial. One key purpose of this activity was to select reliable monitoring wells through which the different aquifers can be monitored in the future. The locations of the new monitoring wells were selected after inspecting the entire Sana'a basin and following the aquifers formation. Accordingly, the survey team looked for any suitable well, either boreholes or dug wells, for water level monitoring. Once the team found a reliable well, intensive study of the well was performed and the depth to water was measured.

28 Dugs wells and 15 new monitoring borehole wells in the volcanic aquifer were selected. In addition 19 boreholes wells were identified within the volcanic aquifer, but these wells were closed by welded steel plates; they can be rehabilitated with minimal effort and can join the monitoring network in the future.

52 Dug wells and 8 borehole wells were selected within the boundary of the limestone aquifer and 12 dug wells and 16 borehole wells were selected for monitoring the sandstone aquifer. 46 dug and borehole wells were selected for the monitoring network in the Alluvial aquifer. Thus, there are now 150 monitoring wells throughout the basin, through which the four aquifers can be regularly monitored and groundwater surface level can be monitored for the future.

Proposed locations for checking the availability of existence of groundwater monitoring stations were determined on maps. The results ended up with a complete monitoring networks that developed for every aquifer separately. Accordingly, six monitoring stations were for the different four aquifers. These six monitoring networks can be listed as follows:

a. Alluvial Aquifer;
b. Deep volcanic groundwater;
c. Shallow Volcanic groundwater;
d. Deep sandstone aquifer;
e. Shallow sandstone groundwater;
f. Limestone aquifer.

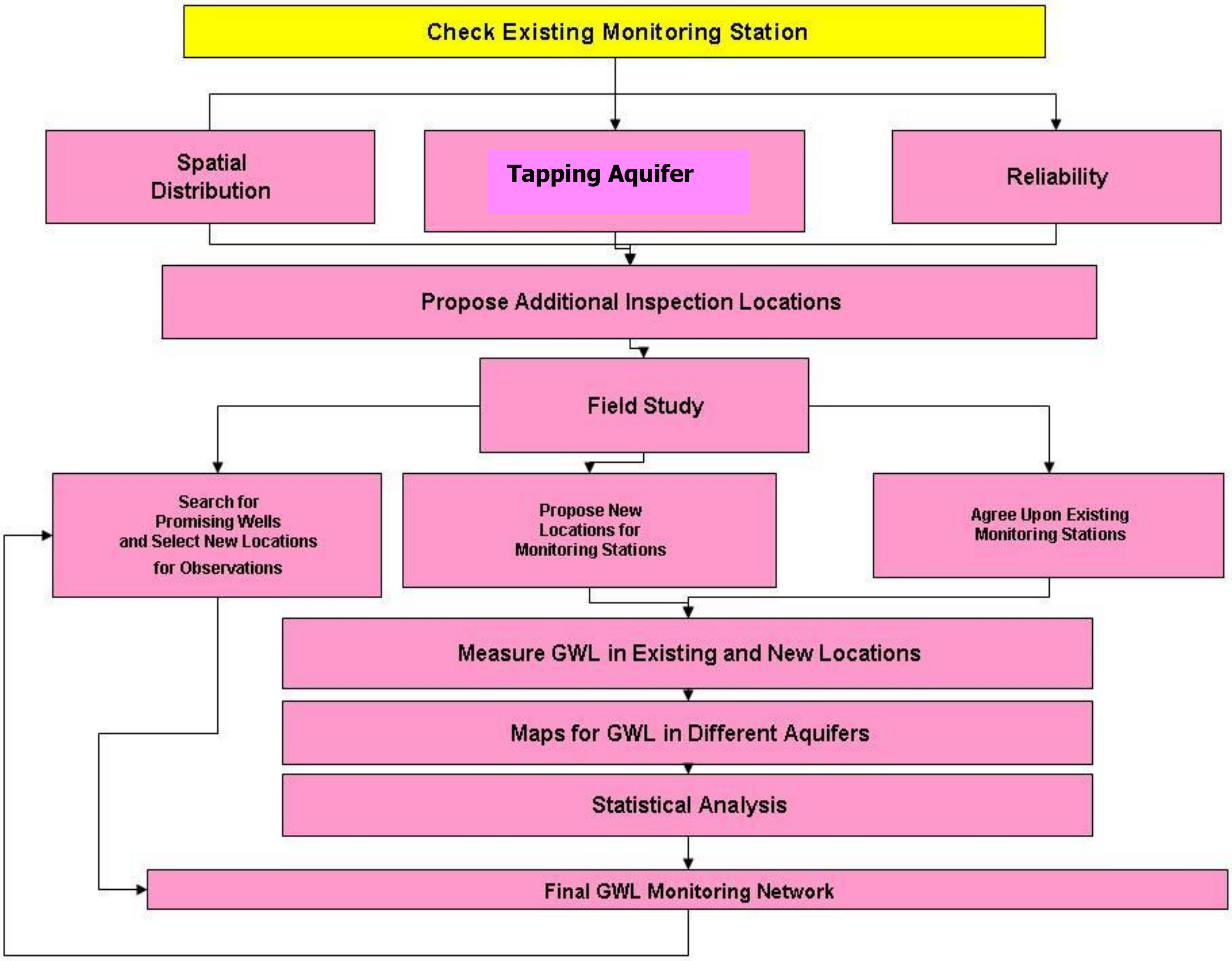


Figure 16 –Selection of Monitoring station

3. OUTCOMES OF THE PROJECT

3.1 MAIN FINDINGS

3.1.1 Integration of results of the four activities

The outcomes of the study are derived from the results of implementation of the four activities of the sub-component 3(d) and the supporting work done by others .

The comprehensive analysis of these results has allowed the Consultant to draw specific conclusions on the state of the water resources in the Sana'a Basin and to highlight directions for the sustainable planning, and management of the basin's water resources and in particular the groundwater resources.

Although the sub-component activities were designed as separate activities, yet the purpose of their implementation was to upgrade and generate data on the water resources, that would allow the SBWMP to better understand the water resources situation in the basin and to help in setting a development strategy for these resources.

Activity 1 addressed the geological and hydrogeological setting of the basin, characterized the aquifers, assessed their hydraulic properties delineated their extent, identified hydraulic connections among them, and assessed depletion and recoverable storage volumes. These outputs were used by all other activities to determine some of their respective outputs such as recharge to the aquifer by Activity 2 and simulation parameters by Activity 3.

Activity 2 main purpose was to calculate the water balance of the basin through 4 sub-basins and their 22 catchments. It also assessed the effect of the reservoirs on the recharge of the aquifers. Activity 4 set up a protocol for monitoring surface and groundwater, and the impact of waste water on the quality of the groundwater. The installed monitoring networks in the four experimental sub-basin.s, selected and assessed by Activity 2 were included in the basin wide monitoring network designed by Activity 4. In addition, results of the monitoring of wells in the shallow aquifer under Activity 2 have been used by all other activities to assess the interaction between surface water and groundwater.

Delineation of the drainage basin by Activity 4 was the basis for the determination of the best locations for the monitoring stations installed by Activity 2.

Activity 3 purpose was to provide the tools that would assist the SBWMP to develop and manage the groundwater resources of the Sana'a basin in a sustainable manner.

Inputs to Activity 3 came from the results of the three other activities in addition to the available relevant data and on-going parallel investigations and projects. Activity 3 was meant to simulate the situation of water resources in the basin according to data either available and or generated during the course of the project implementation. The detailed hydrogeological survey carried out in 2001 covering 13426 water points, including the well type, well location, well depth, construction year, etc, According to the analysis of these data, the following new information have been generated:

- Defining the wells penetrating each aquifer, and the pumping rate for different periods. These data have been projected on shape files format for the; 1972, 1980, 1988, 1993, 1997, and for the year 2000.
- Constructing the shape maps applying the 3D analyst interpolates to Raster Method Griging (the extension of ArcGIS 9.2) for the followings;
  - The distribution intensity of the pumped wells on the grid network.
  - The distribution intensity of the pumped water on the grid network.

Such information was essential for running the model in efficient way, as a tool for future management plan, to define the location of the over- pumped zones.

The water observation data from the available surveys and studies for different periods were compiled by Activities 4 and 2. These data has been projected on the shape layers. The values of the water level in the nearby wells were checked, and distorted values were excluded and were then used for the steady and transient state calibration run.

The recharge boundary conditions were estimated by Activity 2 for the 22 sub-basins. The recharge values were assigned to the upper-most active wet cell for each of the above-mentioned sub-basin.

The analysis of the pumping and recovery tests carried out by Hydrosult staff and previously conducted tests, were rechecked and interpreted by Activity1. Accordingly, the values of the hydraulic parameters were reviewed and the selective values were used as initial representing values for the calibration runs.

Based on the interpretation of the hydrogeological conditions and the hydrogeological cross sections, The applied hydrological boundary conditions were defined by Activity 1. The hydraulic interaction between the constant head boundary and the general head boundary were then simulated and the boundaries of the two simulated layers of the conceptual model representing the actual hydro-geological conditions were defined by Activity 3. Furthermore, the drain boundary conditions module was applied to simulate the effect of agriculture drains or sewage infiltration. The value of the drain head elevation and the conductance of the drain cells were determined and checked according to the prevailing hydrological conditions.

Other key outputs are the determination hydraulic parameters of the aquifers, water balance components, updated water table maps and the equipotential head contour maps, maps of the over-exploitation areas, and the groundwater recoverable maps.

3.1.2 ISSUES AND CONSTRAINTS

The detailed investigations in Sana'a Basin have shown that the basin is now within a water deficiency situation. The results of the activities odf the project including the groundwater model showed that the basin is suffering from over-exploitation conditions. Groundwater extraction from the aquifers exceeds the natural recharge by threefold. Water levels have dropped and in several locales aquifers are subjected to depletion. It should be emphasized here that the abstraction of groundwater has increased at least six fold since 1980.as illustrated in the table below:

Period	No. of new wells	Total no. of wells	Start Time (d)	Stop Time (d)	Pumping (M ^{3}/yr)	Total Pumping (Mm^3/yr)
1902-1972	442	442	0	13140	21.2	21.2
1973-1980	393	835	2920	13140	14,7	35.9
1981-1988	1999	2834	5840	13140	79,7	115.6
1989-1993	966	3800	7665	13140	38,0	153.6
1994-1997	855	4655	9125	13140	31,0	184.6
1998-2000	898	5553	10220	13140	26,4	211.0
2001-2002	412	5965	10950	13140	16,2	227.2
2003-2005	----	-----	10950	12045	16,2	232.3

Water use , especially for irrigation consumes over 90% of the extracted water, and the irrigation practices are far from being efficient.

The areas which have already become dry and require prompt action for proper management were determined. These areas have to be considered for the implementation of a top priority pumping scheme control plan. Meanwhile, measures must be taken to achieve an integrated management plan for the basin. There are numerous reasons for this Water Problem, which may be summarized as follows:

- High rate of population growth and an accelerating rate of social and economic development.
- Limited water resources and insufficient recharge coupled with the continuous improvements in pumping technology and market conditions that are encouraging over-pumping.
- The inefficient approach for planning and management. The integrated approach depends on the implementation of both resource and demand management simultaneously.
- The lack of up-to-date knowledge of the assessment of the water resources in terms of accurate groundwater level, pumped water, as well as reliable forecast of water demand.
- The absence of public awareness in the field of rational use and management of water resources.
- Weakness in enforcing the Laws. Effective implementation of the water policy requires the formulation, application and enforcement of comprehensive regulations and improvement in institutional structure.

