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SANA'A BASIN WATER MANAGEMENT PROJECT

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Sub-Component 3(d)

Hydrogeological and Water Resources

Monitoring and Investigations

ACTIVITY 3: AQUIFER MODELING STUDIES

Final Draft Technical Report

Sana'a

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HYDROSULT Inc.
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EXECUTIVE SUMMARY

Many studies were carried out, covering the main aspects of the geological, hydrological and hydrogeological conditions for Sana'a Basin. The Sana'a Basin Water Management Project (activities: 1, 2, and 4), here referred to as the Project, achieved different working plans concerning Aquifer Storage Investigation and Assessment and Hydrological Monitoring and Analysis. The output of these studies gave a better understanding of the geometry of the main aquifers, and clear picture of the hydrogeological conditions.

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.

A New Model Domain was created including the Grid Network and Grid Layers. The Layers Surface Elevation Maps, including the Ground Surface Elevation Contour Map and the Aquifers Delineations Maps, were edited and imported to the New Model Domain.

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.

The available hydrogeological well data were filtered and their validity was checked. The groundwater abstraction was determined and the corresponding Pumping Wells Data were selected and edited in the MODFLOW format. 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 output of the calibration runs for the old Sana'a Model (Naaman, 2004) was also considered and edited as initial values for the New 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 the rewetting of the "dry" cells if the head dropped below the bottom elevation of the grid cell during the iterations within the simulation runs.

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

Steady State Calibrated Runs were carried out for the base year 1972. The output of the Calibrated Run was presented, including Calibrated Conductivity Values for the First and Second Simulated Layers. The Calibrated Values for the Water Balance Components are presented for each of the seven defined user zones. The details of flow rates were determined, both inflow to and outflow from each Zone to other Zone, whether laterally of vertically. Also the 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 are presented. Finally the Calculated Head Contour Map was submitted.

The Transient Calibration run was carried out. The total groundwater abstraction values were compiled after filtering the available data, including the WEC survey data. These data were grouped for different periods, from 1972 to 2001. The complete information about the pumped wells was prepared in Visual MODFLOW Form, including the coordinates, screen ID, the absolute level of top and bottom of the screen, starting time, stop time, and the 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 distribution of intensity maps (pumped water per square meter for each grid cell) were constructed and documented in soft (PDF and SHP files format) and hard copy. These maps are presented in a special album attached with the Modeling Studies documents.

The observation wells data were also compiled from the different studies carried out since 1972. These data were compiled in the 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 the 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.

The 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 of the different time period data defined for each pumping well and boundary conditions into the uniform stress period format required by the MODFLOW. The transient run was carried out for the defined and each period covering the corresponding time steps.

The primary storage coefficient is calculated by Visual MODFLOW to be equal to the specific storage multiplied by the layer. The storage parameter is using by Visual MODFLOW the constant property values.

The Calibrated Values for the Water Balance Components for the present status were computed for each of the seven defined User Budget Zones.

The variation of groundwater levels during the last three decades was demonstrated in graphs representing the drop of the water level in each of the user-defined zones. The Computed Groundwater Contour Elevation Map and the Depth to Water map were generated. The Drawdown Contour Map was created.

As to the results of the assessment of the present status, the priority areas for management were identified. The simulation of groundwater development strategies was distinguished. A scenario was designed for water augmentation. This scenario focused on the effect of the increase of groundwater potentialities. The scenario was studied, the predicted outputs were defined, and the results were evaluated.

Conclusions and recommendations were presented. The reasons for the water problem were summarized, and the procedures and the measures to be implemented for integrated management and groundwater development were identified.

Taking into consideration all dimensions of the water problem, it is possible to visualize the seriousness of the situation and the problems that should certainly be confronted in the future. The basic reasons thereof may be attributed to the following: high rates of population growth, poor water management, non-rational use of water resources, non-rigorous application of water legislation, low level of awareness, and adoption of ambitious development plans that are not based on an accurate assessment of the available water resources. All of the above occurs within the framework of limiting natural conditions and scarcity of water resources.

1. INTRODUCTION

1.1 Background

The Inception Report for Sub-component 5(d), " Hydrogeological and Water resources Monitoring and Investigations" stated that the aim of the Activity (3) "AQUIFER MODELING STUDIES", is to provide a better understanding and quantification of Sana'a Basin surface and groundwater resources availability, and achieving realistic estimations of the impacts of water saving and aquifer recharge investments in the basin. This sub-component is subdivided into five activities, where activity (3) is consistent to Aquifer Modeling Studies, which will be based on the results of the Hydrogeological Investigations and Assessment of Activity 1 and 2. The objective of this activity is to prepare, implement and consolidate a revised aquifer model of the Sana'a Basin for use in the management of the groundwater resources. The model will be an improved version of the groundwater model of the Sana'a Basin initially prepared by SAWAS in 1996 and also used by Naaman in 2004.

Referring to the document Hydrogeological and Water Resources Monitoring and Investigations sub-component 3(d) REP N: 5/003, TECH3; the following items were to be made available

- The latest version of the of the Sana'a Basin MODFLOW groundwater
- Model modules should be made available to the Consultant (complete and without errors) at the start of the Study.
- Computer facilities for installation and execution of the model software will be provided by NWRA.
- Computer facilities and software to be used by counterpart staff will be provided by NWRA or MAI.

However, some of these items were not avaialble, and the Project was obliged to provide the updated software, "Visual MODFLOW Version 4,2 " and to construct a completely new mathematical model including the following modules: model concept, model domain, aquifers delineations, hydraulic boundary conditions, complete set of input data (hydraulic parameters, abstraction distribution, recharge zones and values, initial water level,…. .)

1.2 Objectives

The main objective of the Sana'a Basin Groundwater Model Studies was to assess the present status of the groundwater potentialities, and to construct a practical tool for proper planning and integrated management of the available water resources. That is, to elaborate the water strategies for the development of the available resources with the prevention of further deterioration and overexploitation.

Considering the sub-activities stated in the activity 3: Aquifer Modeling Studies, and after reviewing the different outputs generated by Project experts in the present contract through carrying out the different activities (1, 2, & 4), and mainly activity (1), the following outputs have to be achieved;

- Setting up a GIS database with the input data of the model.
- Carrying out steady state and unsteady state runs with the base model.
- Define and carry out scenario calculations.
- On-the-job training.

- Prepare a technical note.

1.3 Basin Location

The Sana'a Basin is an inter-montane plain located in the central Yemen Highlands. Yemen covers a total area of approximately 536,000 square kilometers, and consists of 19 governates, (Fig.1 Location Map). The plain has an elevation of about 2,200 m asl. but is surrounded to the west, south and east by mountains rising to more than 3,000 m asl. The Basin has an area of some 3,200 km^2 and forms the upper part of the catchment of Wadi al Kharid, a subcatchment of the Wadi al Jawf. The climate is semi-arid with an average annual rainfall of 235 mm at Sana'a. In 1995 the population of the city was estimated to be about one million inhibitants. In Sana'a Basin there are two rainy seasons, separated by a distinct dry interval (May to mid July). The annual rainfall generally varies between 150 and 250 mm, with some years having, higher rainfall amounts above 350 mm. The first rainy period starts in mid March-beginning of April, the second rainy period begins mid July-beginning of August and stops abruptly in the end of August. The months of September through February are generally dry, although occasional thunderstorms may bring some rain during these months. Sixty-five to seventy-five percent of the rain falls during the months of January to June. The average amount of rainfall per rain day is about 16-17 mm. Thirteen stations are used to represent the 22 sub-basins of Sana'a Basin (Activity 2).

The Sana'a Basin relies to a large extent on groundwater for both irrigation and the urban water supplies. Historically water supplies were obtained from dug wells and ghayls tapping the unconsolidated Quaternary deposits in the plain. Borehole construction and the introduction of pumps began in the 1960's and increased rapidly from the mid-1970's onwards. This enabled deeper aquifers to be exploited for irrigation and municipal supplies. The groundwater development has been largely uncontrolled.

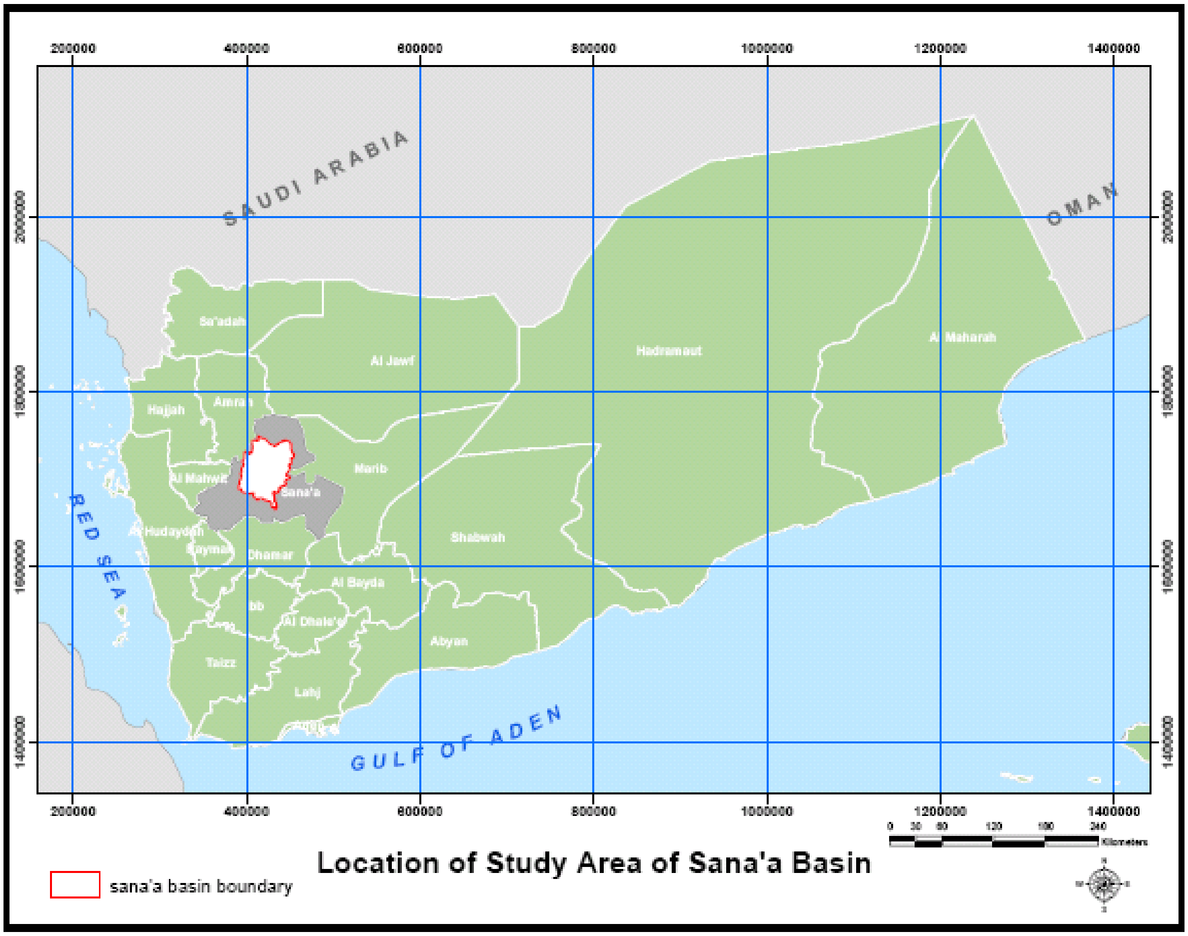


Figure 1: Location Map

1.4 Previous Studies

Until the early 1970's, 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, the economic development and the growth of Sana'a resulted in the need for a modern public water supply system. For the implementation of such a system, Italconsult studied the groundwater potential in the Sana'a Basin during the period 1972-1973, under a contract with the World Health Organization. The main outcome of these investigations was the identification of the regional Cretaceous Tawilah Sandstone aquifer, from which the City could be supplied in the future. The potential of this aquifer was considered to be sufficient to supply Sana'a until at least the year 2000.

As a consequence of the rapid growth in population 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 undergroundwater-based irrigation, the groundwater levels in the Sana'a Plain show a steady decline, from about 30 m below ground surface in the early 1970's to more than 150 m below ground surface in 1995. This has caused problems with Sana'a water supply.

Since 1972, many studies were carried out by different organizations and institutions, covering geological, hydrological, and hydrogeological investigations. Sources of data and information were compiled mainly from the output of these surveys (Russian 1982; SAWAS 1993; NWAS 2000,2004; WEC 2002; NAWRA 2004,2005,2006). Recent field surveys and studies were conducted through the present Project in the different activities. The computer code used to model the groundwater flow system of the Sana'a Basin is MODFLOW (McDonald and Harbaugh 1988). Pre- and post-processing of model runs was carried out using the pre- and post-processing software developed by Chiang and Kinzelbach (1992). Additional pre- and post-processing facilities were developed in a spreadsheet.

Also, a groundwater MODFLOW Model of the Sana'a Basin was initially prepared by SAWAS and the Netherlands Institute for Applied Geosciences in 1996. In the year 2001, the Water and Environment Centre of the Sana'a University carried out a multi-criteria analysis of sub-basins in Sana'a Basin aimed at optimal demand and supply-driven management of Sana'a Basin as a whole. The same MODFLOW model was used with simple modifications. The model was upgraded to “Processing MODFLOW Version 5”, and data on basin-wide abstraction were increased on an annual basis of 3,5% . Also a MSc Thesis on Sana'a Basin Model was submitted By Mazen Naaman in 2004 .

2. HYDROGEOLOGICAL CONDITIONS

2.1 Geology

The oldest sedimentary Formation in the region of Sana'a is the Amran Series (Middle to Upper Jurassic) which comprises of limestones, marls and shaly limestones some 350 to 1,000 m thick. The Amran outcrops in the north of the Basin, covering about 15% of the Basin area. It occurs at depth beneath the Sana'a plain. At the airport, the top of the Amran is approximately 350 m deep, at Ar Rawdah it is 500 m deep and further south near Sana'a it is 900 m deep or more. The Amran is overlain by a sequence of lagoonal shales, marls and fine grained sandstones interbedded with lignite probably of Upper Jurassic or Lower Cretaceous age (equivalent to the "Unnamed Formation" of Italconsult) which outcrop in a narrow band in the north-eastern part of the Basin (Fig 2 Geological Map of the Basin).

The Tawilah Sandstone (Cretaceous to Tertiary) comprises a series of continental cross bedded sandstones generally medium to coarse grained with interbedded mudstones, siltstones and occasional silty-sandstones.

The overlying Medj Zir Formation is a finer grained sandstone with a higher proportion of siltstones and clays. It also contains decomposed volcanic tuffs and "soapy clay beds" associated with the start of regional volcanic activity. It has proved difficult to distinguish the Tawilah and Medj Zir both in aerial photographs and drill cuttings. They are therefore mapped as one formation and referred to as the Tawilah Sandstone or "Cretaceous Sandstone". The Cretaceous Sandstone outcrops over about 15% of the Basin area in the northern part of the Basin. It is thought to reach a thickness of 400 to 500 m where it has been protected from erosion by the overlying Tertiary Volcanics. The Tertiary Volcanics (formerly called the Trap Series) outcrop over some 35% of the area of the Sana’a Basin. They form high plateaus to the south, west and east of the Sana'a plain and underlie the Quaternary deposits in the south of the Basin. The sequence is divided into two groups. The lowest group is the "Stratoid Volcanics" which include the Basal Basalt (a dense homogenous basalt flow with columnar jointing), basalts, tuffs and pyroclastics interbedded with fluvio-lacustrine deposits. The upper "Chaotic Volcanics" comprise mixed basalt flows and rhyolite lavas. The total thickness is variable, reaching an estimated maximum of 700 to 900 m.

Basic intrusive rocks of Tertiary age are present throughout the area in the form of volcanic plugs, dykes and sills. The alignment of the volcanic necks is oriented NNW-SSE. Dykes are well fractured and oriented NNW-SSE and NNE-SSW.

Volcanic activity continued into the Quaternary forming a plateau of extensive basalt cones in the north west of the Basin interlayered with tuffs and alluvial sediments. The Quaternary Basalts have a total thickness of about 100 to 300 m and cover about 20% of the area of the Basin. They overlie the Amran Limestone, Cretaceous Sandstone and Tertiary Volcanics.

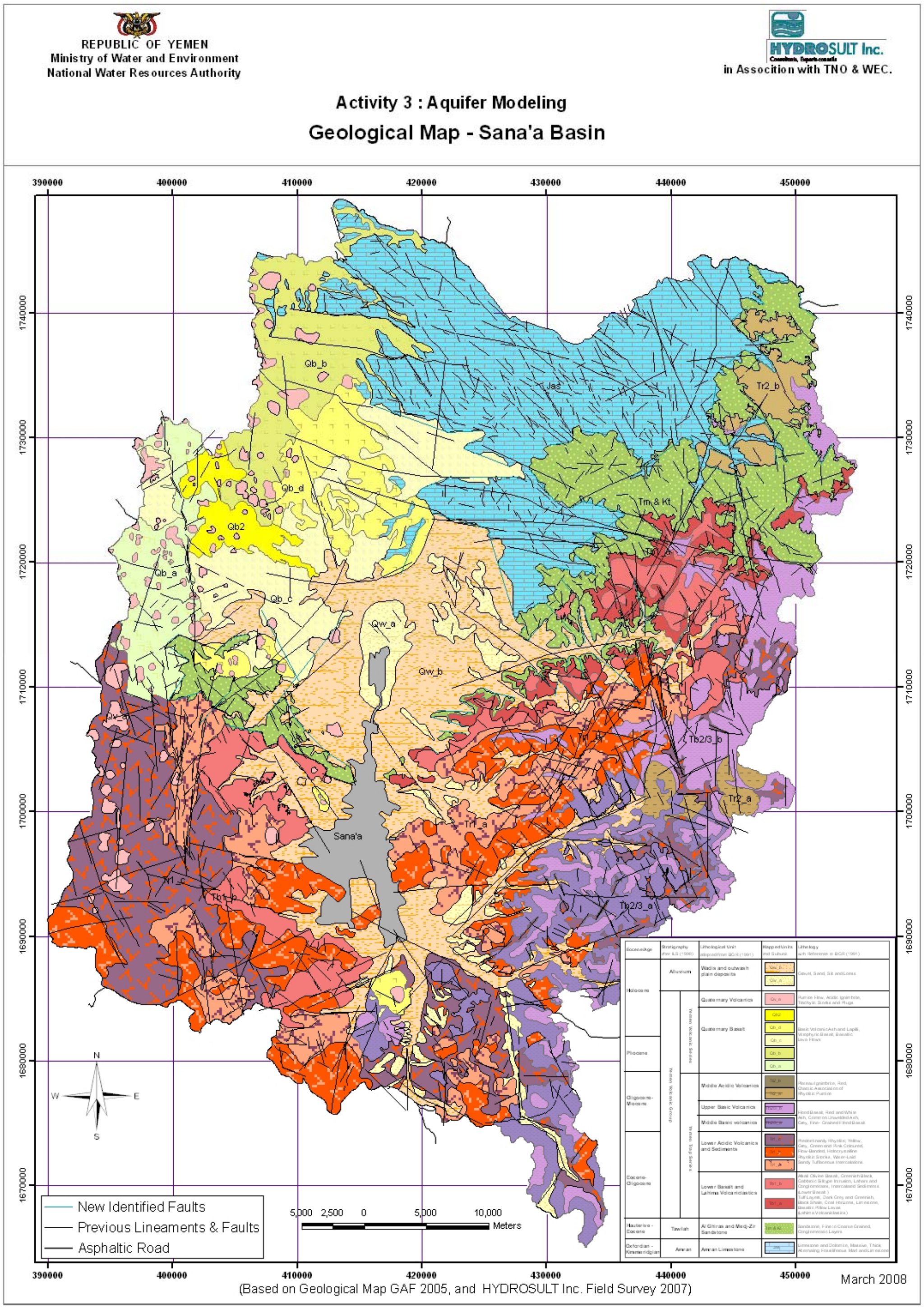


Figure 2: Geological Map

Unconsolidated deposits of the Quaternary cover approximately 15% of the Basin area. They are confined to wadi beds and low areas that form the Sana'a plain. Deposition appears to have been of fluvio-lacustrine nature which led to the accumulation of clays and silts in basins 100 to 300 m deep. Coarse grained colluvium and alluvium occurs in the wadi beds at the foot of hills.

The sedimentary sequence is block faulted and gently folded. The regional dip is southwards under cover of the Tertiary Volcanics.

2.2 Groundwater occurrence

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 35m and groundwater is abstracted mainly by means of dug wells.

The Unnamed Formation is believed to act as an aquiclude although the regional permeability may be similar to the Amran Limestone.

The Cretaceous Sandstone forms 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 1970's but have declined by 2 to 4 m/yr since. In the south of the Basin the Sandstone is confined beneath several hundreds of meters of Tertiary Volcanics.

The basalt flows and stratoid 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 to 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.

2.3 Main Hydrogeological Formations

The main aquifer systems can be considered as follows:

- Quaternary Alluvium: these sediments are located in the centre of Sana'a Plain, and are mainly composed of sands, clays, and silts. It is considered mainly as unconfined aquifer. It was an essential source in the past, but due to overexploitation serious decline in water level has been recorded.

- Tertiary and Quaternary Volcanic Group: this formation is characterized by basalts, andesites, trachytes, tuffs and ignimbrites. It is mainly unconfined, but in some locations is confined. This group is hydraulically connected with the Quaternary Alluvium and with the other aquifers.

- Cretaceous Sandstone: this formation is composed of sandstone with intercalation of conglomerates, siltstones, and clays. It is partly confined and partially unconfined. In the south, this formation is dipping under the volcanic rock and is intercalated with alluvial sediments. Therefore, it is hydraulically connected with the other formations.

- Jurassic Unnamed and Amran Formations: outcrops are located at the Northern and Eastern part of the Basin, the thickness is not determined and no data is available. It is considered as a poor aquifer, and as an impermeable layer for the overlain different water formations.

2.4 Application of Unified Geographic System

The available well data were compiled from the previous studies (ITALCONSULT 1972; Russian 1982; SAWAS 1993; NWAS 2000,2004; WEC 2002; NAWRA 2004,2005,2006), and from the recent field surveys and studies conducted by the Project in the different activities. These data were reviewed and verified. It was found that each study applied its own projection system for determining the altitude of each water point. Some have applied projection of the location (X, Y, Z) from topographic maps of different scales; others applied G.P.S. system of different accuracy. Under these circumstances, the values of the absolute level of the water points were defined by different projection systems. Thus, the contouring maps, whether for aquifers geometry, water table maps, hydraulic parameters, or hydrological factors, are not consistent.

Therefore, it was essential to transfer the available well data to a unified geographic coordination system (X, Y, Z). It was recommended to apply advanced and dependable digital geographic system. The digital elevation model (DEM) map system was selected as it represents GIS delineation process and starts with a grid representation of topography. The DEM map was obtained from the Shuttle Radar Topographic Mission (SRTM). STRM consisted of a specially modified radar system that flew onboard the Space Shuttle during its 11-days mission in February of 2000. The SRTM data covered the entire globe with an arc second (approximate 90 days) digital elevation model. [HYDROSULT, 2007].

2.5 Aquifer Delineation

The entire inventory of available data and information on the dug and drilled wells (about 14,000 water points) in the Sana'a Basin, compiled from the previous and present studies, were revised. Their coordinates (X,Y) were verified, and the contour maps for the geometry were projected on the available unified DEM map. The altitude for each water point was determined. Accordingly, the altitude values for the top and bottom in every well or water point penetrating each water bearing formations, were defined.

The consistency of overlaying of the available delineation of the contour maps of the different layers has been checked. The contour map of the bottom of the first layer was overlapped over the contour map of the top of the successive one. The GIS method was applied for converting the contour lines of each contour map from vector to raster. By subtracting the raster values of each of the two successive maps, it was found that the contour lines of the bottom of each formation coincide exactly with the top contour lines of the top of the successive layer.

As stated in the contract no. RFP5/003/2005, the following aquifer systems have to be simulated in the modeling studies activity: Quaternary Alluvial, Quaternary and Tertiary Volcanic, and Cretaceous Sandstone.

Different regional and local hydrogeological cross-sections were constructed, and the hydrogeological units were verified Activity 1. The study of these cross-sections in combination with the available well lithology data, the following aspects were defined and checked:

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

The following steps were implemented to verify the consistency of these maps with the available geological and hydrological materials:

1- The delineation of the different water bearing formations was checked with the geological map established by Russian, GAF, and with the updated map prepared by the Project.
2- Within the implementation of Activity (1) of the present Project, a geological survey was carried out for some locations mainly in the areas: Nihm (NE), Hamadan (W), Beni Hushaaish (E). The boundary of each formation was checked and enhanced according to the results of this survey.
3- The contouring of the outcrops of each aquifer was identified and then compiled for all the aquifers in one contour map. This map was checked with the topographic map of the Basin prepared by DEM map, and with the available geological maps.
4- The geometry of the aquifers was verified with the available Geological and Hydrogeological Cross-Sections (Annex (1) Regional Cross Sections prepared by Russian 1986, and the seven sections developed by HYDROSULT 2007).
5- Referring to the recent hydrogeological surveys conducted, the location of depletion areas in the top layer of the water bearing formations was characterized where the wells became dry.

These locations were identified in the reconstructed delineation maps of the water bearing formations.

Therefore, the contour maps representing the geometry of the water bearing formations were constructed considering all available Geological and Hydrogeological information. A consistent and complete set of maps representing the delineation of the different water bearing formations were constructed;

1- Bottom Contour Elevation Map of the Quaternary Alluvial Formations – Fig (3), covering an area of approximately 605 square kilometers (outcropping). The maximum bottom level is located at the south of the Basin and it has a value of 2,428 m asl., and the minimum is at North and elevation of 1,920 m asl.
2- Thickness Contour Map of the Quaternary Alluvial Formations- Fig (4), has a maximum value of approximately 160 m near the north of the formations.
3- Bottom Contour Elevation Map of the Quaternary and Tertiary Volcanic Group - Fig (5), covering an area of approximately 2,260 square kilometers. The bottom elevation of the Volcanic formation varies between 1,660 m asl. (at the south), and 2,514 m asl. at the south of the Basin.
4- Thickness Contour Map of the Quaternary and Tertiary Volcanic Group – Fig (6), maximum thickness has a value of approximately 660 m at the south of the basin.
5- Top Contour Elevation Map of the Tawila Sandstone Group – Fig (7), covering an area of 2,330 square kilometers, and outcropping of an area of 315 square kilometers ,
6- Bottom Contour Elevation Map of the Tawila Sandstone Group – Fig (8), has a maximum elevation at 2,387 m asl. at the West of the Basin.
7- Thickness Contour Map of the Tawila Sandstone Group – Fig (9), a maximum thickness of 850 m and is located at the south of the Basin.
8- Top Contour Elevation Map of the Omran Limestone Group covering the whole Basin, an area of approximately 3,240 square kilometers , and outcropping of 440 square kilometers.