The following section summarizes the major issues that require immediate attention and that constitute the key causative elements to the present situation in the basin:

3.1.2.1 Technical Issues

Based on the studies and investigations conducted under this project, and particularly the water balance studies , it can be confirmed that the water resources of the Sana'a Basin are insufficient to fill the needs due to insufficient recharge and replenishable water resources. As indicated earlier in section 2.2, the volume of unmet needs is of the order of 192.7 Mm^3, which is derived from mined groundwater resources. Recharge of groundwater is mainly from surface flow in wadi beds, while recharge from direct rainfall is a rare phenomenon occurring only during intensive rainfalls. Groundwater recharge from all sources is in the order of 51.2 Mm^3.

At this point there are still unanswered questions in relation to the extent of the Tawila Sandstone Aquifer, and its usable saturated thickness as well as its recharge. The water balance estimated in this study is based on the Sana'a Basin hydrological catchment. Part of the recharge area of Sana'a deep aquifer might be outside the Sana'a hydrologically based catchment. However, without suitable groundwater monitoring coupled with additional exploratory drilling and testing it is unlikely that new conclusions can be made to assess exactly the size of the recharge and the contribution from groundwater flow across the basin's boundary. During the course of this study, a drilling exploration and testing project was conducted but the results were not conclusive in so far as the Tawila sandstone potential is concerned

The main issue in water use remains to be the Irrigation practices in the basin, which are not efficient and not conducive to water savings. Irrigation is the largest water consumer of the available replenished and un replenished resources As indicated earlier the total estimated consumption is 221 Mm^3 for 18953 ha (GAF 2007). In the case of farms with the traditional system of irrigation, irrigation efficiency is about 56% whereas at the farms, where modern irrigation systems such as drip irrigation, are installed and practiced, irrigation efficiency of water application is close to 90%.

3.1.2.2 Institutional Issues

The high rate of population growth and accelerating rate of social and economic development, particularly in the agricultural sector, has led to high rate of water consumption for irrigation purposes, and urban water supply. This fact has been exacerbated by the inefficient approach to planning and management of water resources, through an integrated framework, coupled with lack of up-to-date knowledge of assessment of water resources. In addition information in terms of accurate groundwater pumped water, as well as reliable forecast of water demand is lacking.

The water balance estimated in this study is based on Sana'a basin hydrological catchment. However, part of the recharge area of Sana'a deep aquifer might be outside the Sana'a hydrologically based catchment. There is need to reassess the previous studies in light of the present one, and to conduct additional investigations. However, without suitable groundwater monitoring it is unlikely that new conclusions can be made to assess exactly the size of the recharge and the contribution from groundwater flow across the basin's boundary.

Farmers are accustomed to traditional irrigation methods that are not conducive to water savings. Farmers knowledge and experience in the rational use and management of water resources, on-farm water management and crop water requirements is inadequate. Proper extension services to address this issue are urgently needed.

The Water Law stipulates ways and means to govern the water sector and the resource, however, the enforcement of the law requires more efficient tools. There is an urgent need for regulatory control of groundwater development and enforcement of an effective drilling licensing procedures as well as water abstraction metering.

Aquifer management rules in so far as abstraction volumes are concerned are inadequate. This is exacerbated by the inadequate documented knowledge of the vulnerability of aquifers to over exploitation. This would require the preparation of aquifer vulnerability maps outlining the degree of spatial vulnerability of the aquifers.

Institutional capacity in the areas of groundwater monitoring, aquifer management and IWRM requires development and strengthening, and training of young engineers in hydro meteorological data collection and analysis should be given great attention. It should also be mentioned that cooperation and coordination among the stakeholders institutions (water resources and agriculture) and water users is weak .

3.1.3 OPTIONS AND FUTURE DIRECTIONS

Options for the sustainable development and management of the water resources in the Sana; a Basin should be based on clear objectives for the protection and use of the water resources in the Basin. This should address immediate priorities mid-term and long term objectives.

These options and strategic directions should address institutional, governance and technical aspects of water resources, building on lessons learned from on-going and previous initiatives. These options should Support and strengthen water management infrastructure, provide clear mandate, sufficient means, adequate capabilities and good knowledge of the water resources.

Based on the outcomes of the present project, the following options are suggested to respond to the issues and constraints facing the water resources of the Sana'a basin.

3.1.3.1 Supply Management options

One key supply management option is to increase the water availability and accessibility through artificial groundwater recharge, whether from dam reservoir, catchment runoff, or return flow from demand sites. A review of previous work on water supply augmentation attempts and drawing lessons from such experience is highly recommended.

Construction of small hill retention dams with small capacity reservoirs in adequate geological terrain and the rehabilitation of some of the existing ones in addition to underground dams to retain flows in wadis, spate breakers and water harvesting structures are viable options for augmenting water supply.

Moreover, traditional water harvesting methods such as cisterns, ponds, terraces, and the diversion of floods have been successful in several semi-arid and arid countries. It is important in the case of Sana'a basin that such options be encouraged , fostered and promoted. The on-going water harvesting activities undertaken by NWRA in the Sana'a Basin are promising and should be fostered and enhanced.

Use of treated wastewater and low quality and brackish water sources should be further investigated and planned within an IWRM policy. A number of studies on re-use of wastewater have been conducted in the Basin and follow-up on these initiatives through feasibility studies and public awareness would contribute to mobilizing additional water supplies for specific use.

An exploratory drilling campaign of three boreholes to explore the extent of the Tawila Sandstone Aquifer was conducted during the course of the project under a separate contract. Results were encouraging , but not comprehensive. Additional exploratory deep boreholes to improve the knowledge base of the aquifer and to gain a better understanding of the basin's hydrogeological characteristics are still needed. Location of these exploratory boreholes should be well chosen and should extend to the extremities of the basin The investigations may need to be extended to areas outside of the basin to cover potential additional water sources to be imported to the basin.

3.1.3.2 Demand Management Options

Irrigation is the largest water consumer with 221 Mm^3 for 18953 ha (GAF 2007). In the case of farms with the traditional system of irrigation, irrigation efficiency ranges between 50-55%, whereas at the farms, where modern irrigation systems are practiced, irrigation efficiency is nearly 90% in terms of water application. Therefore, irrigation water savings of about 40% could be achieved by modernizing the traditional farms. Moreover, if all existing traditionally irrigated areas are converted to modern farms, total annual water balance of Sana'a basin would then be improved from -192.7 Mm^3 to -114.2 Mm^3. Table 3 shows Comparison of average annual water balance with traditional and modern irrigation systems.

There is urgent need to maximize the utilization of available water, especially as 93% of available resources are used for irrigation. Water conservation through the reduction of water consumption in the irrigation sector can be accomplished by increasing the farmers' experience in improved irrigation systems. Thus it is highly recommended that irrigation systems be improved and that losses in conveyance and distribution of irrigation networks be reduced. Introduction of improved irrigation system would be very effective in controlling water supply consumption. wadi protection works in vulnerable areas. Introduction of improved irrigation system is very effective in controlling water supply. Water management and Conservation by introducing farmers to modern irrigation improved equipment and methods that may save up to 40 percent of water to achieve water savings and conservation in agriculture by increasing the efficiency of water use for irrigation through introduction of modem irrigation technologies.

Introduction of Water Conservation including physical interventions would be demand-driven with an incentive system. Improved overall irrigation efficiencies in the target area are expected through upgrades of existing piped conveyance systems; conversions of open channel to piped conveyance systems; and introduction of modem pressurized irrigation to fields already served by satisfactorily piped systems and wadi protection works in vulnerable areas.

To that effect, there is need to enhance farmers' awareness and knowledge in the rational use and management of water resources, modern irrigation techniques such as drip irrigation and sprinklers, on-farm water management and crop water requirements through well designed extension work.

Finally it is important to improve regulatory control of groundwater development and enforcement of effective drilling licensing procedures as well as water abstraction metering. Furthermore, an urgent need for the introduction of aquifer management rules in so far as pumping volumes are concerned. Changing pumping and water use behavior in the basin through a comprehensive public awareness and extension is highly imperative.

Water resource planning and delivery from Sana'a basin should be regulated to match the available recharge volumes and water savings as a result of adopting modern irrigation technologies and crop water requirements. To that effect, pumping from deep aquifer should be limited to domestic and industrial water supply purposes.

3.1.3.3 Institutional and Capacity Building Options

Hydro-meteorological and hydrogeological data monitoring should be continued to update water resource information specially groundwater recharge in the basin and to lead to improved water management. Any future direction or strategy for the development of the water resources of the Sana'a basin should be based on reliable scientific information on the water resources.

To that effect hydrogeological and hydrometeorological monitoring in the basin is a sine-qua-non for any sustainable development alternatives. This process has started during this project and should be continued.

Given the critical water situation in Sana'a Basin, the state of knowledge of the available resources must be updated and improved continuously. Scientific and effective planning of water resources must be supported by reliable data and information managed by well trained human resources in the fields of water resources planning, development and management.

Sana'a Basin must be subjected to an integrated approach water resources development in addition to the measures to be accomplished for proper management. The inefficient approach in planning and management has led to programs that are not focused on strategies for curbing the water wastage and the rapid deterioration of good water quality and the unsustainable use of renewable and fossil groundwater resources. The integrated approach depends on the implementation of both resource and demand management at the same time. The demand management will increase water resources availability and the water resources can be augmented through different means; **water harvesting, groundwater recharge**.

Monitoring activities can only be useful and effective if there exists an adequate institutional enabling environment with proper capacity building and training for the staff engaged in this activity. This includes the adequate equipment, maintenance facilities and know-how, transportation and adequate financial resources. Monitoring alone is not sufficient, since the process has to extend to assessment of the resource, and to that effect, capacity building and training in water resources assessment and management is essential. Water resources data bases fulfil the urgent need for documentation, storage, and dissemination of data required for assessment, planning, managing, and rationalizing the exploitation of water resources.

Institutional and staff Capacity building in the areas of aquifer management, hydrology and IWRM is of utmost importance and should be given great attention. A capacity building and training gaps analysis of the ministry is necessary to determine the real in-country or overseas training needs in the subjects addressed above.

Cooperation among water sector stakeholders, planners and users should be enhanced and should allow for a better decision making process on water allocation and distribution among users. To that effect, an institutional platform that includes decision makers from the water sector and the water users should be established and fostered**. Real water needs for all uses should be determined** and continuity and fairness in allocation and distribution observed in water resources planning and regulation.

A reform of the Sana'a Basin institutional arrangement is thus warranted and a regulatory system and procedures for water rights management, registration and permits of **well users and drillers** would be established within the Basin. The **Sana'a Basin institutional** arrangement would also be empowered to assume responsibility for overall basin-wide water resources investigation and governance.

Water allocation and reallocation strategies should be the focus of a water policy for the development and management of the water resources of the Sana'a Basin over the short term and long term horizons The Policy should introduce a full range of governance instruments to improve efficiency in water resources use and promote their allocation,. It should promote and support science and technology, capacity building and provide an enabling environment for private participation in the development and management of the resource through public-private participation process.