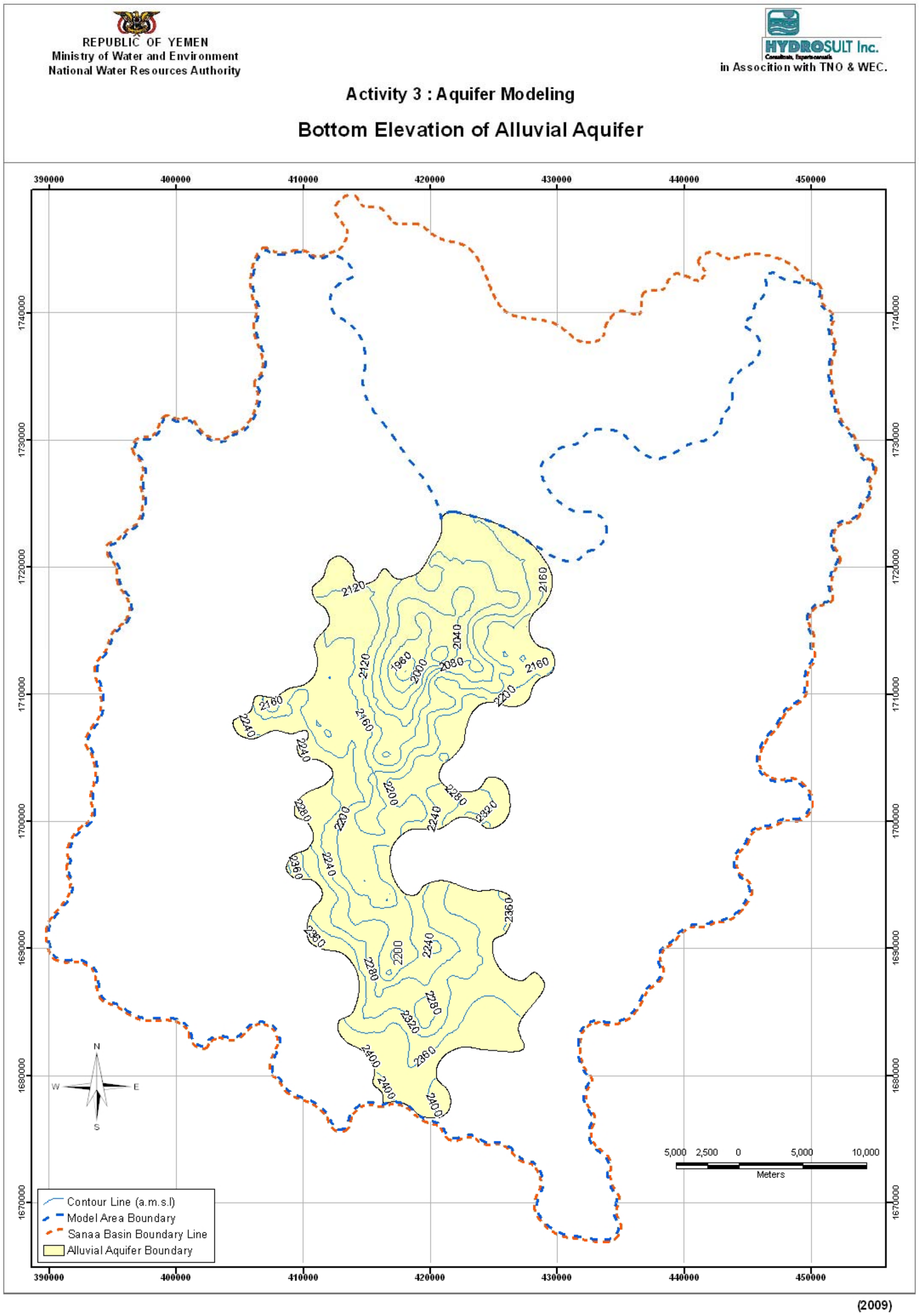


Figure 3: Bottom Contour Elevation of Alluvial Aquifer

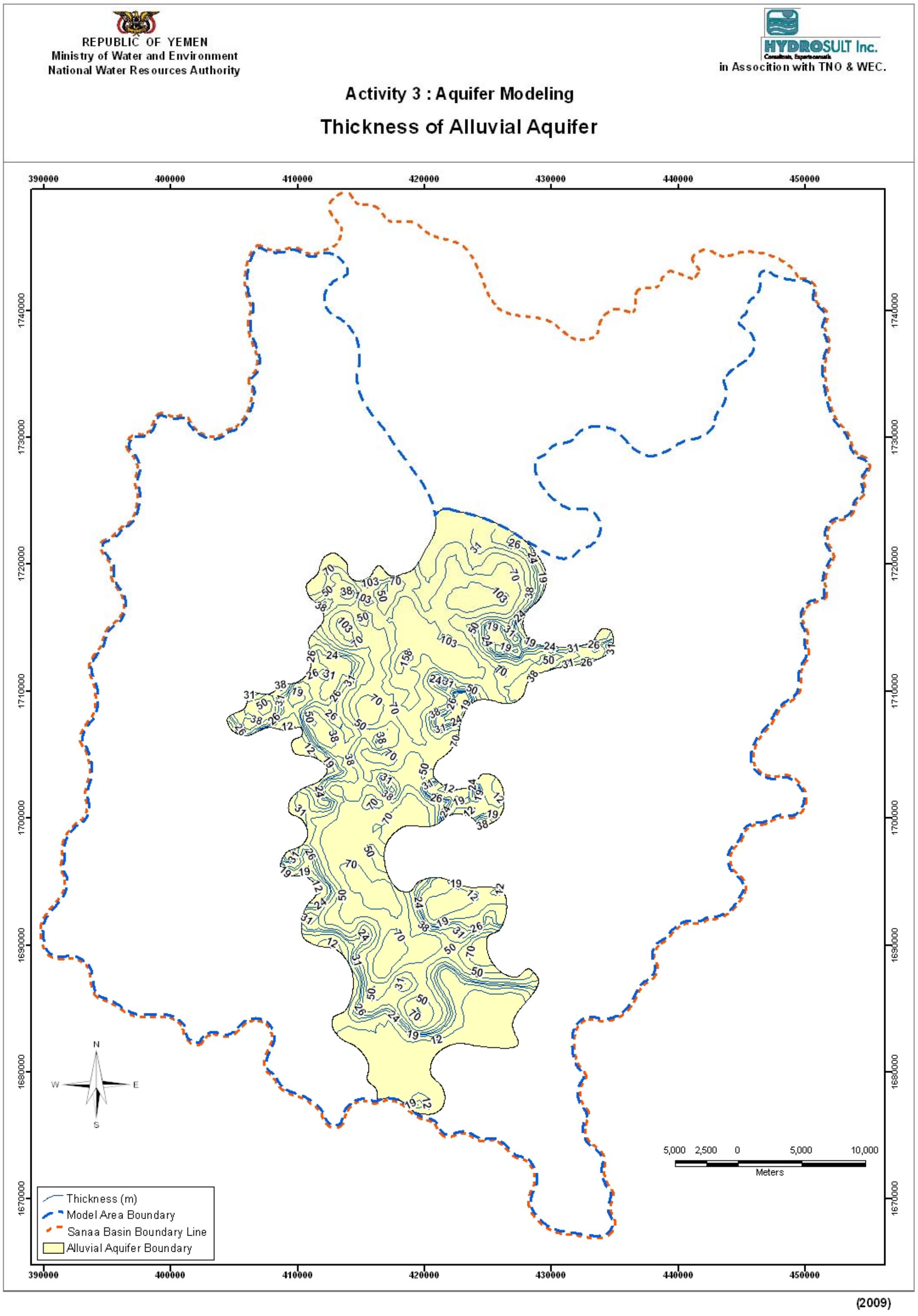


Figure 4: Contour Thickness of Alluvial Aquifer

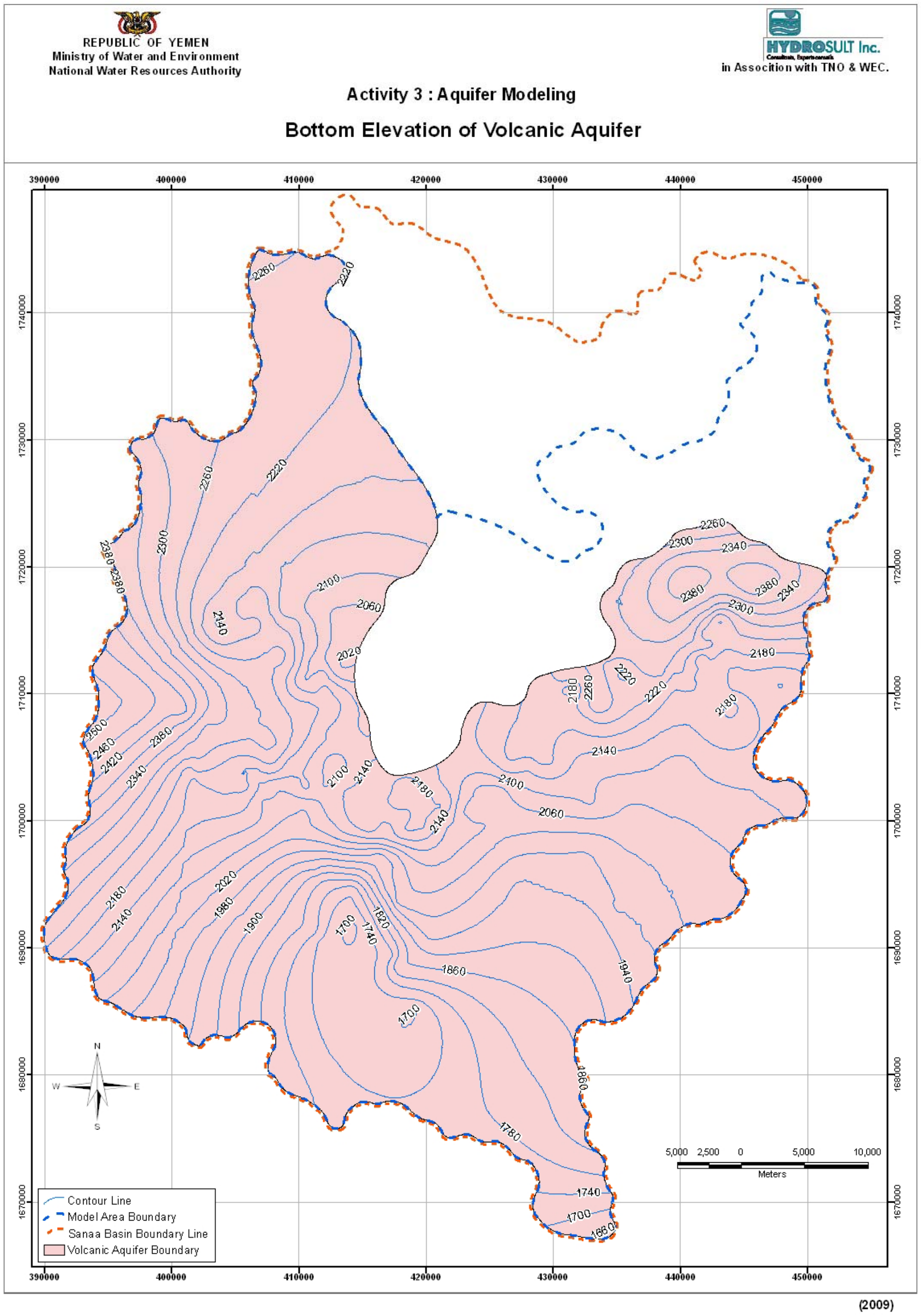


Figure 5: Bottom Contour Elevation of Volcanic Aquifer

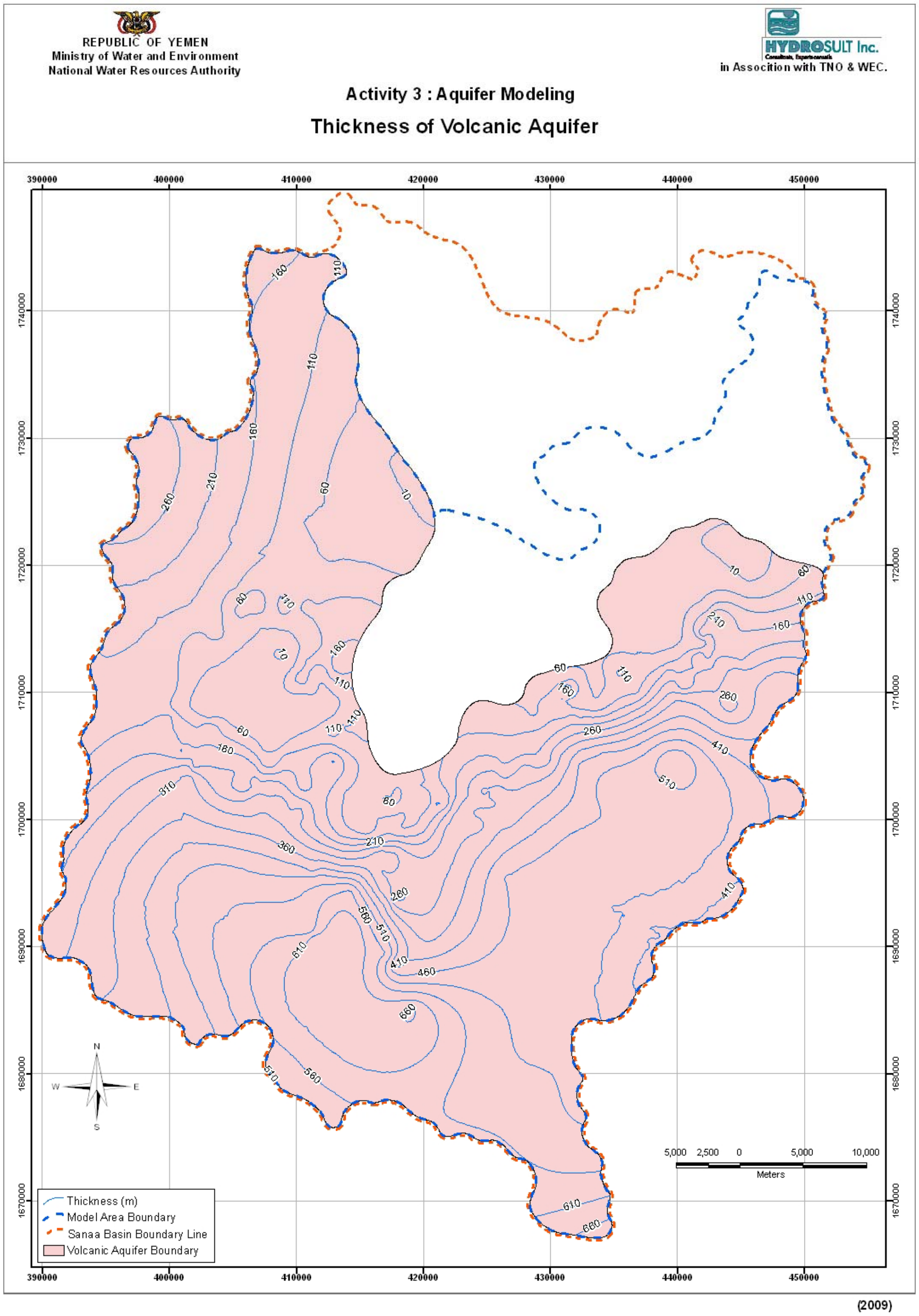


Figure 6: Contour Thickness of Volcanic Aquifer

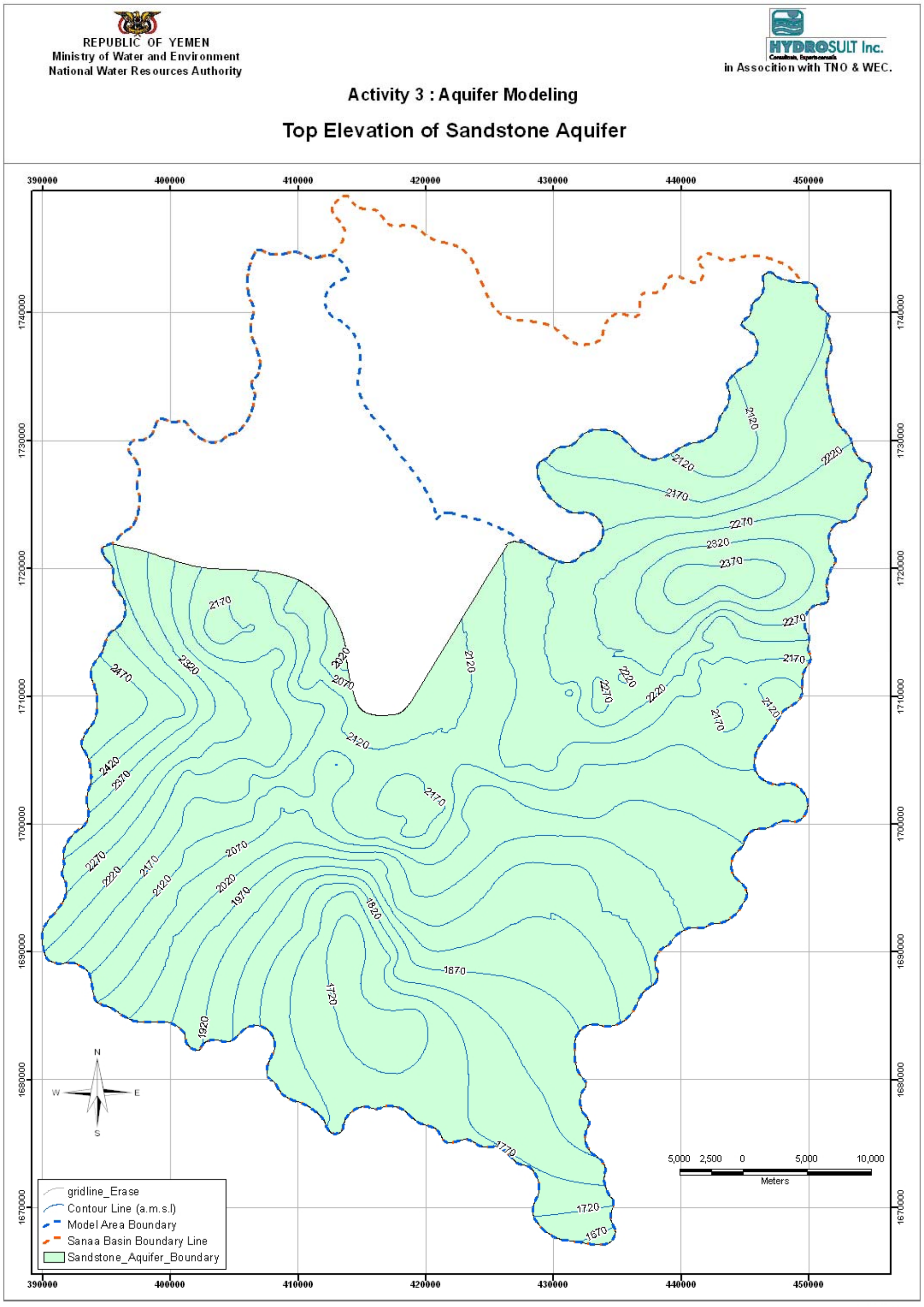


Figure 7: Top Contour Elevation of Sandstone Aquifer

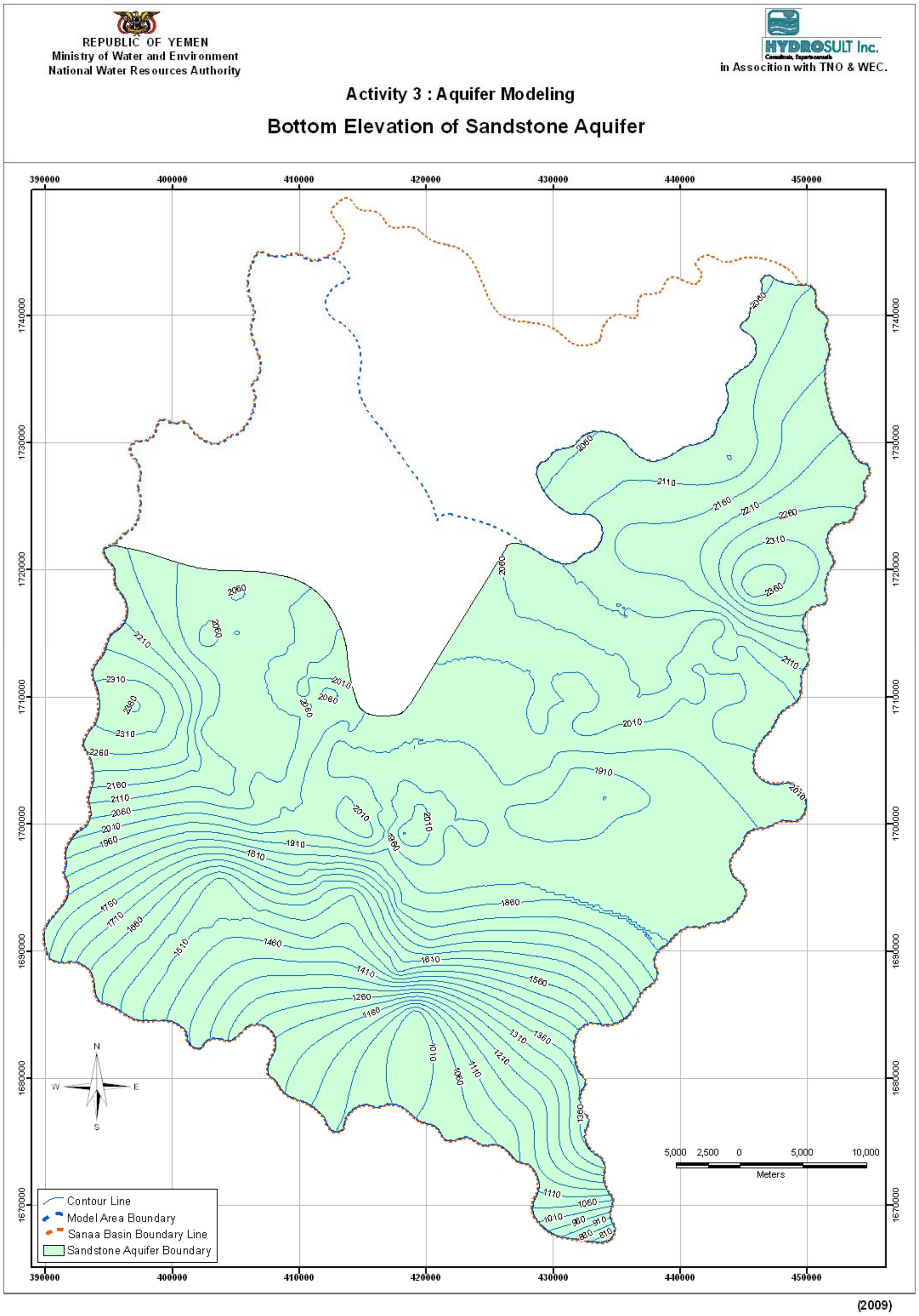


Figure 8: Bottom Contour Elevation of Sandstone Aquifer

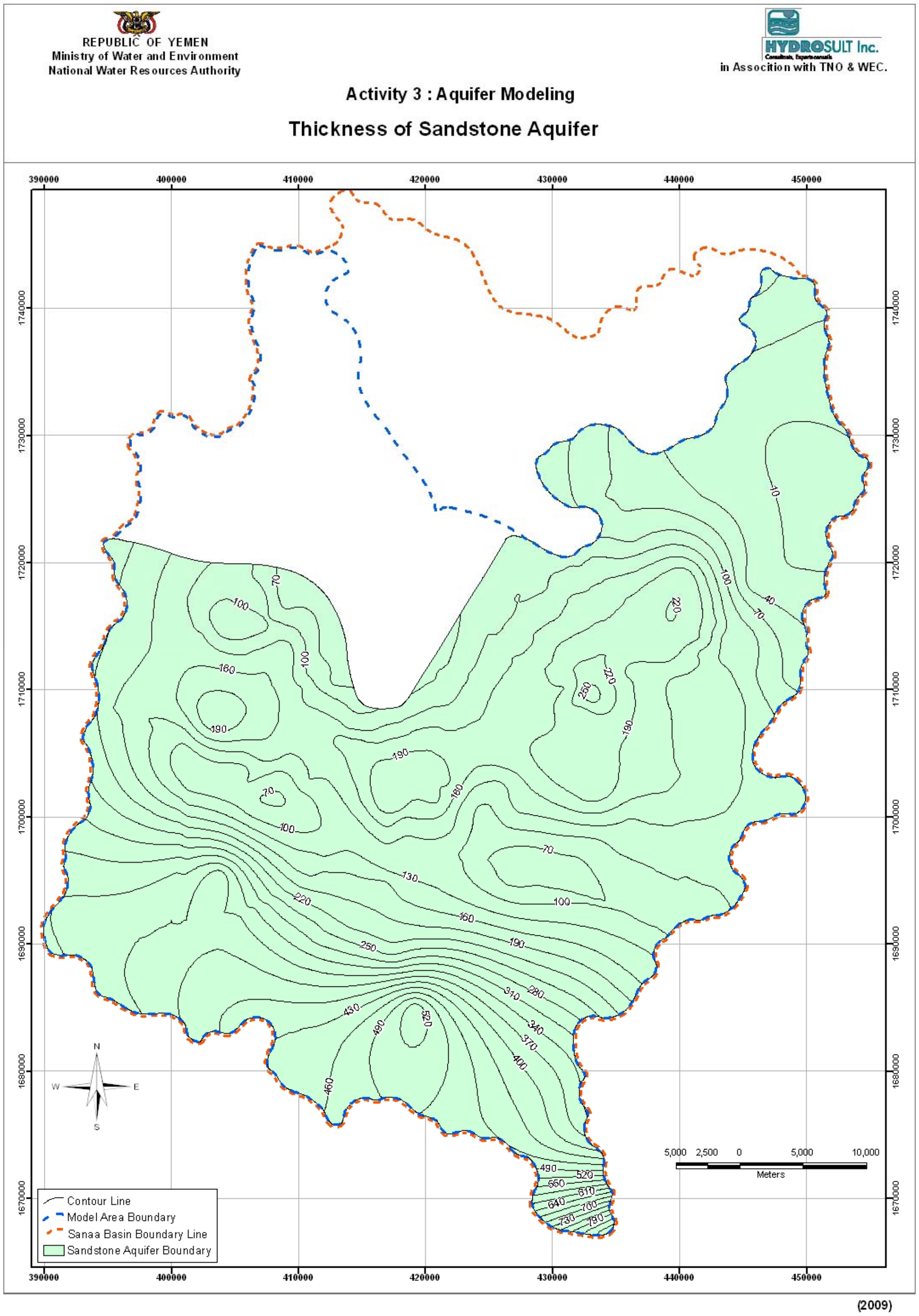


Figure 9: Contour Thickness of Sandstone Aquifer

Therefore, it was essential to study the methods of interpolation of the basic data for map importing to the Visual MODFLOW. Different methods of interpolation (Inverse Distance, Kriging, and Natural neighbors) were checked. Each method has its own mathematical background basis. For example, the Inverse Distance Squared method, a weighted average interpolation method, is considered very fast and efficient. Kriging is a geostatistical method that produces visually appealing maps from irregularly spaced data. Finally the natural Neighbors method is based on the Thiessen polygon method.

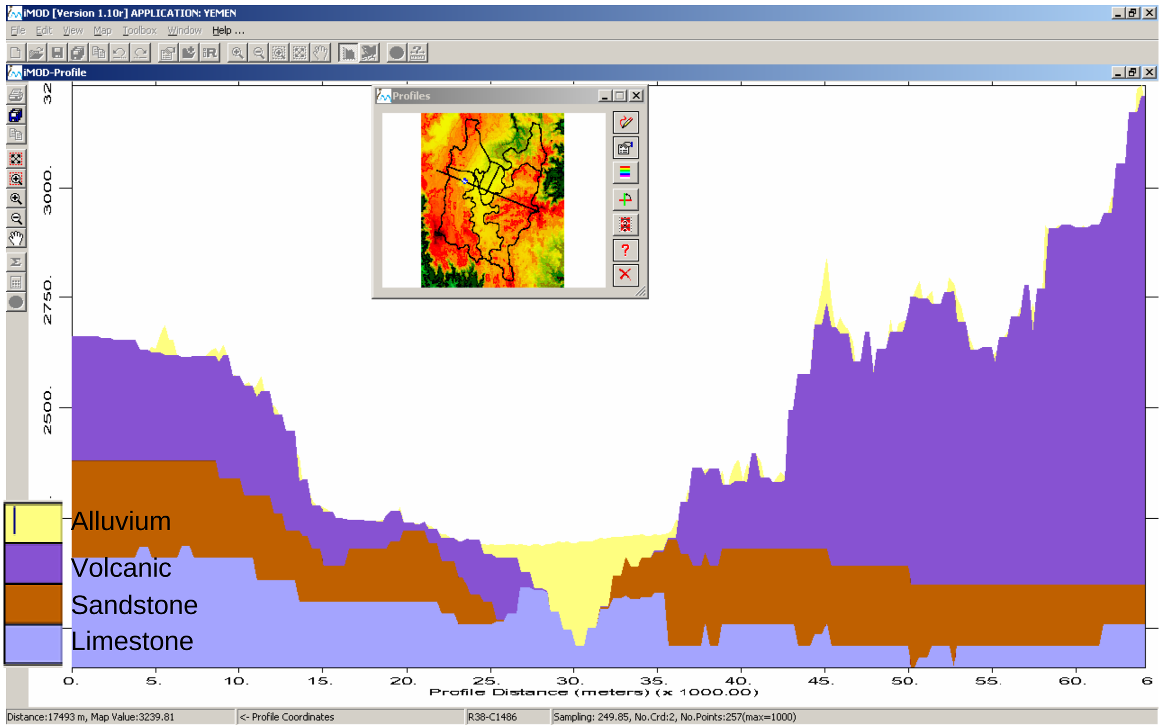


Figure 10: Hydrogeological Cross Section (East – West)

These methods were reexamined with different sizes of the applied pixels. Finally, the actual grid and database files were constructed, and were exported to the Software MODFLOW files, giving complete overlay of the successive layers without recording any difference in values of the simulated layers. The modified final contour maps of the top, bottom, and thickness of the different aquifers were checked and reconstructed.