Farmer's awareness should be raised and their capacity developed on the adoption of modern technologies in water management. The results of the current study (Activity 2) has put into evidence that adopting modern irrigation technologies have higher irrigation efficiencies than those under traditional irrigation.

The Participation of the Public and community is an important factor for sustainable development and management of water resources. This participation is dependent on an awareness of the importance of water and the need to conserve it. Farmers, users and irrigation water users need to increase their awareness of the importance of water and rationalisation of water use.

3.2 CONCLUSIONS AND RECOMMENDATIONS

The above findings and proposed options to address the issues related to the water resources availability of the Sana'a basin lead us to recommend the following measures:

3.2.1 Technical Recommendations

The issues raised in this context are related to the availability of the resource and the options to augment it for the different uses. To that effect, **artificial recharge of the shallow unconfined aquifers merits consideration**. It is thus recommended to conduct a detailed study on the possible means of artificial recharge in the basin, **through the mobilization of runoff and flash floods to favorable sub-basins where the geological and hydraulic conditions permit**

Maximizing the available water supply can also be done through water harvesting structures after a thorough evaluation of the possible options.Traditional water harvesting methods such as **cisterns, ponds, , and the diversion of floods, wadi-bed systems; including small reservoirs and Jessour, off-wadi systems such as water spreading systems, Hafair (dug-outs) and contour-bench terraces**. have been successful in several semi-arid and arid countries. It is important in the case of Sana'a basin that such options be encouraged , fostered and promoted.

To that effect, the on-going **water harvesting activities undertaken by NWRA in the Sana'a Basin** are promising and should be fostered and enhanced and technical assistance and capital investment should be provided, primarily to test some of the possible options and consequently to construct a number of these structures in the appropriate locales.

Use of treated wastewater and low quality and brackish water sources should be further investigated and planned within an IWRM policy. A number of studies on re-use of wastewater have been conducted in the past in the basin and outside the basin. The issue with the re-use of wastewater lies in the acceptance of this option by the public. **A well designed public awareness would contribute to acceptance of such an option.**

Water balance studies have put into evidence that **water savings are possible when improved irrigation methods are used.** It is thus highly recommended to raise **awareness** and **provide extension training to the farmers on the advantages** of applying the appropriate crop water requirement and the use of improved irrigation methods where possible, such as **drip irrigation**, **sprinkler** and other methods. This can be effected within a close cooperation **between the Agriculture and water resources institutes**

The present study provided substantial information and generated new data on the water resources of the Sana'a Basin, however, there are still a number of unanswered questions in relation to **the extent of the Tawila Sandstone Aquifer,** which presumably transcends the limits of the basin. An attempt **to explore the depth of the aquifer through deep drilling was completed in the Sana'a basin**. The results were not conclusive , but encouraging. It is recommended to explore the extent of the aquifer beyond the basin with the aim of **identifying options for inter basin transfer** to augment the available water supply in the Sana'a basin.

It should be emphasized that **with the help of the present Mathematical model and the various maps constructed for it, simulation of different scenarios has been made easy. It is therefore recommended to update the data and information through regular monitoring of the established monitoring network.**

3.2.2 Institutional Recommendations

Recommendations of institutional nature focus on the governance issues related to the water resources in the Sana'a basin and on the management of the basin as a whole.

The study has identified areas where over extraction has led to the depletion of the aquifer and the water balance study has estimated the volumes mined from the main aquifers. The demand is threefold the supply and the only source of water supply for the unmet demand is groundwater mining. This of course is not an environmentally sustainable situation. The situation is exacerbated by the **uncontrolled drilling** and abstraction of groundwater. Yemen has a **water law** and disposes of instruments to apply the law. However these instruments and mechanisms must be enhanced and effectively applied. **An improved and controlled licensing and drilling permits process must be established**. **More importantly a restriction on water abstraction in critical areas must be institutionalized.**

The volume of **groundwater abstracted from aquifers of the basin** must be drastically reduced to **match the natural recharge** and other available sources. This option should be applied in conjunction **with the introduction of improved irrigation methods** and **reallocation of the scarce water resources from one use to the other**. To that effect, irrigation water supply should be derived from **surface impounded water and or shallow aquifers**, while the deep Tawila aquifer groundwater should provide domestic, rural and urban as well as industrial water demand. The outputs of Activity 3 (Modeling studies) have provided scenarios through which **the groundwater system in the basin can be**

improved through pumping regulation ,artificial recharge and improved water consumption levels in irrigation

Nevertheless, order to effectively manage the precarious water resources of the Sana'a Basin, **an effective institutional arrangement adequately empowered to monitor plan and develop the water resources in the basin is highly recommended**. Such an institutional arrangement, which could be in the form of a basin authority, would be a multi-stakeholder governing body that would be responsible for water allocation and re-allocation and is empowered to effectively **enforce the water law** and the appropriate regulations for the allocation and use of the water resources in the basin.

Institutional and staff Capacity building in the areas of **aquifer management**, **modeling**, **network management** , **data management hydrology** , **groundwater assessment** and **IWRM is highly recommended** This should be preceded by a capacity building and training gaps analysis to determine the real in-country or overseas training needs in **the within the Ministry , the Sana'a Basin and the ministry of Agriculture**

ANNEXES

ANNEX I

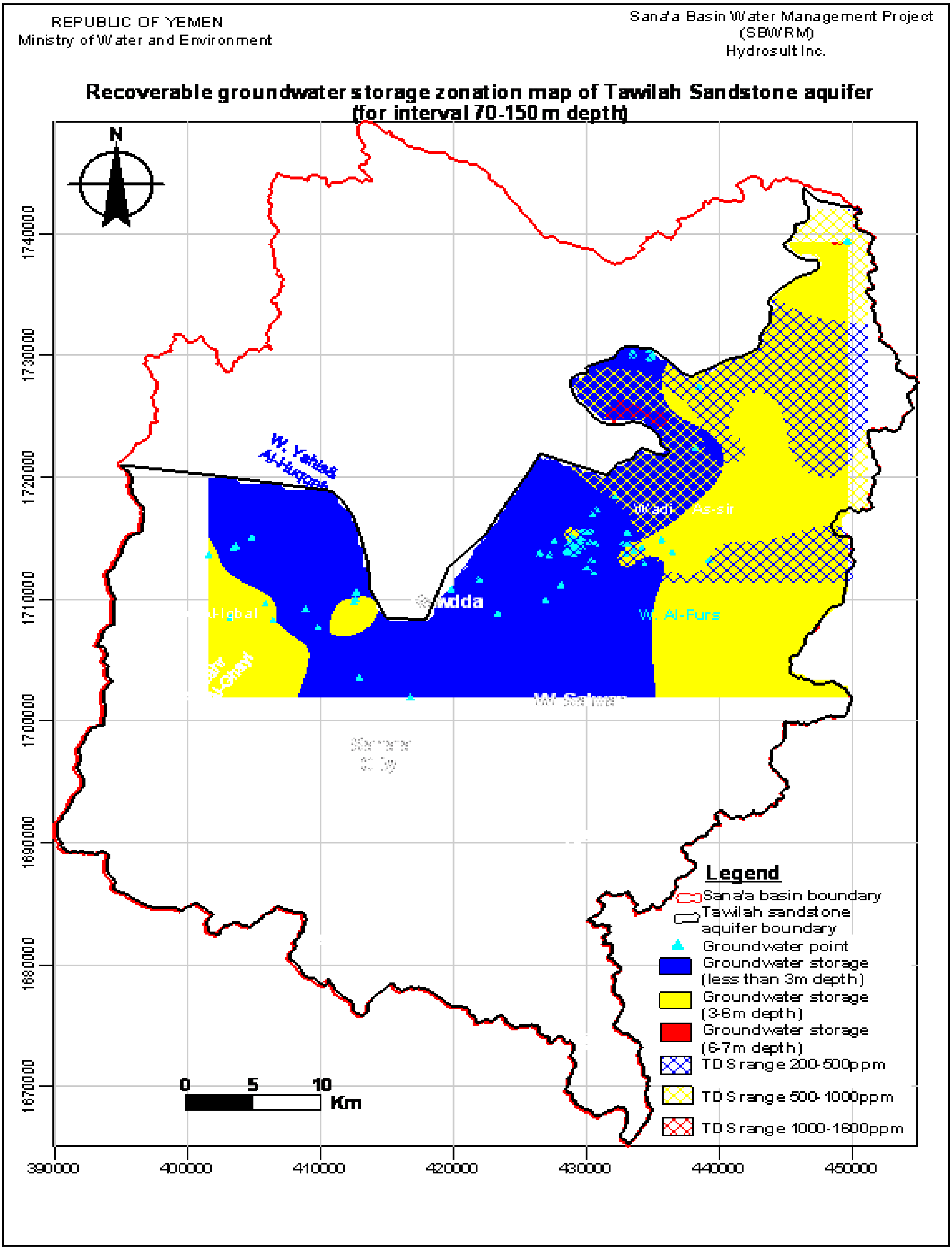


Figure 1A **The recoverable groundwater storage maps of the deep zone of the Tawilah sandstone aquifer**

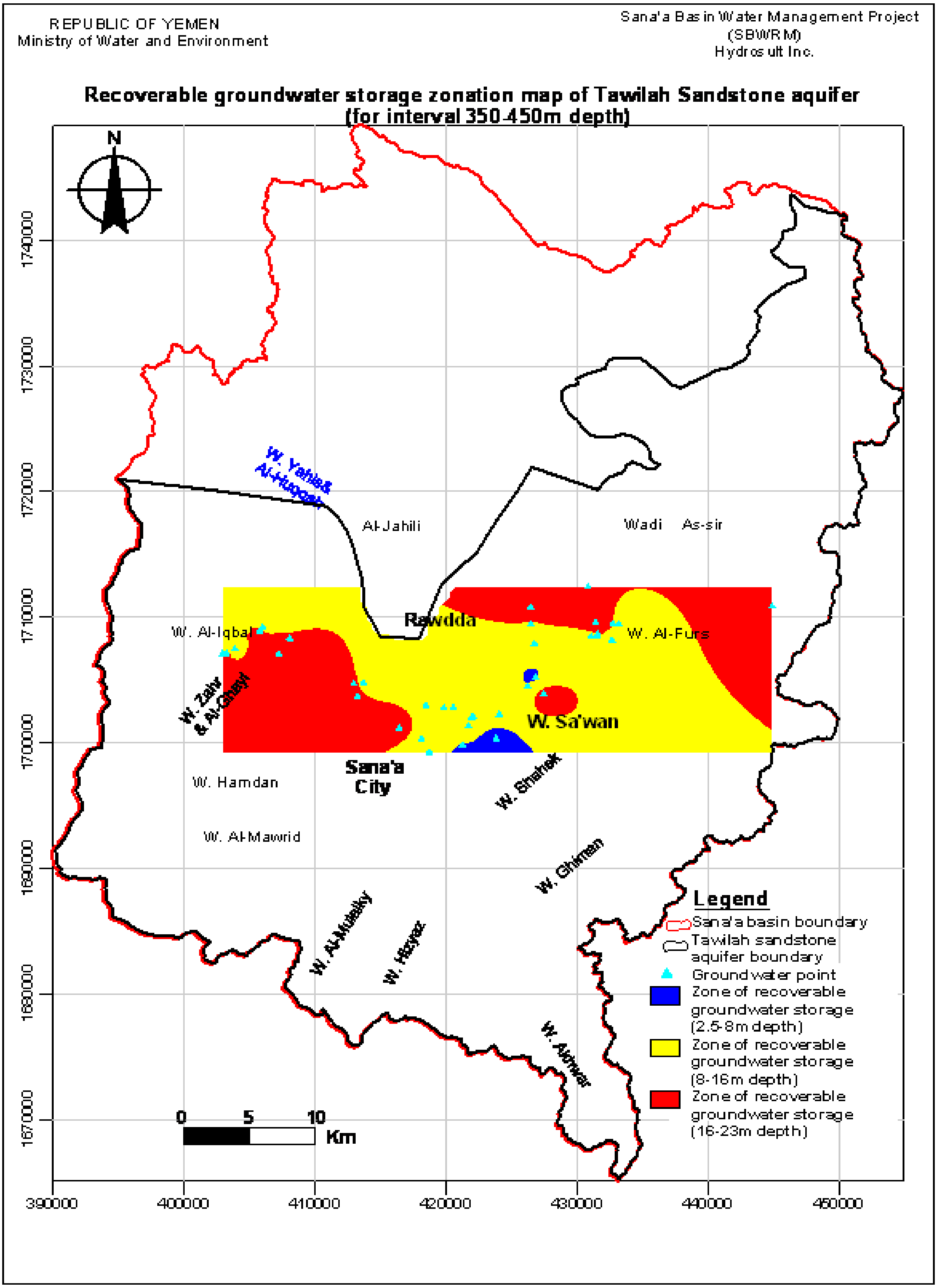


Figure 1B **The recoverable groundwater storage maps of the deep zone of the Tawilah sandstone aquifer**