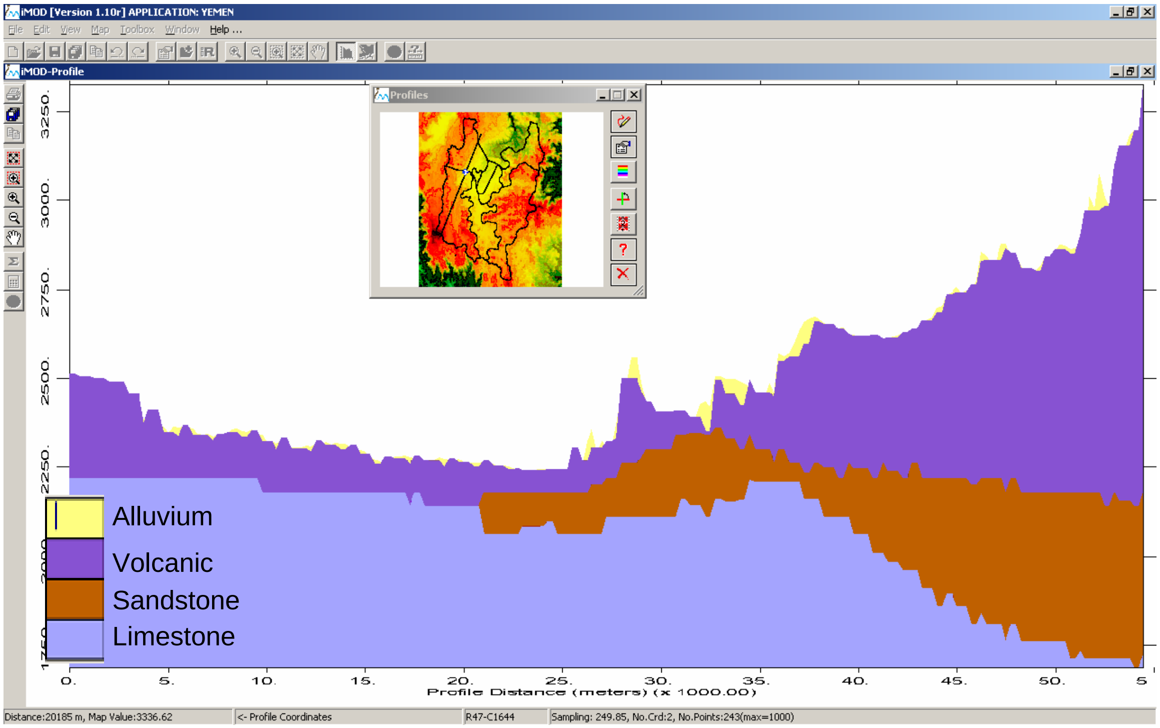


Figure 11: Hydrogeological Cross Section (North - South)

Figures (10) and Figures (11) show the delineation of the main aquifers: Alluvial, Volcanic, and Sandstone formations, over the impervious Limestone formations.

3. CONCEPTUAL MODEL

Different maps were established to determine the flow system and the hydraulic connection between the different aquifersin order to determine the partial differential equation governing the dynamic of groundwater flows in the Basin.

3.1 Groundwater Dynamics Flow System

The vertical conductance is calculated by VISUAL MODFLOW Software assuming the nodes are in the center of cells and that there can be discrete changes in vertical hydraulic conductivity. This is commonly referred to as a "Quasi-Three-Dimensional" Approach, and consequently the flow system constitutes one complex hydraulically connected system.

These three main aquifers (Quaternary Alluvium, Tertiary and Quaternary Volcanic Group, and Cretaceous Sandstone), were overlapped by GIS technique. Accordingly, the boundary of each hydraulic unit, which were considered for modeling simulation, was defined. The flow System in the Sana'a Basin as shown was mathematically simulated according to the location of each cell with respect to the adjacent corresponding cells, whether the location of the cell was in a one layered aquifer, a two layered aquifers, or a three layered aquifers.

The flow system is defined according to the conditions of the dynamic flow of each unit. The complex is subdivided into 7 interconnected zones as follows (Fig. 12):

I - One Layer Aquifer Flow was found in the following formations:

- Zone (1); Quaternary Alluvium, (area of 91 square kilometers)
- Zone (2); Tertiary and Quaternary Volcanic Group, (area of 350 square kilometers)
- Zone (3); Cretaceous Sandstone, (area of 315 square kilometers)

II – Two Layered Aquifer Flow was found in the following combined formations:

- Zone (4); Quaternary Alluvium and Tertiary and Quaternary Volcanic Group, (area of 25 square kilometers)
- Zone (5); Quaternary Alluvium and Cretaceous Sandstone, (area of 122 square kilometers)

III – Three Layered Aquifer Flow was found in the following combined formations:

- Zone (7); Quaternary Alluvium, Tertiary and Quaternary Volcanic Group, and Cretaceous Sandstone, (area of 366 square kilometers)

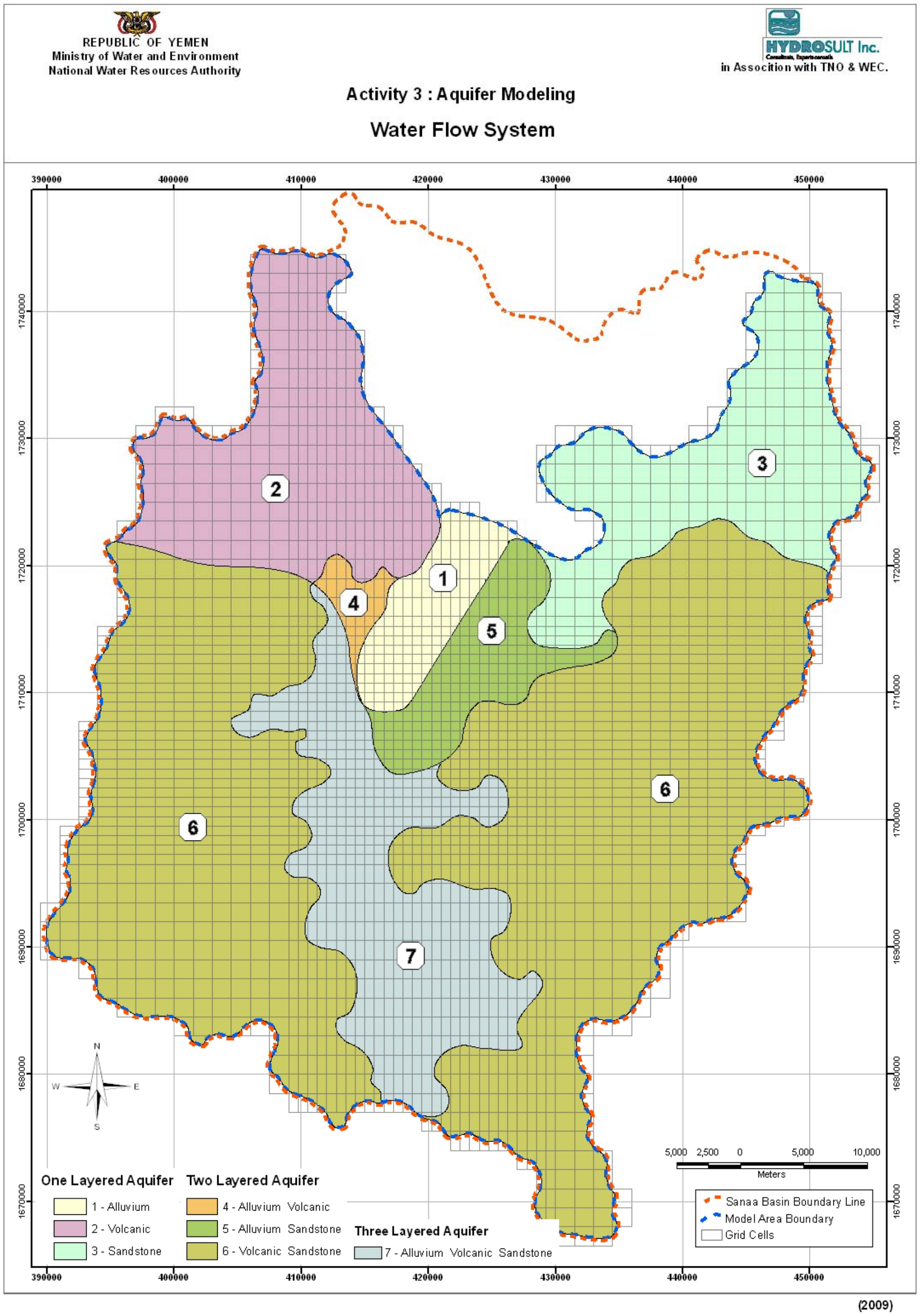


Figure 12: Water Flow Systems

3.2 Layered Aquifer Simulation

With reference to the Groundwater Flow System for the Sana'a Basin, considering the lateral and vertical hydraulic connection between the above-mentioned zones (7 zones), the two hydraulically connected layers were simulated;

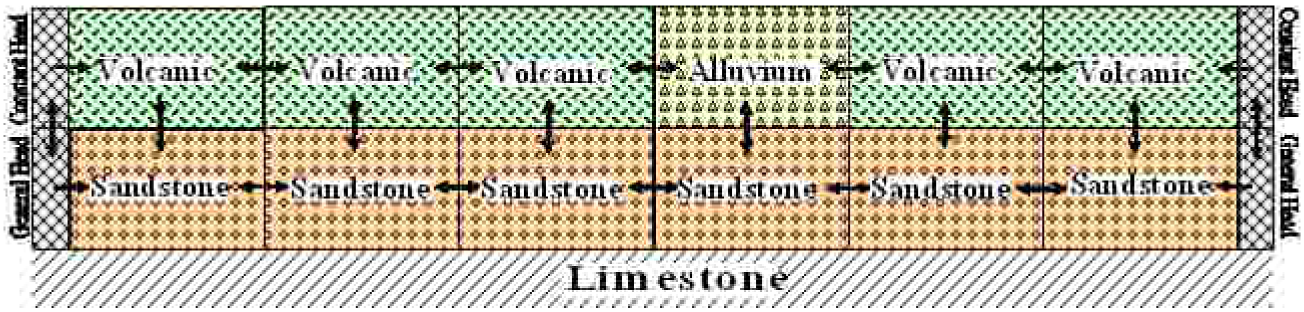


Figure 13: Schematic Conceptual Model 1

3.2.1 First Simulated Layer

The Tertiary and Quaternary Volcanic Group is bounded on the East and West Directions by the Constant Head Boundary which is located at the water divide boundary. The value of Constant head is variable along the different cells, but it has a constant value for each cell for each stress period during the running of the model. These values can be adjusted during the unsteady state calibration run according to the quantity of flow to be considered for the basin to balance with the total inflow and outflow from the basin.

The North direction of this layer is bounded by the General Head Boundary representing the groundwater flow connected with the Limestone Amran Formations. The flux across the boundary is calculated with a given boundary head value. If the calculated head exceeds the boundary head value, water will flow out of the model area, Fig (14).

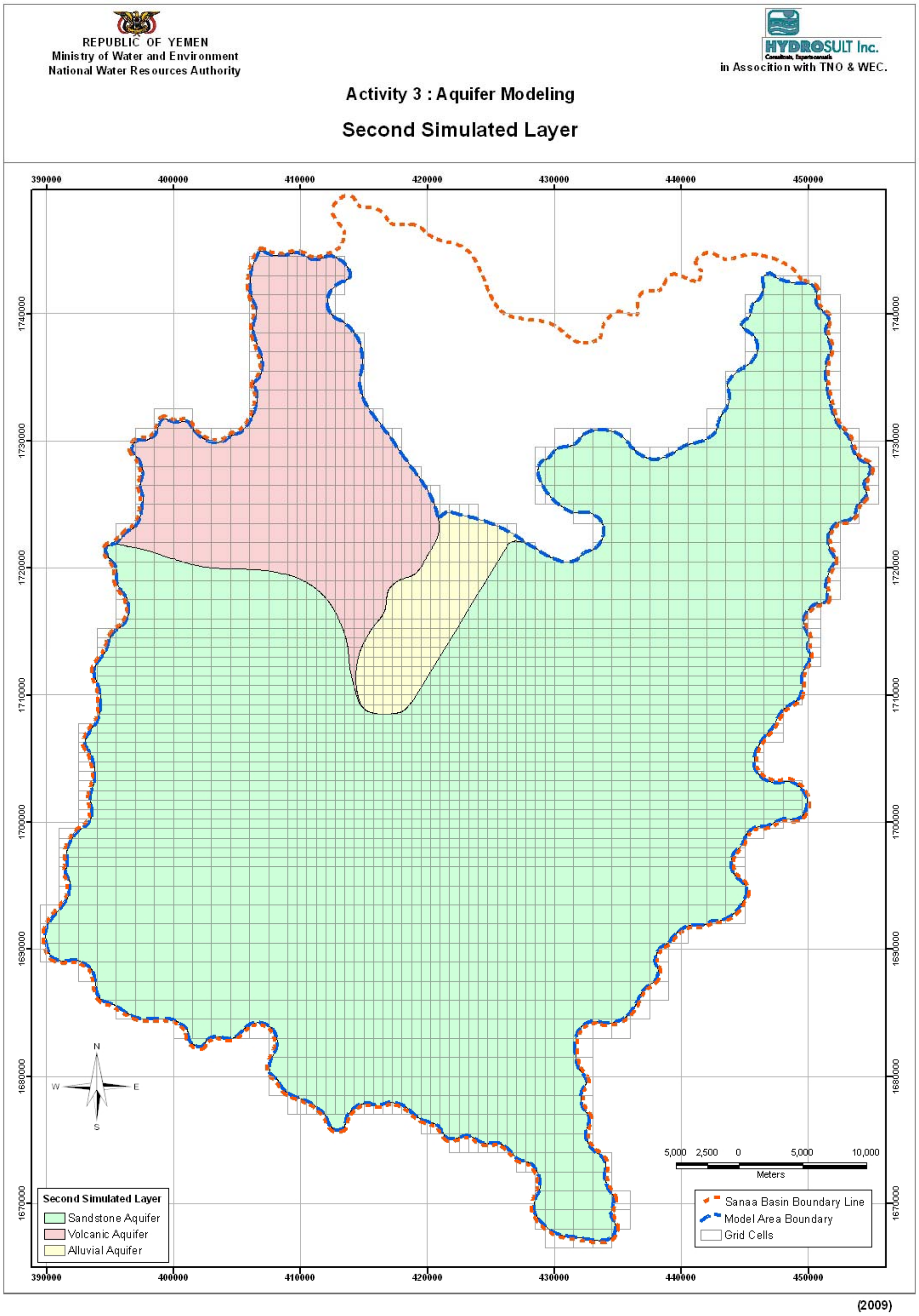
The drain cells are assigned at the first layer, where the infiltration of seepage occurs from sewage water under Sana'a City. Also, the location of the fault-line directed South-North just a few kilometers west of Sana'a City is represented by a low value of conductivity in both simulated layers.

3.2.2 Second Simulated Layer

The second simulated layer is bounded from all directions (North, East, and West) by the General Head Boundary Conditions (GHB), representing the flow into or out of a cell from an external source or at the internal hydrogeological boundary. This boundary simulates the continuation of flow between two adjacent hydrogeological formations. For the Sana'a Basin model, this condition is applied at the nodes where there are hydraulic contacts between the different layers, either in x-direction or z-direction (considering the horizontal conductance, or vertical conductance). Therefore, it is applied at the boundary of adjacent layers (Quaternary Alluvium, Tertiary and Quaternary Volcanic Group, and the underlying the Cretaceous Sandstone formations), where there is a contact with Amran Limestone.

Also, a permeable Boundary Fault line in the Wadi as Sirr, at Ratikh and Qa`As-Salahi areas is considered, where there is a significant variation of thickness and corresponding transmissivity on both sides of the fault line Fig. (15).

Figure 14: First Simulated Layer


REPUBLIC OF YEMEN
Ministry of Water and Environment
National Water Resources Authority
HYDROSULT Inc.
in Association with TNO & WEC.
Activity 3 : Aquifer Modeling
Second Simulated Layer
Second Simulated Layer
Sandstone Aquifer
Volcanic Aquifer
Alluvial Aquifer
Sanaa Basin Boundary Line
Model Area Boundary
Grid Cells
Meters
(2009)

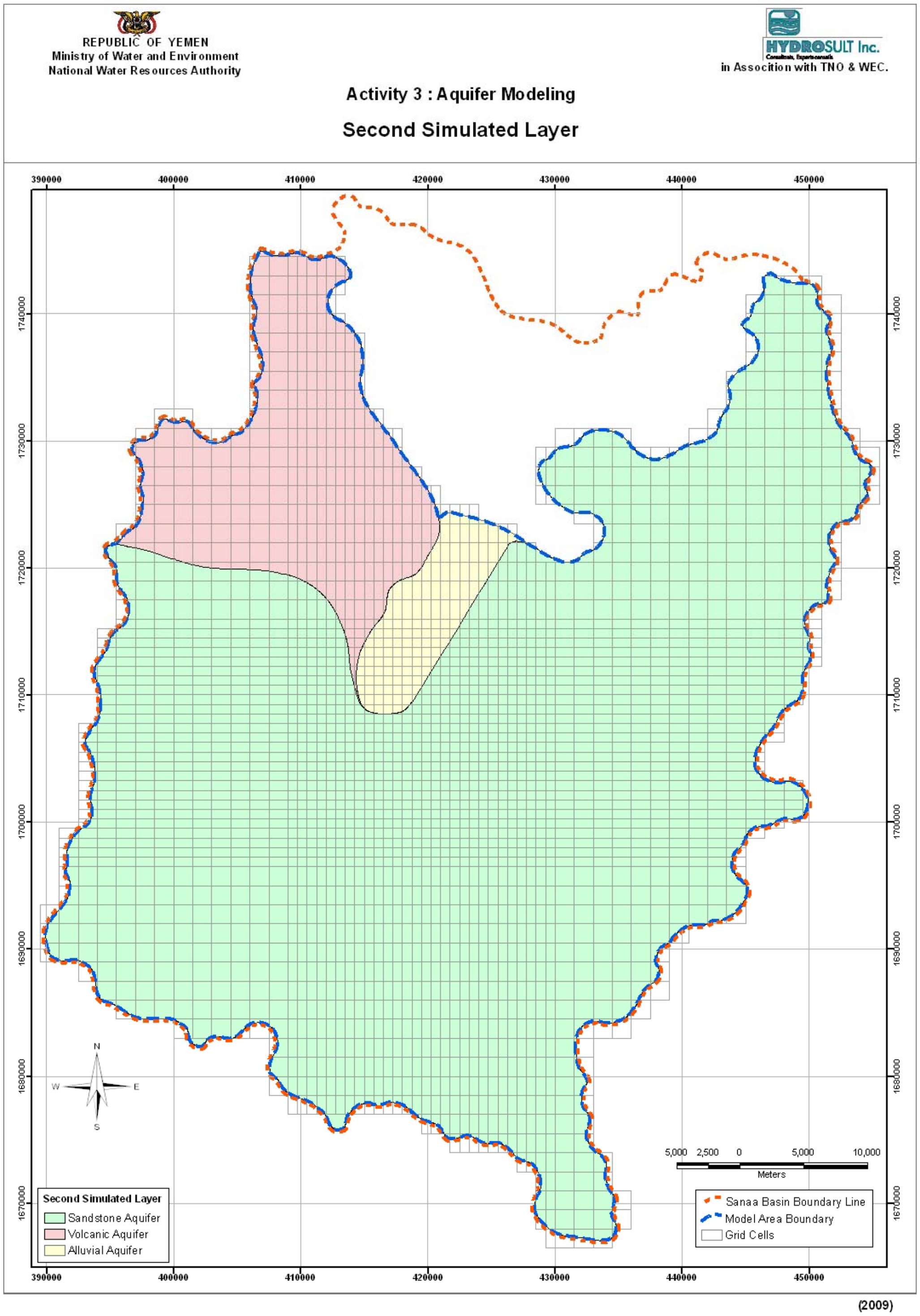


Figure 15: Second Simulated Layer

4. MATHEMATICAL BACKGROUND

4.1 Applied Flow Equation

The general case for unsteady state flow in both unconfined and confined layers was investigated. Parabolic partial differential equations were used, taking into account the various hydraulic conditions that may influence water flow within the studied water complex. These may be expressed in the following general form [2]:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial Y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_S\frac{\partial h}{\partial t} \qquad (1)$$

Where:

K_{xx}, K_{yy}, K_{zz} : Hydraulic Conductivity in (x,y,z) (Lt^{-1})

h : Hydraulic Potential (L)

W : Recharge or discharge in unit volume (t^{-1})

S_S : Specific storage (L^{-1})

t : Time (t)

Finite difference implicit schemes were considered for solving equation (1) applying backward –difference approach. These schemes are unconditionally stable. Equation (1) will have the following form (equation 2) considering the different external stresses (Mc Donald, Horbaugh, USGS, 1988).

$$\begin{aligned} (2) \qquad & CR_{i,j-\frac{1}{2},k}\left(h^m_{i,j-1,k}-h^m_{i,j,k}\right)+CR_{i,j+\frac{1}{2},k}\left(h^m_{i,j+1,k}-h^m_{i,j,k}\right) \\ & +CC_{i-\frac{1}{2},j,k}\left(h^m_{i-1,j,k}-h^m_{i,j,k}\right)+CC_{i+\frac{1}{2},j,k}\left(h^m_{i+1,j,k}-h^m_{i,j,k}\right) \\ & +CV_{i,j,k-\frac{1}{2}}\left(h^m_{i,j,k-1}-h^m_{i,j,k}\right)+CV_{i,j,k+\frac{1}{2}}\left(h^m_{i,j,k+1}-h^m_{i,j,k}\right) \\ & +P_{i,j,k}\,h^m_{i,j,k}+Q_{i,j,k}=S_{S\,i,j,k}\left(\Delta r_j \Delta c_i \Delta v_k\right)\frac{\left(h^m_{i,j,k}-h^{m-1}_{i,j,k}\right)}{t_m-t_{m-1}} \end{aligned}$$

Where:

Δr_j : Dimension of cell along the row direction (L)

Δc_i : Dimension of cell along the column direction (L)

Δv_k : Dimension of cell along the vertical direction (L)

$h^m_{i,j,k}$: Head at node (i , j, k) at time step m (L)

$$CR_{i,j-1/2,k} = KR_{i,j-1/2,k} \; \Delta c_i \Delta v_k \, / \, \Delta r_{j-1/2}$$

: The conductance in row i and layer k between nodes

(i , j-1 , k) and (i , j, k) (L^2t^{-1})

$P_{i,j,k}$ and $Q_{i,j,k}$:

Constants represent external stresses into cell (i , j, k) (L^3t^{-1})

$CC_{i-1/2,j,k}$: The conductance in *Y* - direction (L^2t^{-1})

$CV_{i,j,k-1/2}$: The conductance in *Z* - direction (L^2t^{-1})

$$C = \frac{KA}{L}$$

4.2 Vertical Conductivity

The value of the vertical hydraulic conductivity is required to determine the vertical exchange of flow between layers. The Visual MODFLOW requires the value of the vertical hydraulic conductivity for each cell for each layer of the model, rather than specifying a vertical conductance (*VCONT*) value between layers. Visual MODFLOW then automatically calculates the required *VCONT* values for each layer interface.

The conductance, C, is defined as; Formula missing here!

Where:

Q is the volumetric flow (L^3T^3);
K is the hydraulic conductivity of the material in the direction of flow (LT^{-1});
A is the cross-sectional area perpendicular to the flow (L^2);
h_1-h_2, is the head difference across the prism parallel to the flow (L); and
L is the length of the prism parallel to the flow path (L).

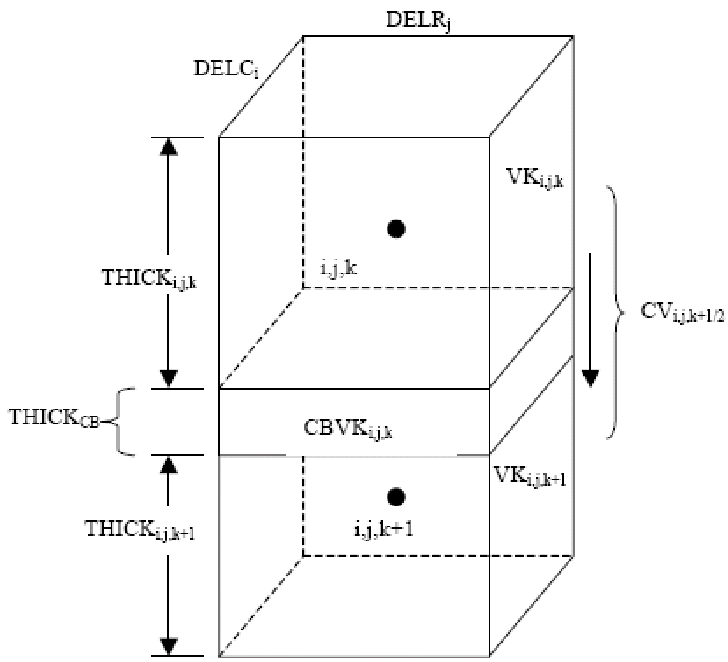


Figure 16: Vertical Flow Hydraulic Conductivity

In order to work around this limitation, Visual MODFLOW starts with the bottom layer of the model, and calculates a *Kz* value for each cell by assuming a horizontal to vertical anisotropy value (*Kx/Kz*) of 10 for each cell. This *Kz* value of the bottom layer is then used as a "seed" to calculate the *Kz* value of the overlying layer, using the following calculation:

$$Kv_{i,j,k} = 0.5*THICK_{i,j,k}/[DELR*DELC/VCONT - 0.5*THICK_{i,j,k+1}/Kv_{i,j,k+1}]$$

Where:

- $Kv_{i,j,k}$ is the vertical hydraulic conductivity of the grid cell in the upper layer
- $Kv_{i,j,k+1}$ is the vertical hydraulic conductivity of the grid cell in the lower layer
- $THICK_{i,j,k}$ is the thickness of the grid cell in the upper layer
- $THICK_{i,j,k+1}$ is the thickness of the grid cell in the lower layer
- *DELR* is the width of the grid cell in the Y-direction
- *DELC* is the width of the grid cell in the X-direction

5. CREATING A NEW MODEL DOMAIN

5.1 Transforming World Co-ordinates to Model Projected

Co-ordinates

The Sana'a Basin model region map has been imported to the model domain in geo-referenced co-ordinates. The model uses the World Co-ordinates, while maintaining the UTM Zone 38N, based co-ordinate system. Thus, the model uses the two co-ordinate systems.

The model domain covers the dimensions of the model, and the Finite Difference Grid. The site map was imported to the model and accordingly the model region was selected.

For Sana'a Basin the following parameters were defined according to UTM co-ordinates;

- X min = 386 500 Y min = 1 663 500
- X max = 460 000 Y max = 1 749 000

5.2 Grid Network

The Computer Software "Visual MODFLOW" is used for defining the applied Grid Network for the Modeling and Simulation Studies for Sana'a Basin Water Management Project.

The boundary of Sana'a Basin and the boundary of the simulated model were imported to the Visual MODFLOW. The area has been adjusted to cover the entire Sana'a Basin boundary region of approximately 3,270 square kilometers, and the simulated model boundary area was kept almost the same for approximately 85% of the basin area.

The active cells were selected for flow simulation and the head values were calculated for each of the active cell. The complete model area was assigned as active cells. The non-uniform grid spacing generated was adjusted, particularly in the area of interest at the middle of the Basin where detailed information is available. The simulated region was discretized into 2,600 cells to cover an area of approximately 2,900 square kilometers. Also, the inactive cells for each layer were assigned, thus assisting in the computation of the hydraulic flow within and between the aquifers.