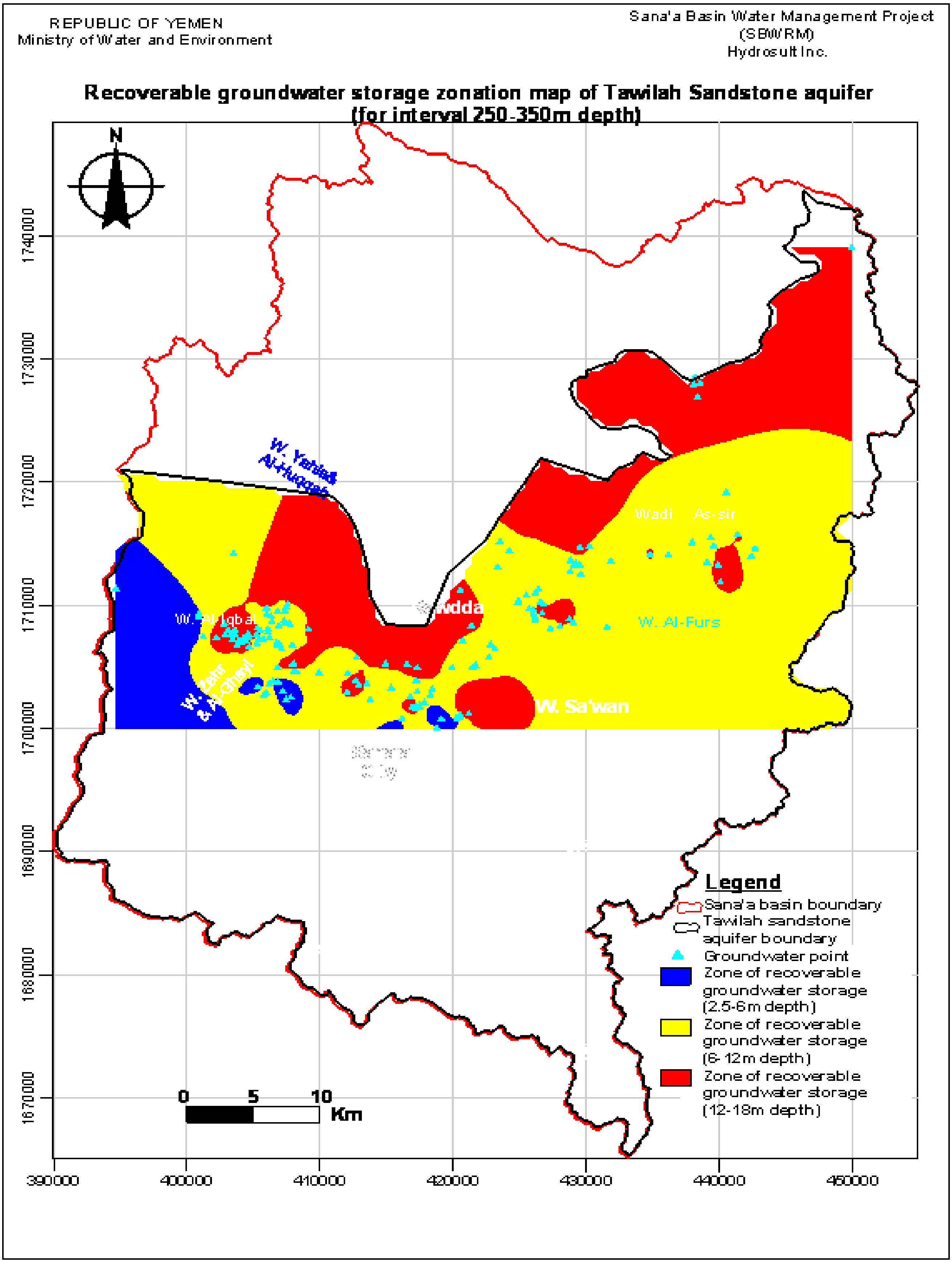


Figure 1C **The recoverable groundwater storage maps of the deep zone of the Tawilah sandstone aquifer**

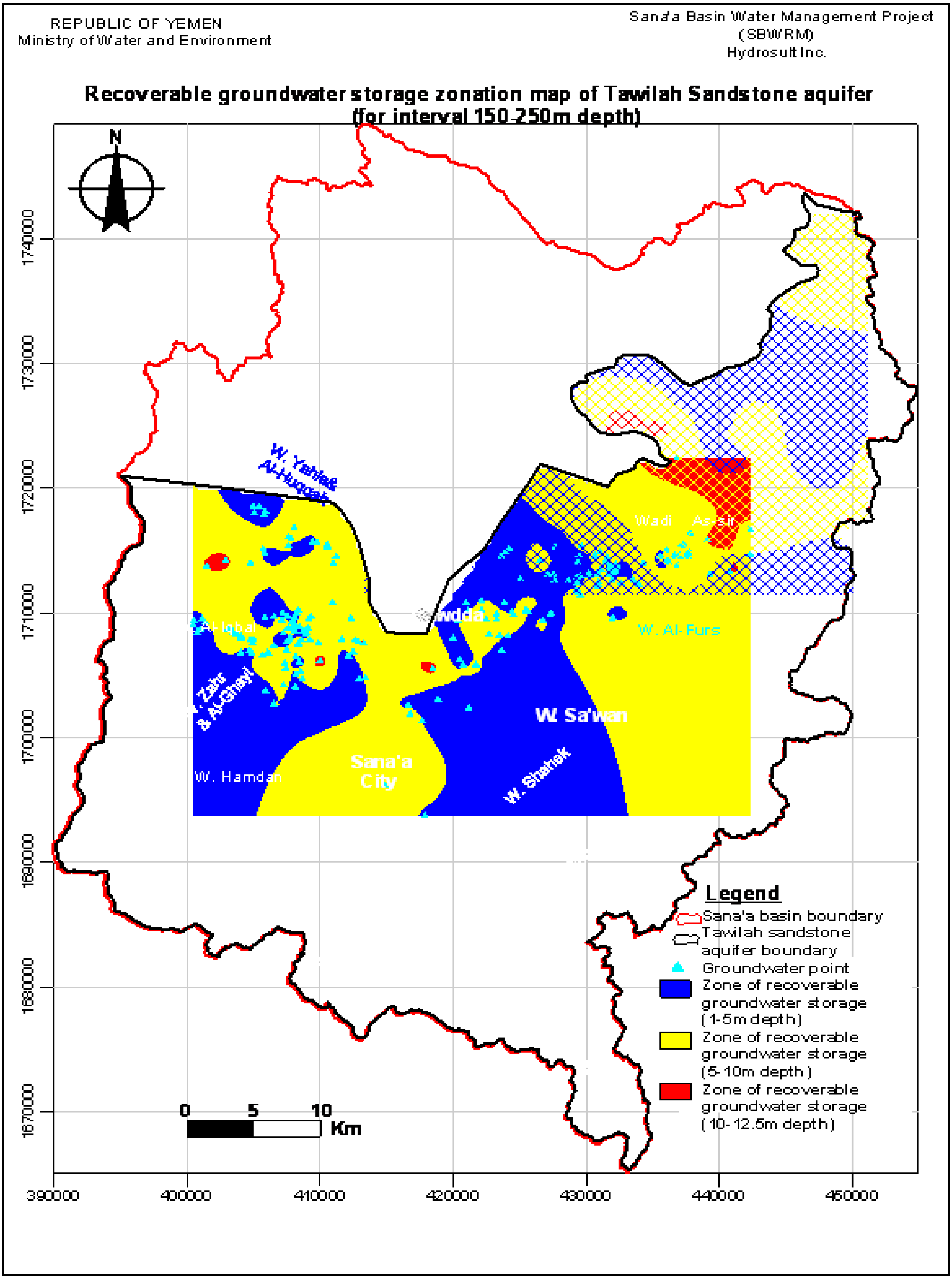


Figure 1D **The recoverable groundwater storage maps of the deep zone of the Tawilah sandstone aquifer**