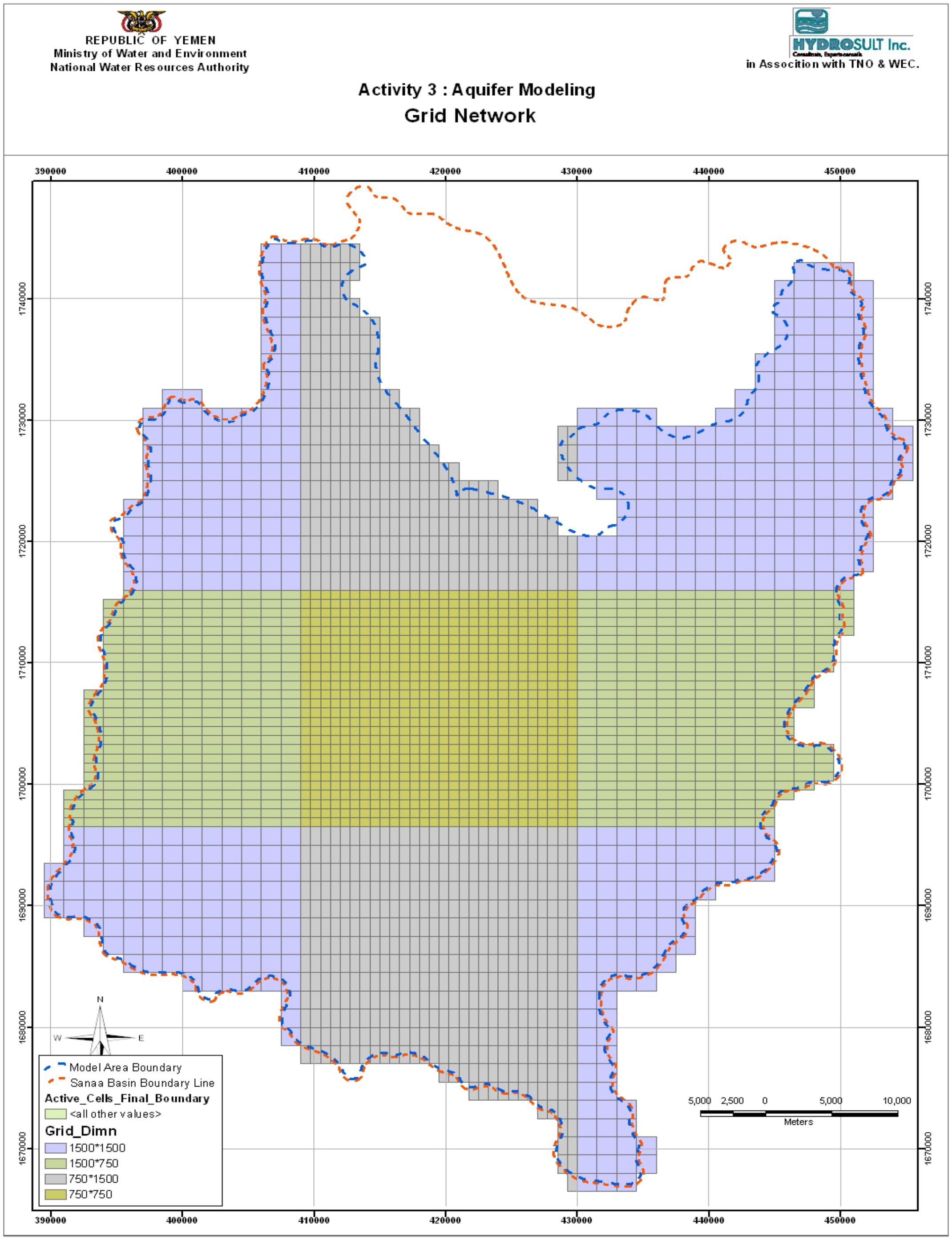


Figure 17: Grid Network

The simulated area was discretized into a finite difference grid covering the entire basin. The rows and columns were selected by applying refine and coarsen modules of the Visual MODFLOW Software for the proposed model grid. Meanwhile, the X and Y limits of the model grid were expanded to meet the required dimension of the different cells.

Accordingly, the area was discretized into 63 columns and 70 rows. The cell size ranges from 750 * 750 meters in the centre to 1,500*1,500 meters near the boundaries. The design of such a grid was based on the following conditions:

- Dense cells (750*750) meters were assigned in the case of:

  * Areas of complicated Hydrogeological conditions
  * High relative intensity of the available Hydrogeological data
  * Availability of periodical field data: level, discharge
  * Areas are subjected to over pumping, recharge, pollution
  * Areas of interest for future development

- Fine grid cells (1,500*1,500) meters were assigned in the boundary areas where the hydrogeological and hydrological data are limited.

Therefore, the simulated region was discretized into 2,339 active cells to cover an area of 2,855 square kilometers distributed as follows (Fig.17):

- 656 cells of 1,500* 750 meters size (738 square kilometers)
- 462 cells of 1,500*1,500 meters size (1,040 square kilometers)
- 728 cells of 750*750 meters size (410 square kilometers)
- 593 cells of 750*1,500 meters size (667 square kilometers)

5.3 Grid Layers

Three layers were edited representing:

- The First Simulated Layer.
- The Second Simulated Layer
- The Amran Limestone (as an impervious Layer).

The grid cells that are previously created are kept the same for all the edited layers. The process of adding and moving layer elevations may create invalid boundary condition data where grid cells contain specified head values less than the bottom elevations of the grid cells. Warning messages will provide an option to fix the offending grid cells.

5.4 Applied Model Units

The following measurement units were selected;

- Length : meters Time: year
- Conductivity: meters per day Pumping rate: cubic meters per day

N.B. these units can be changed according to the model run settings (e.g. steady or unsteady run).

6. IMPORTING AND EDITING LAYER SURFACE ELEVATION

6.1 Interpolation Schemes Setting

The Hydrogeological Conditions can be affected by the variable thickness and surface topography due to the data importand the selection of the mathematical approach applied during importing of the delineation contour maps for the different layers. The MODFLOW applies three data interpolation methods: Inverse Distance, Kriging, and Natural Neighbors.

The complex system was simulated and edited by applying the "Visual MODFLOW' for the three hydraulically connected layers and overlaid the Amran Limestone as impervious layer.

For the interpolation of sparse elevation data, one may apply the Inverse Distance Interpolation, Natural Neighbor, or Kriging methods.

The Inverse Distance Squared method is a very fast and efficient, weighted average interpolation method. The weighting factor for the data depends on the distance of the point from the grid cell, and inversely to the distance squared. Consequently, the greater the distance the data point is from the grid node, the smaller the influence it has on the calculated value. The Inverse Distance Squared method for interpolation may generate patterns similar to a bull's eye surrounding points of observations and therefore this method is undesirable, and other methods are recommended.

Kriging is a geostatistical method that produces visually appealing maps from irregularly spaced data. Anisotropy and underlying trends suggested in raw data can be incorporated in an efficient manner through Kriging by choosing the appropriate set of parameters. Generally, the variogram information is not available, and sometimes this method is not recommended.

The Natural Neighbors (Watson, 1994) is based on the Thiessen polygon method used for interpolating hydrological and hydrogeological data. The grid node for interpolation is considered a new point, or target, to be added to the existing set data. With the addition of this point, the Thiessen polygons based on the existing points are modified to include the new point. The polygons reduce in area to include the new points, and the area that is taken out from the existing polygons is called the "borrow area". The interpolation algorithm calculates the interpolated value as the weighted average of the neighboring observations where, the weights are proportional to the borrowed area. Combining the gradients or slopes with the linear interpolation provides results that are smoother, and may anticipate the peaks and valleys between data. Therefore, the Natural Neighbors approach was selected.

Accordingly, the minimum and maximum limits of the elevation domain of the model for each layer were adjusted There are also possibilities for adding control points to a sparse data set or assigning constant elevation or constant thickness values to avoid interpolation errors. The thickness cannot be assigned when Ground Surface is the selected layer.

6.2 Editing and Importing Surfaces

Visual MODFLOW provides an improved set of tools for importing, creating, and modifying layer surface elevation for the finite difference model grid. The importing procedure involves four steps:

- File selection including the data file format,
- Matching of imported data to column number required by Visual MODFLOW fields for X Co-ordinate, Y Co-ordinate, and Elevation.
- Data Validation of importing elevation data, the set of data for each of the cell parameters, and insuring the data points are within the model domain.
- Specification of the imported Co-ordinate system (World Co-ordinate system, Model Co-ordinate system, Geographic Co-ordinate system, or user defined Co-ordinate system), and applied units.

Therefore, the importing of the elevation data includes ensuring that the three fields X-co-ordinate, Y-co-ordinate, and Elevation are matched with each of the model grid cells. The different delineation maps were imported to the model. Also, the model was checked for the validation values of the imported surfaces (where the bottom elevation value at any cell for any layer is not encountered below the top value of the successive layer). Thus the delineation of the different layers was simulated and the corresponding thickness of each layer at every cell was defined.

The Visual MODFLOW supports surfaces in an existing model by importing different data formats for elevations data from grid data files including;

Grid	ASCII text files	(.TXT, .DAT, .TAB, .CVS)
Grid	Surfer Grid files	(.GRD)
Grid	USGS DEM files	(.DEM)
Points	Access Database	(.MDB)
Points	ESRI Shape files	(.SHP)
Points	Excel Spreadsheet files	(.XLS)

Also, Visual MODFLOW supports five different options for assigning grid cell elevations: Single, Line, Polygon, Window, and Database.

6.2.1 Importing the ground surface elevation contour map

The ground surface elevation contour map must be imported to the model (Fig.15). It is essential because it is considered as the top of the First Simulated layer. The interpolation of the elevation data includes ensuring that the three fields X-co-ordinate, Y-co-ordinate, and Elevation are matched with each of the model grid cells. Any other imported surface data is related to the ground surface contour map.

6.2.2 Importing the aquifer delineations

The groundwater complex system has been simulated and edited by applying the “Visual MODFLOW’ for the hydrogeological hydraulically connected zones.

The interaction of the different layers is automatically defined according to the overlapped delineation of the above-mentioned zones.