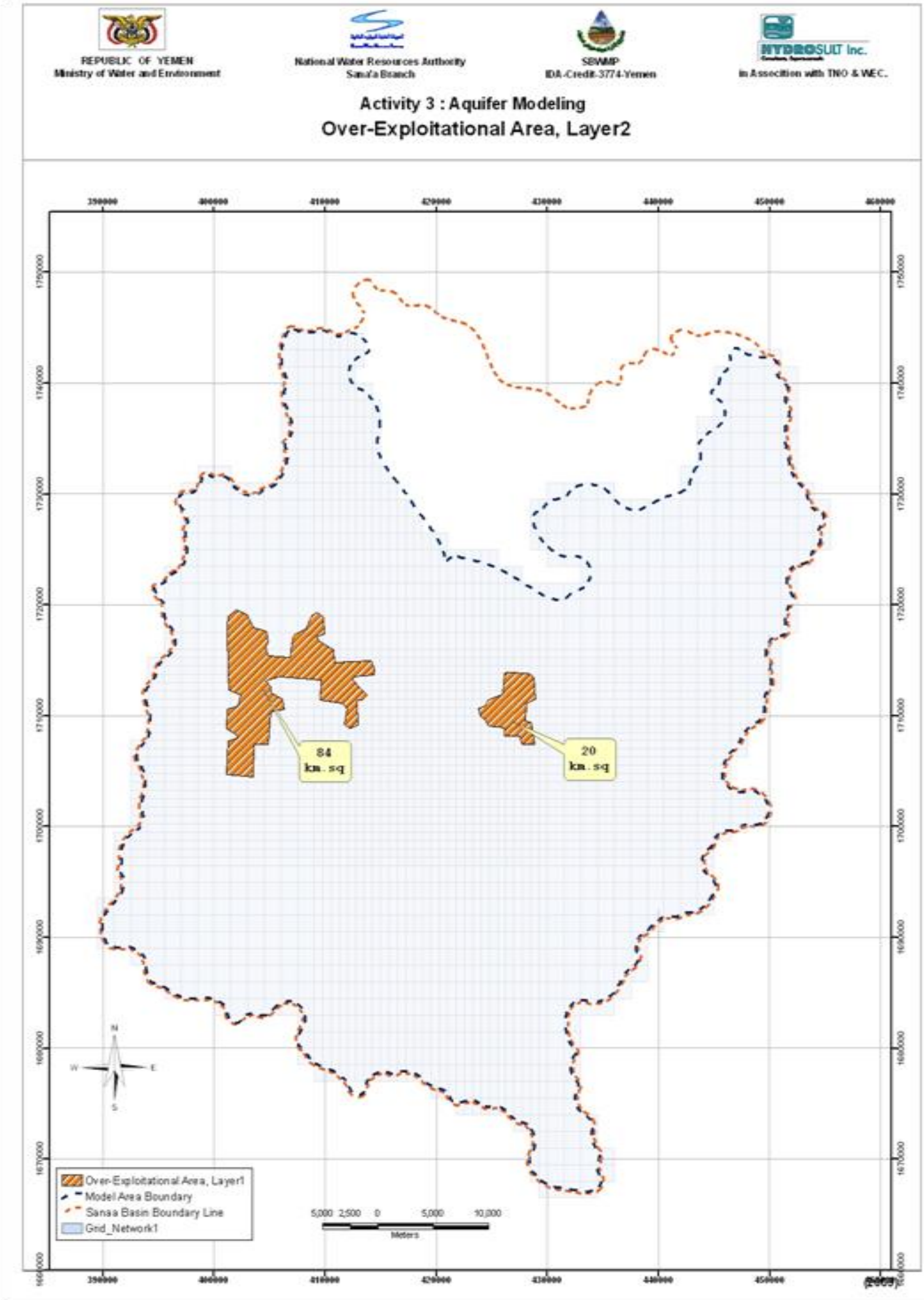


Figure 7 Expected Over-Exploited Areas for the year 2020 In the Second Simulated Layer (Scenario 1)

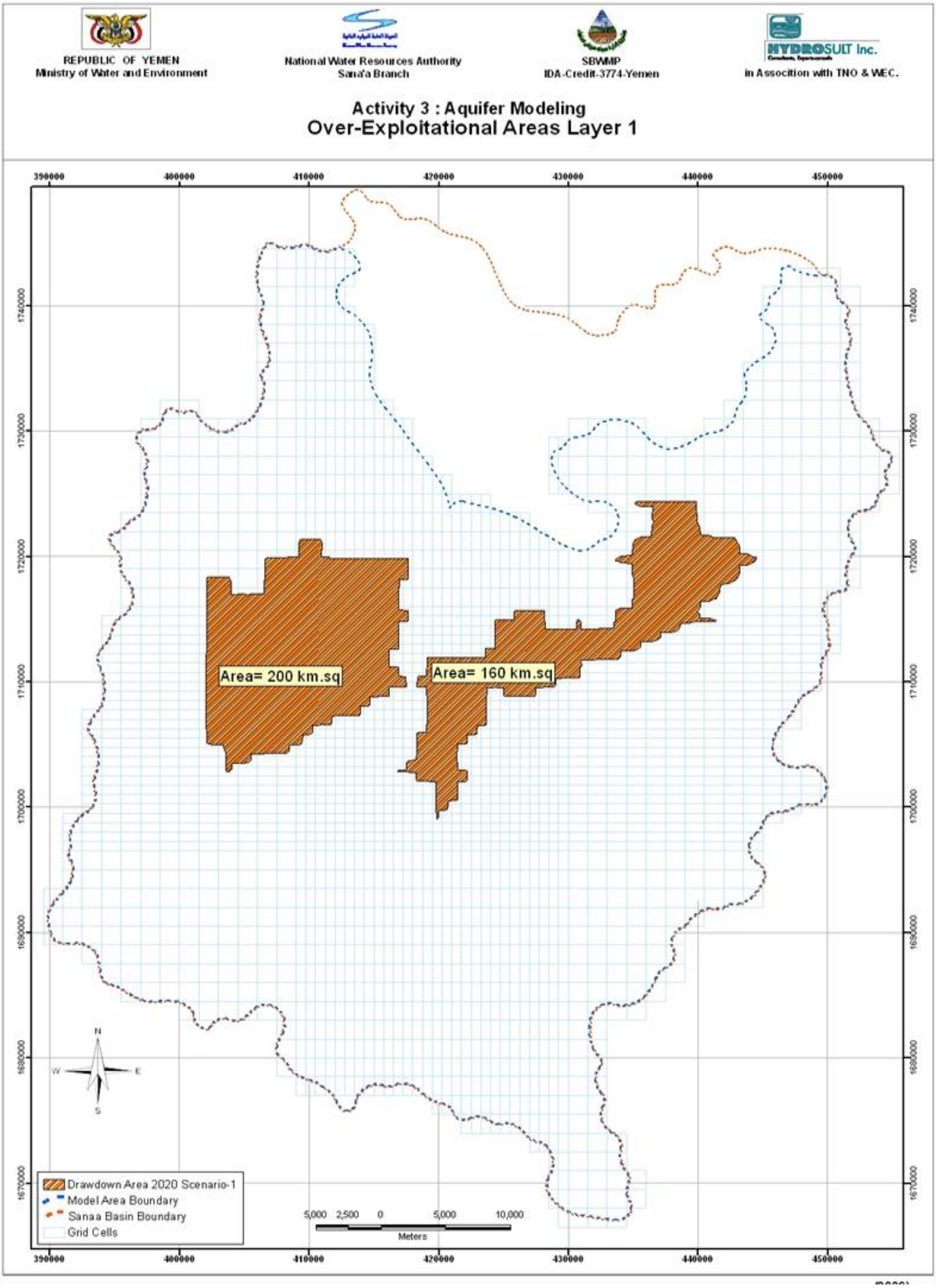


Figure 8 Expected Over-Exploited Areas for the First Simulated Layer for the year 2020 for (Scenario 1)

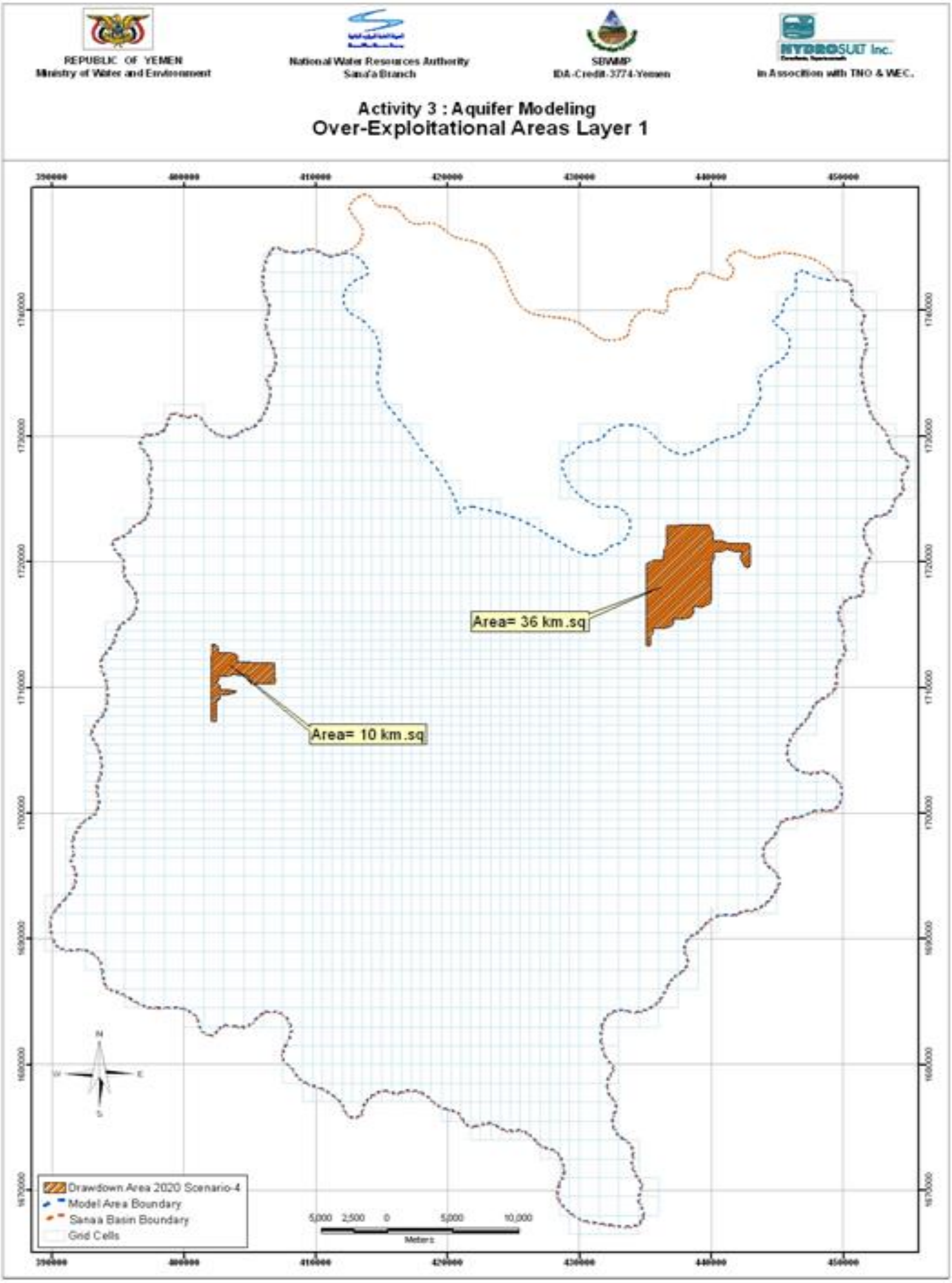


Figure 9 Expected Over-Exploited Areas for the year 2020 In the First Simulated Layer 1 (Scenario 4)

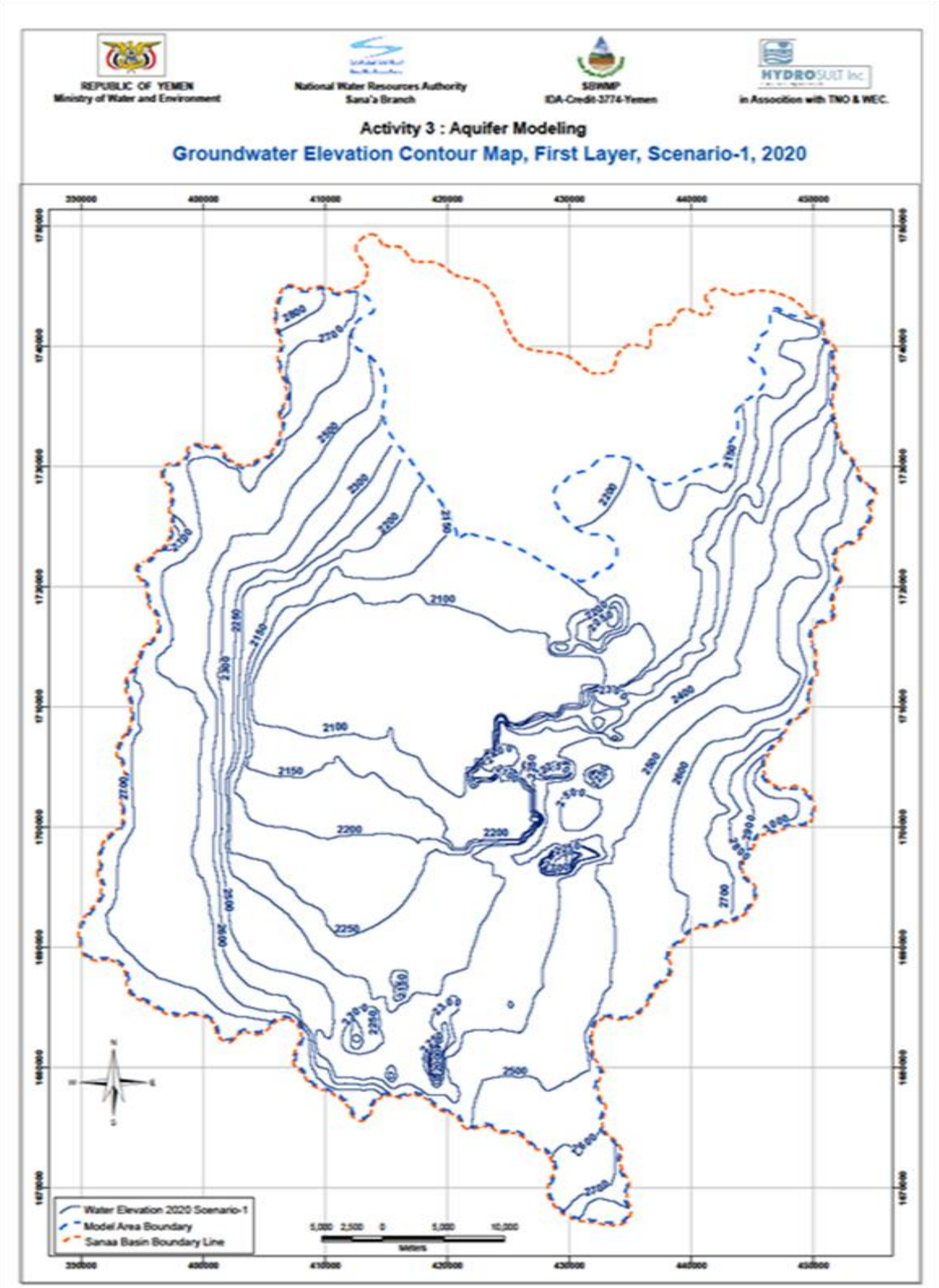


Figure 10 Groundwater Contour Elevation Map for the First Simulated Layer for the Year 2020 (Scenario 1)

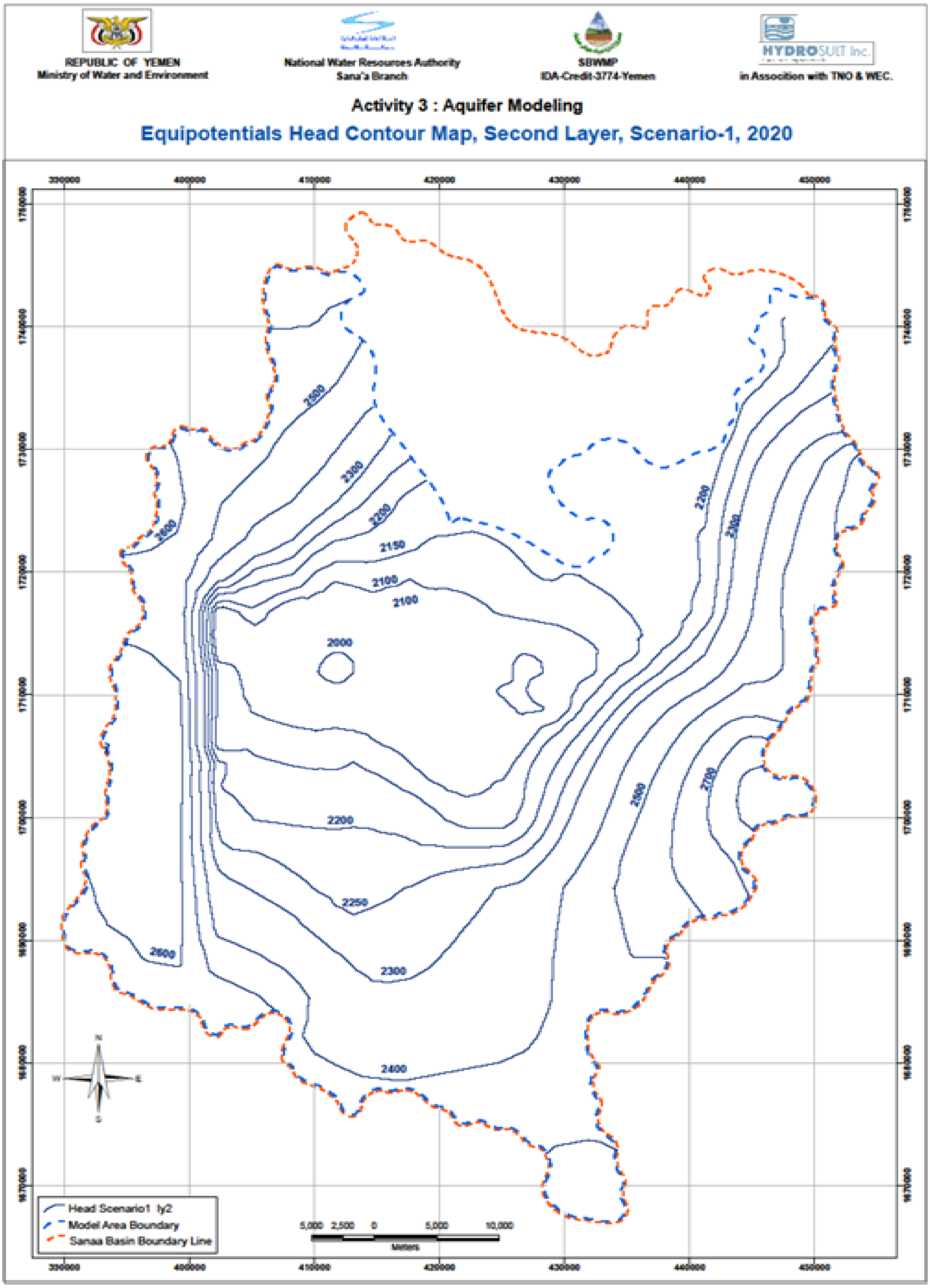
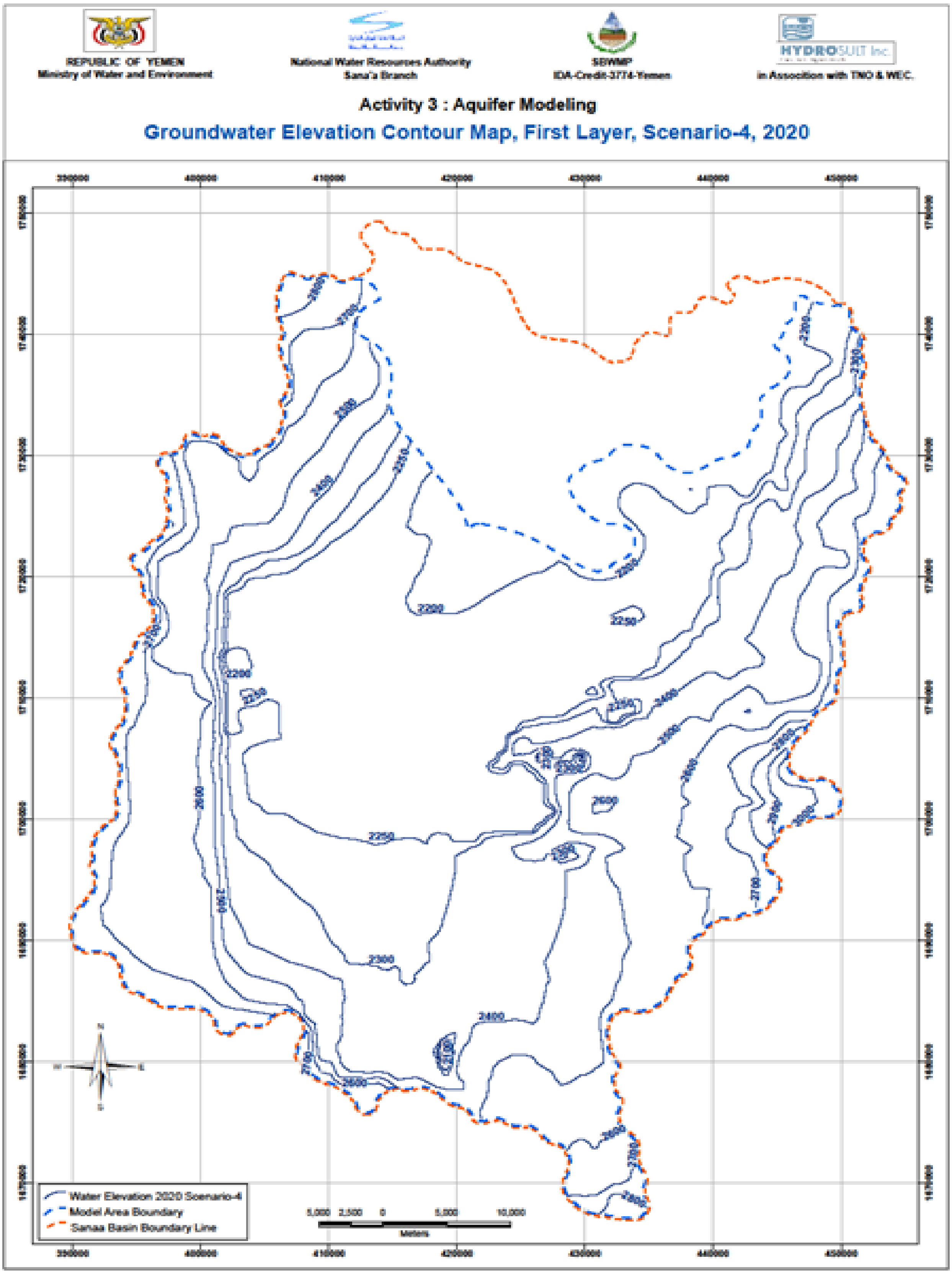


Figure 11 Equipotential Head Contour Map For the Second Simulated Layer for the Year 2020 (Scenario 1)



(2009)

Figure 12 Groundwater Contour Elevation Map for the First Simulated Layer for the Year 2020 (Scenario 4)

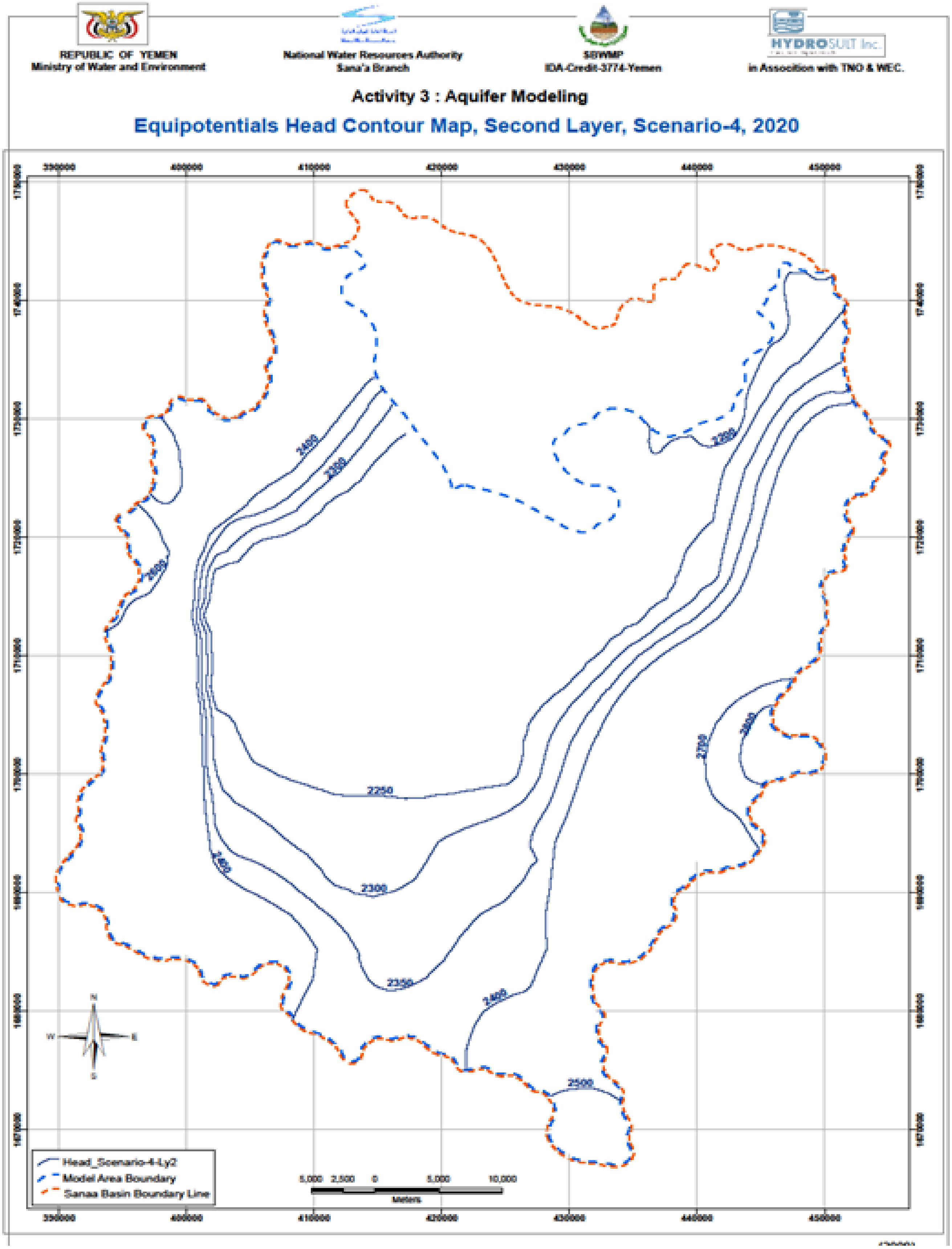


Figure 13 Equipotential Head Contour Map for the Second Simulated Layer for the Year 2020 (Scenario 4)

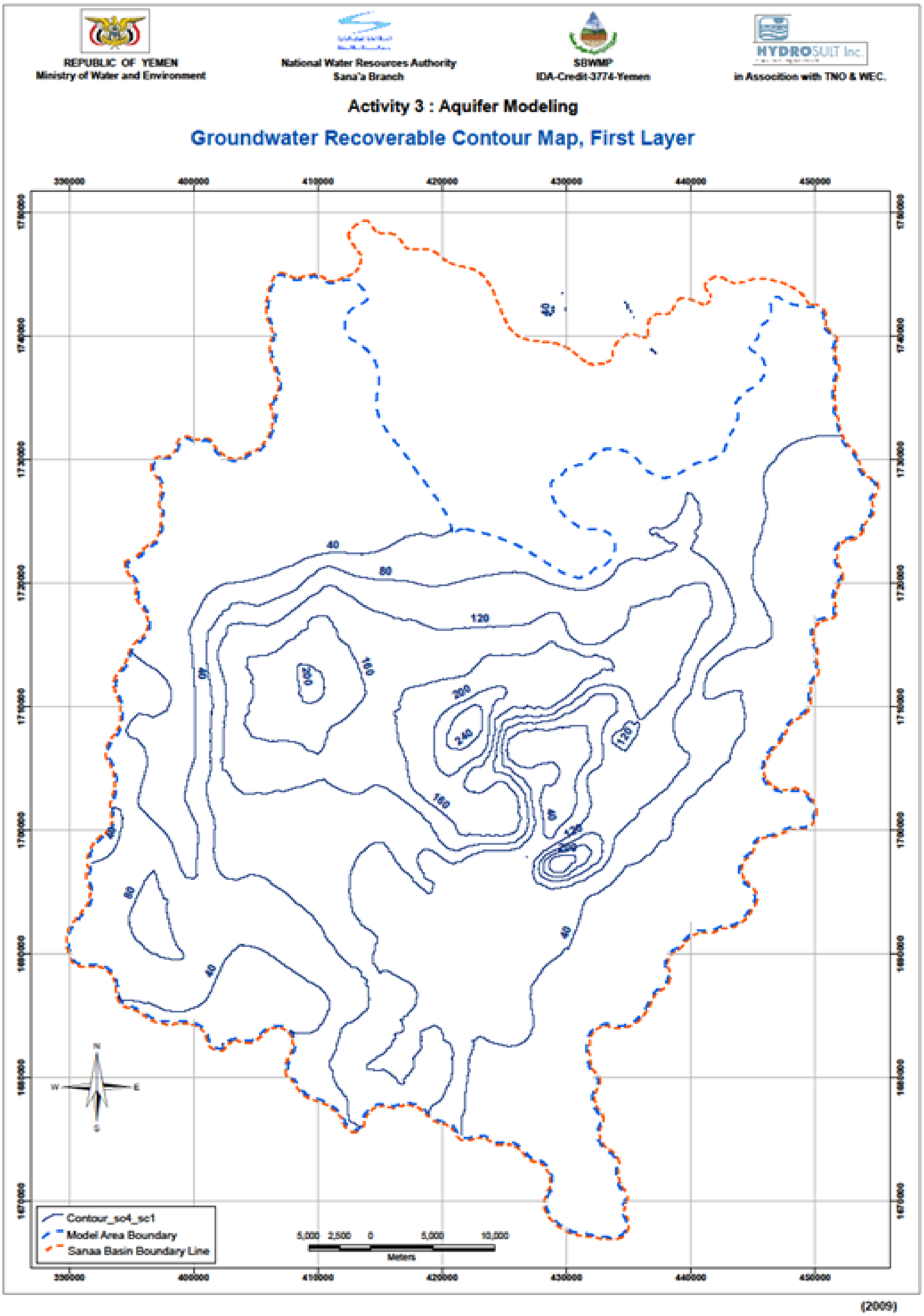


Figure 14 Groundwater Contour Elevation Map for the First Simulated Layer for the Year 2020 (Scenario 1)

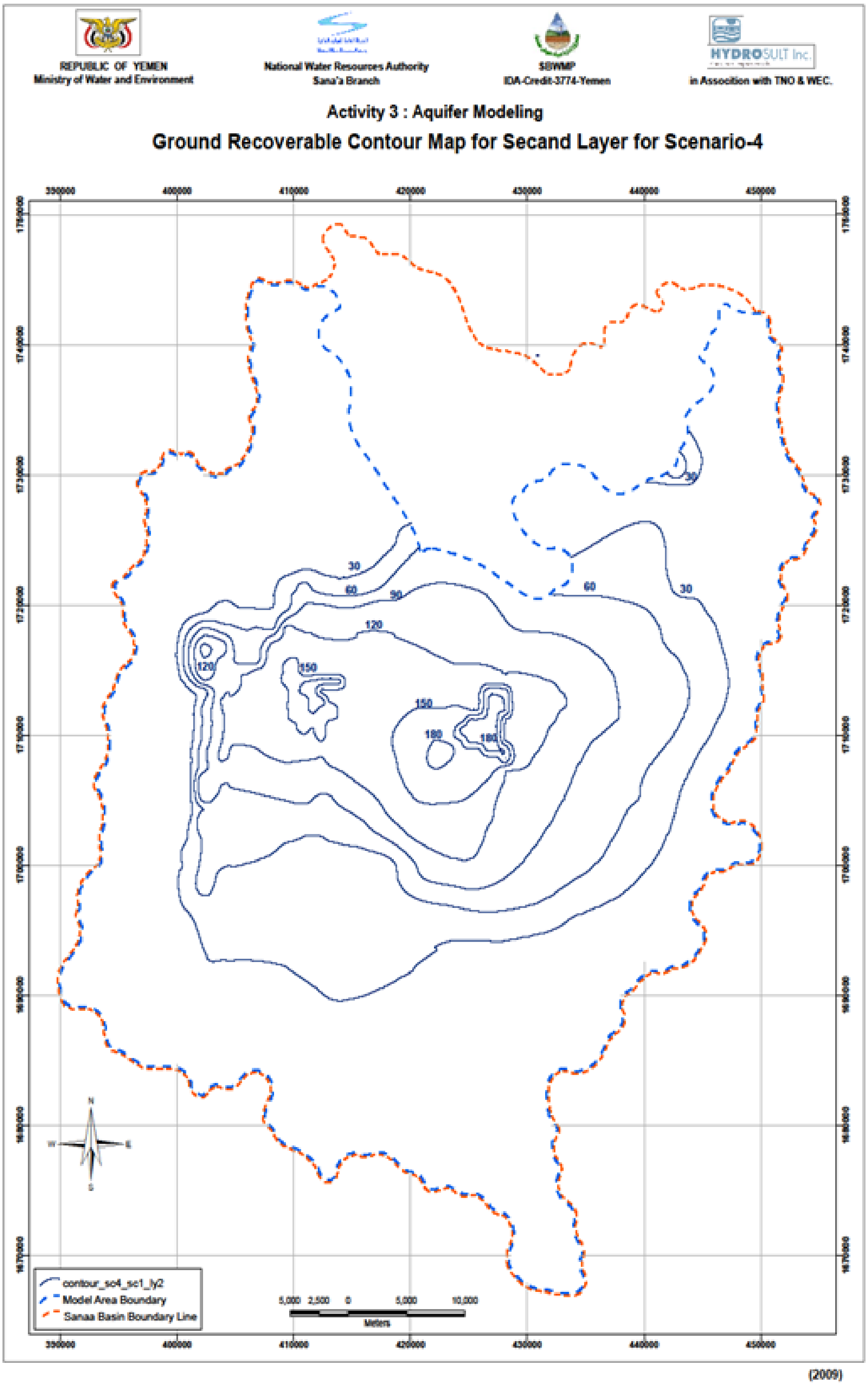


Figure 15 Groundwater Contour Elevation Map for the Second Simulated Layer for the Year 2020 (Scenario 1)

ANNEX II

Terms of Reference for the Project

Terms of reference were elaborated for Component 3 (d) for the Provisions execution of a comprehensive hydro-geological and water resources monitoring and investigation program. The purpose of the project was to arrive at a better understanding and quantification of Sana'a Basin surface and groundwater resource availability, and at achieving realistic estimations of the impacts of water saving and aquifer recharge investments in the basin.

(i) Aquifer Storage Investigations and Assessment: This investigation and assessment package would aim at quantifying the storage volume of the Cretaceous Sandstone and overlying Quaternary Alluvial aquifers, both the portions already drained out and the portions that would be drained over the coming years. It would focus on the aquifers underlying the irrigation areas in the vicinity of the NWSA NW and NE well-fields. The package would include: (a) construction of maps and sections to delineate the aquifers and the amount of historical depletion; (b) qualitative geological assessment of water storage properties; (c) drilling of three exploratory boreholes for core sampling, geophysical logging, groundwater sampling **(tenders for these were invited separately)**; and (d) laboratory testing of rock drill cores and field samples. The assessment would make use of both historic and current well inventory data relating to groundwater levels and abstractions, and all available geological information. Expected outputs include delineation of aquifer boundaries, spatial density of related information, substantially improved estimates of hydro-geological characteristics and of groundwater availability and computerized data base for all relevant data which would become 'input data' required for the Aquifer Model (MODFLOW) for the Aquifer Modeling Study envisaged under (iii) below.

The assessment would be carried out in the initial year by a small team of regional and local consultants, and NWRA staff.

(ii) Hydrological Monitoring and Analyses: The project would also provide for an intensive hydrological monitoring and analysis program at three levels: (a) sample sub-basin level, for monitoring and analyzing of groundwater levels, abstraction volumes, chemistry, as well as rainfall and surface water flows, to determine the impacts of recharge enhancements interventions and to establish sub-basin water balances; (b) field level, for monitoring and analyzing of water deliveries, beneficial ET, non-beneficial ET and evaporation, soil moisture content, runoff and deep percolation, to estimate field water balances and net water saving/recharge impacts; and (c) basin level, for deriving overall Sana'a Basin water balances. In earlier water balance studies, the recharge component due to domestic sewage in Zone 16 on Basin Characterization and Selection of Pilot Study Areas was not considered. However, treated waste water is a valuable resource in the water budget of the Basin and therefore this should be accounted for in estimating the overall Sana'a Basin water balances.

(a) The basin-level hydrological monitoring would be conducted by the NWRA Sana'a Branch, while the sub-basin and field-level monitoring would be carried out by the specialized MAI monitoring and extension units (e.g. CWMU and AREA). Support in the form of equipment and incremental staff costs would be provided under the project.

(b) Specific hydrological analyses and evaluations would be performed at three points in time during the course of the project. An early (Year 2005) study for baseline assessment would be followed by middle (Year 2006-07) and late (Year 2008) studies for mid-term and final impact assessments. The results would be compared and combined with monitoring program results to date, as well as available historic data, current well inventory data, supplementary study-specific investigations, outputs from the aquifer assessment study (see above), from the satellite imagery and aquifer modelling studies (see below). A small team of regional and local consultants would analyze the data with NWRA and MAI staff.

(iii) Satellite Imagery Studies: The studies would seek to estimate cropped and irrigated areas, cropping patterns and evapo-transpiration levels, all of which are important for project impact and water balance analyses. This would also enable retrospective testing of groundwater abstraction from 1980 the 2005. A Consulting Firm (**GAF**AG of Germany) has already been recruited for this activity for the first time-point (baseline).

(iv) Aquifer Modeling Studies: Based on the results of the hydro-geological investigations and assessments, refined aquifer characteristic values and abstraction estimates would be used in the updating of the basin-wide aquifer model (USGS MODFLOW) and subsequent simulation of current (for verification) and potential future aquifer use scenarios. Regional and local consultants supported by NWRA and MAI staff would conduct the modeling work. The relevant data collected under '(i) Aquifer Storage Investigations and Assessment' above would be used as input data for the aquifer model (MODFLOW) under these studies.

(v) Monitoring Water Quantity, Quality and Pollution: A system would be developed for **four** selected sub-basins to monitor and record rainfall, wadi flow, evaporation, groundwater level, and recharge rates. Data recording, collection and analysis mechanisms would be established, emphasizing sustainable community management. In particular, groundwater levels would be closely monitored to check pumping regulation and recharge effects including analysis of project impacts through dam and other wadi structures on aquifer recharge and groundwater levels. Deep boreholes and Sana'a basin-wide monitoring would also be conducted to better understand hydro-geological and geological formations and aquifer balance. The equipment, investigation and recurrent costs for monitoring, the latter on a declining basis, as well as training would be provided by the project. NWRA Sana'a Branch and its designated community groups would assume primary responsibility for these activities.

Other monitoring measures are planned in the project, including groundwater pollution and pesticide residuals, to be monitored by NWRA Sana'a Branch with MAI PPD. As existing data in these areas are limited, it would be necessary to establish a baseline from which any changes can be measured. In addition. The quality of WWTP effluent and sludge would be monitored by Sana'a Local Corporation. EPA would ensure compliance with the established standards.

ANNEX III

Institutional Linkages to SBWMP

The Sub-Component 3(d) is an integral part of the Component 3 of SBWMP. The latter comprises seven components, each of which has specific purposes but all of which contribute to meeting the basic project objectives. The component objectives and scopes are outlined below.

Component 1 - Demand Management and Irrigation Improvement. This component seeks to achieve water savings and conservation in agriculture by increasing the efficiency of water use for irrigation, through introduction of modern irrigation systems and equipment in about 4,000 ha and establishment of community organizations (WUG/WUA) through technical and organizational support and technical and managerial training and extension programs, involving both farmers and staff of MAI assigned to its Sana'a office (MAI/SO).

Component 2 - Supply Management and Recharge Improvement. This component has three objectives: (i) evaluate recharge capacity, (ii) dam safety and recharge improvements, and (iii) establishment of institutional arrangements for sustainable dam safety and recharge systems management.

Component 3 - Institutional Development and Capacity Building. This component is to develop institutional and managerial frameworks and capacities for overall basin water resources management, through (i) development of water sector legal, regulatory and monitoring frameworks and processes, and (ii) institutional development and capacity building for government and basin-level stakeholder water management entities.

In contrast to the specific focus on the demand and supply management improvements of Components 1 and 2 respectively, the proposed institutional and management interventions of Component 3 are intended to be overarching and integrating, covering sector-wide, basin-wide and project-wide aspects. They address: (a) water sector legal, regulatory and monitoring framework and processes for NWRA; (b) basin water resources planning and management capacity building for NWRA Sana'a Branch; (c) basin-level stakeholder water management institutional development relating to the proposed WUFs and the SBC; and (d) , and the subject of this report, (d) development of specific hydro-geological and water resources monitoring, and investigation studies and capabilities, with and for the NWRA Sana'a Branch and MAI. These are all aimed at building a sound, efficient and sustainable institutional and managerial base for water resources management, both during the project period and beyond

Component 4 - Information and Public Awareness Campaign (IPAC). This component is to raise the level of public understanding and awareness of water scarcity issues.

Component 5 - Environmental Management Plan and Mitigation Program. This component covers implementation and/or monitoring of the project's environmental management measures.

Component 6 - Project Management and Monitoring. This component covers project management and monitoring activities.

Component 7 - Phase II Project Preparation. This component covers preparation of the Phase II project.

ANNEX IV

Project Team Members

The project was executed by Hydrosult Inc. of Canada, in association with the TNO of the Netherlands, and WEC of the University of Sana'a .A team of Regional and local specialists advised by a team of international specialists drawn from Hydrosult Inc and TNO implemented the project in close working relationship with the Sana'a Basin (Sana'a Branch) and MAI.

The RFP did not call for a team Leader nor for a coordinator for the Team. However, Hydrosult inc. assigned Ismail Najjar, president of the firm and a senior hydrogeologist/water resources specialist as Project Director to oversee the implementation of the project activities. Towards the end of the first year, the need for a resident coordinator became obvious, and to that effect, Dr. Samir Hijazin, hydrogeologist and Hydrosult's resident project Manager for the supervision of drilling of three deep exploratory boreholes, provided some of his time to coordinate the project. After the early termination of exploratory drilling activities, Dr. Hijazin remained as the coordinator of the project at no cost to the project. A list of the project team members is shown below:

Names and functions of consultants. Activity 1

Name	Status	Firm
Dr. Wim v.d. Linden	International hydrogeological consultant	TNO
Dr. Mohamed Gad	Regional hydrogeological consultant	HYDROSULT
Dr. Naif Abu-Lohom	Local hydrogeological consultant	WEC
Dr. Mohamed El-Hosary*	Hydrogeological consultant	HYDROSULT
Dr. Ahmed Marjoa	International Hydrogeological consultant	HYDROSULT
Eng. Amin El-sabry	Geologist	NWRA (Sana'a Branch)
Eng. Ahmed Sharaf	Geologist	NWRA (Sana'a Branch)
Eng. Mohamed Soltan	Geologist	NWRA (Sana'a Branch)
Eng. Serwah Abdel-Baqi	Geologist	HYDROSULT
Eng. Khaled El-Bar	Geologist	NWRA (Sana'a Branch)
Eng. Mohamed Emad	GIS expert	HYDROSULT
Eng. Mohamed Mozahim	GIS expert	HYDROSULT
Miss Mona El-Sofi	On-the-job training (GIS specialist)	NWRA (Sana'a Branch)
Abdel-Aziz El-Raboe'i	Technician	NWRA (Sana'a Branch)
Fuad Amin	Technician	NWRA (Sana'a Branch)

Names and functions of consultants. Activity 2

Name	Status	Firm
Dr. Abdallah Noman	Local Hydrologist	WEC
Dr. Michel Wakil	International water resources specialist	HYDROSULT
Dr. Yilma	Regional Hydrologist	HYDROSULT

Names and functions of consultants- Activity 3

Name	Status	Firm
Dr. Nabil Rofail	Regional Groundwater Modeller	HYDROSULT
Dr. Al Khateeb Al Kebsy	Local Groundwater modeller	WEC
Mr. Mamdouh Ayyad	Regional GIS specialist	HYDROSULT

Names and functions of consultants-Activity 4

Name	Status	Firm
Dr. Khaled Kheriiddin	Regional surface water specialist/Monitoring	HYDROSULT
Mr. Mamdouh Ayyad	Regional GIS specialist	HYDROSULT

International Advisors and Backstopping

The Inception report was prepared by Jac Van der gun , Wim Van der linden of TNO and Ismail Najjar and Michel wakil of Hydrosult.

During the course of the project implementation, Mr. Wim Vander linden provided technical services in the fields of hydrology, hydrogeology and mathematical modeling,. Ismail Najjar and Michel Wakil conducted periodic missions and assisted in the planning of investigations as well as in the preparation of the periodic reports. In addition to the contracted services of the regional and local experts, Hydrosult provided the services of both Ismail Najjar and Michel Wakil as backstopping and support to the team,. In addition, Hydrosult assigned another senior international hydrogeologist Ahmad Marjouah at no cost to the project to assist the team in the field for a period of 4 months. During that period, Mr. Marjouah reanalyzed the previous pump tests and conducted new tests in selected dug wells and boreholes. .