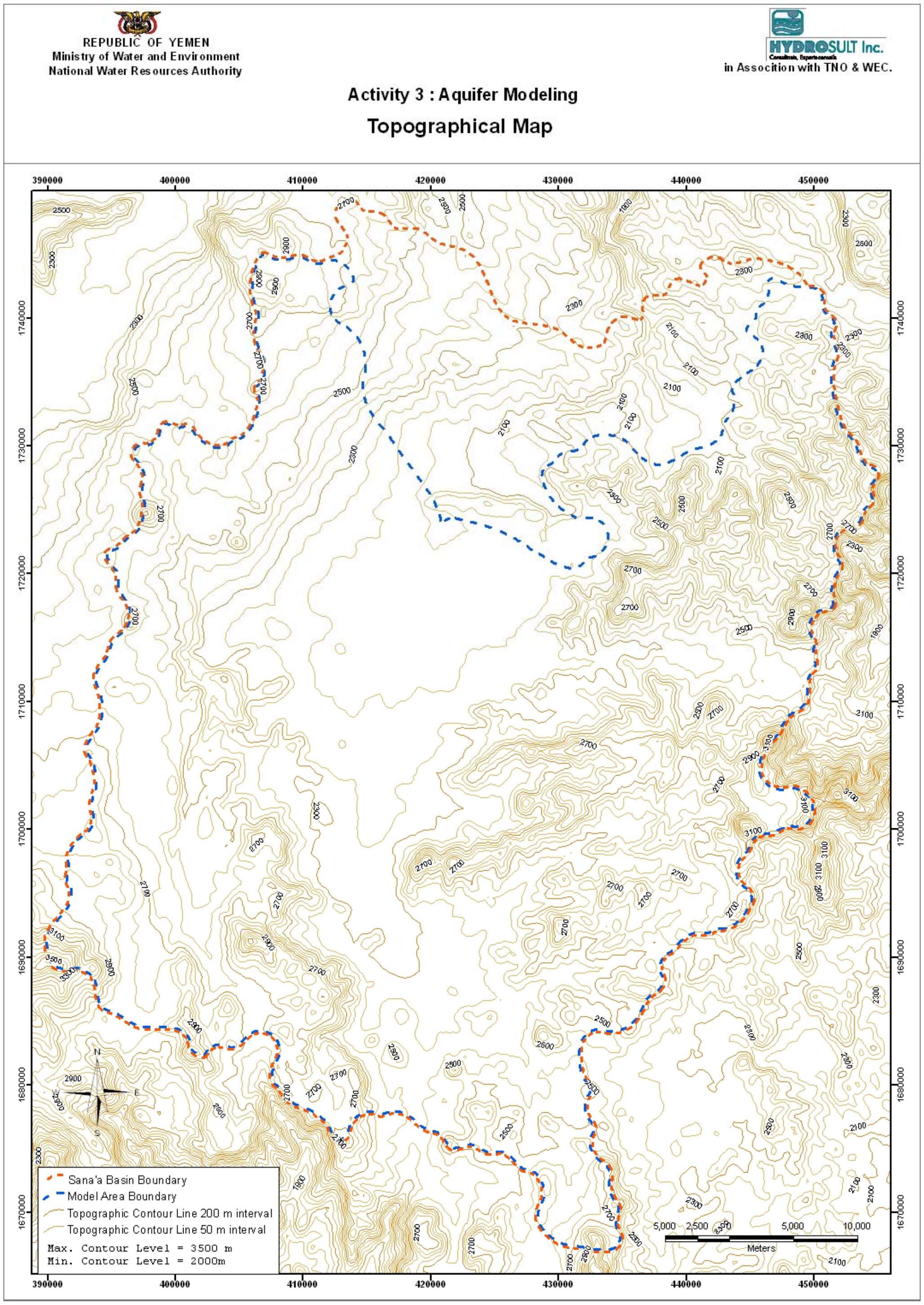


Figure 18: Surface Contour Elevation Map

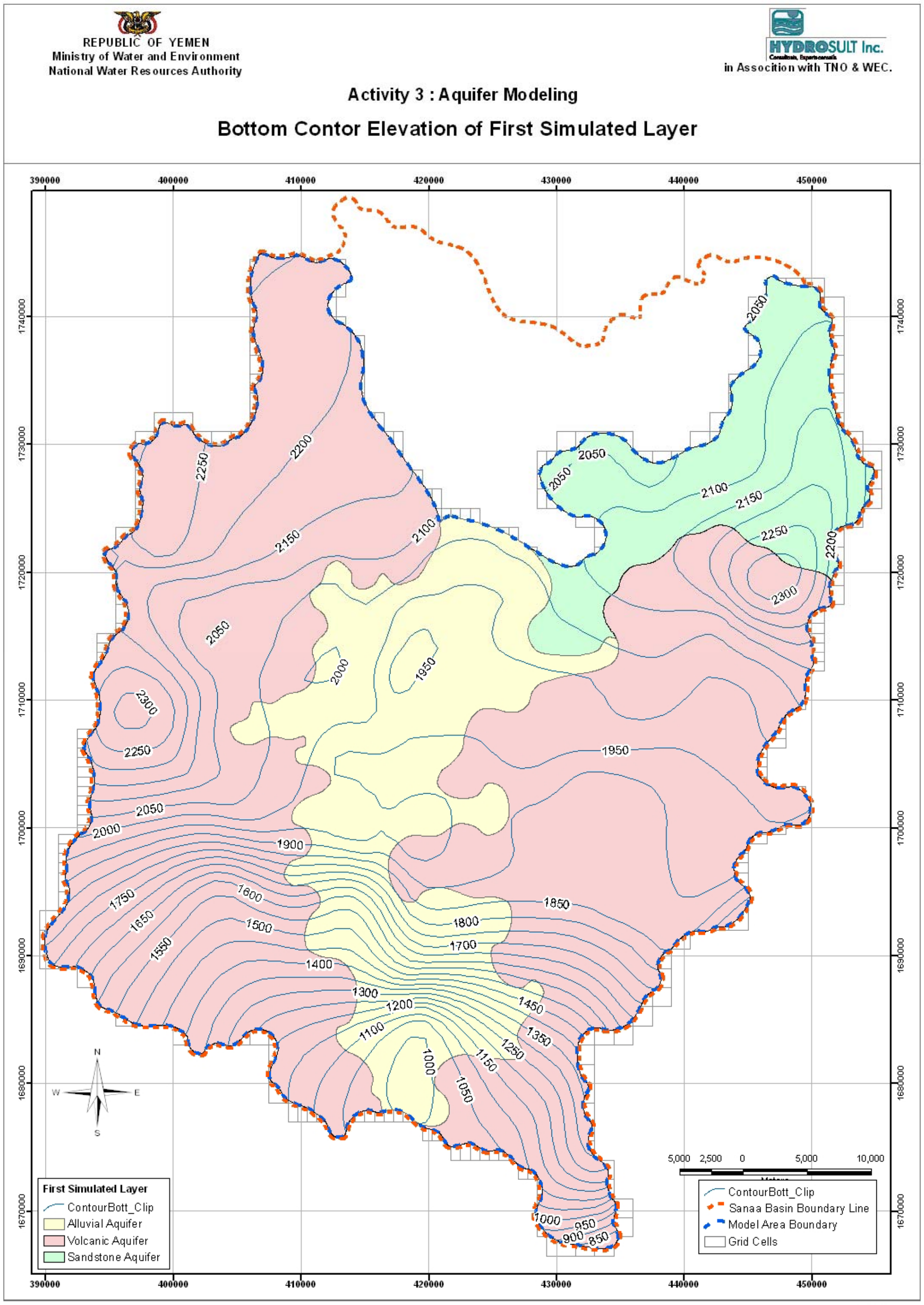


Figure 19: Bottom Contour Elevation for First Simulated Layer

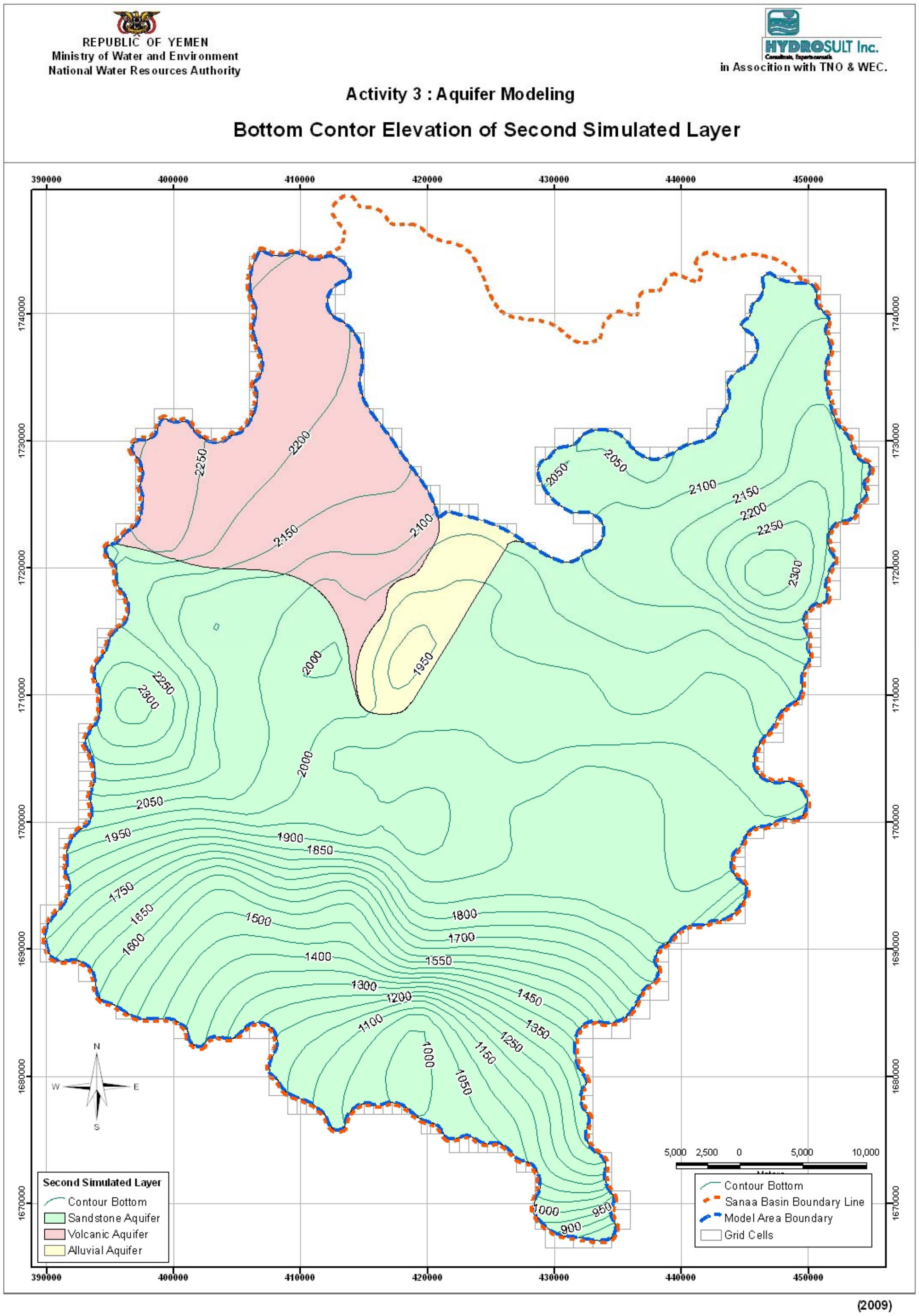


Figure 20: Bottom Contour Elevation for Second Simulated Layer

The bottom elevation contour map of the First Simulated Layer (Fig.19) was imported for defining the lower boundary of this layer; also the bottom contour map of the Second Simulated Layer (Fig.20) was imported to define the boundary of the second layer.

Finally, the contour map of the Amran Limestone impervious layer was defined as the lower boundary of the third layer of completely horizontal bottom elevation of 500 m asl.

The model has checked the validation values of the imported surfaces where the bottom elevation value at any cell for any layer did not encountered a situation of being below the top value of the successive layer. Thus, the delineation of the different layers was simulated and the corresponding thickness of each layer at every cell was defined.

7. THE PREVAILING HYDROLOGICAL BOUNDARY CONDITIONS

7.1 Constant Head Boundary Conditions (CHD)

The area included in the groundwater model is bounded by the watershed boundary of the Sana'a Basin. It is assumed that this boundary coincides with the groundwater water divide and that generally no groundwater flow exists across the boundary. Therefore, in the model, boundary conditions are determined such that groundwater flow may occur, both towards the Basin or outward from the Basin.

The Constant Head Boundary Condition is applied to fix the head value in a selected grid cell regardless of the flow system conditions in the surrounding grid cells. It does not mean that this boundary has a constant value with respect to time, but it may have a function linearly or non-linearly interpolated in time. Therefore, the installation of observation wells along the water-divide is needed in order to record the level with respect to time. In this case, the constant head boundary values can be simulated with extrapolation over a long period. Also, the different effects such as climate change phenomena can also bee simulated.

The Eastern, South, and Western part of the Sana'a Basin for the Volcanic Group is characterized by a Water-Divide Hydraulic Effect. The value of Constant head is variable along the different cells, but it has a constant value for each cell at each time period.

7.2 General - Head Boundary Conditions (GHB)

The general head boundary condition is the flow of this boundary simulating the continuation of the hydraulic flow between two adjacent hydrogeological formations, and representing the flow into or out of a cell from an external source or at the hydrogeological boundary. This flow is provided in proportion to the difference between the head in the cell and the reference head assigned to the external source. The function of the General-Head Boundary (GHB) is mathematically similar to that of the river or a drain. In some cases the general head boundary condition is to represent heads in a model that are influenced by a large surface water body with a known water elevation.

The Conductance value may be physically based; representing the conductance associated with an aquifer between the model area and a large sink source, or may be obtained through model calibration. The Conductance (C) may be calculated by applying the following formula:

$$C = \frac{(L \times W) \times K}{D}$$

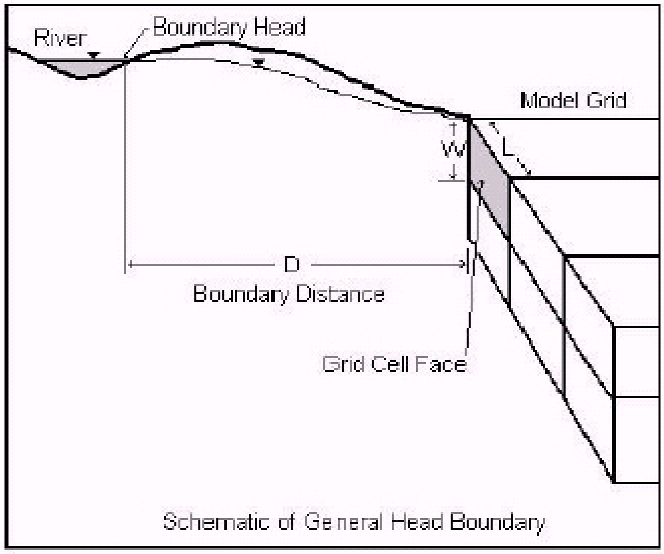


Figure 21: Schematic of General Head Boundary

Where;

LxW	the surface area of the grid cell face exchanging flow with the external source/sink
K	the average hydraulic conductivity of the aquifer material separating the external source/sink from the model grid
D	the distance from the external source/sink to the model grid

The General Head Boundary is known as head dependent flow, (Cauchy or mixed boundary conditions; Anderson and Woessner, 1992), in which a flux across the boundary is calculated given a boundary head value. The boundary head values can estimated as follows:

Boundary head = 0.75 * D+H

Where;

D	thickness of aquifer (m)
H	elevation of the bottom of the aquifer (m)

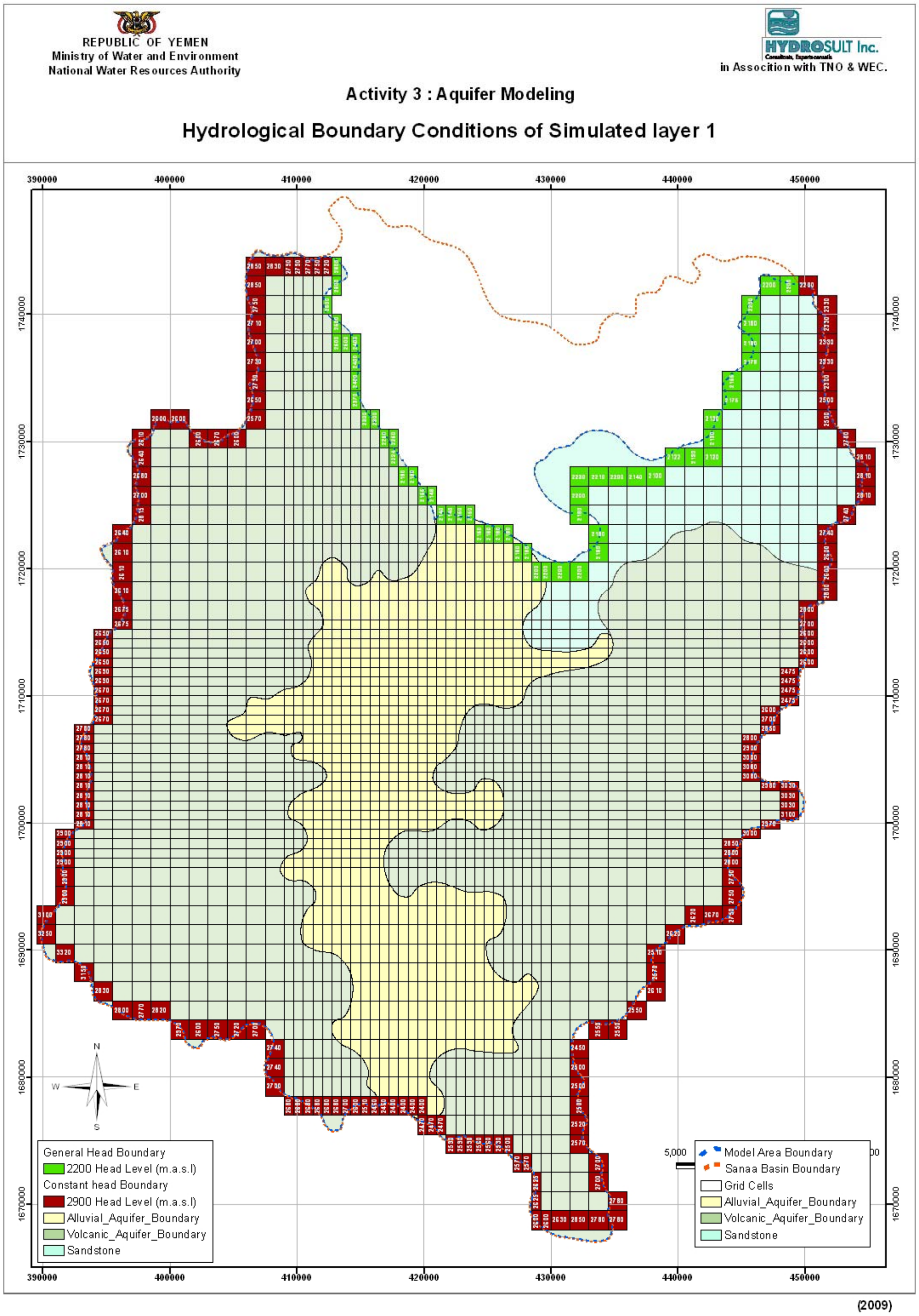


Figure 22: Boundary Condition of First Simulated Layer

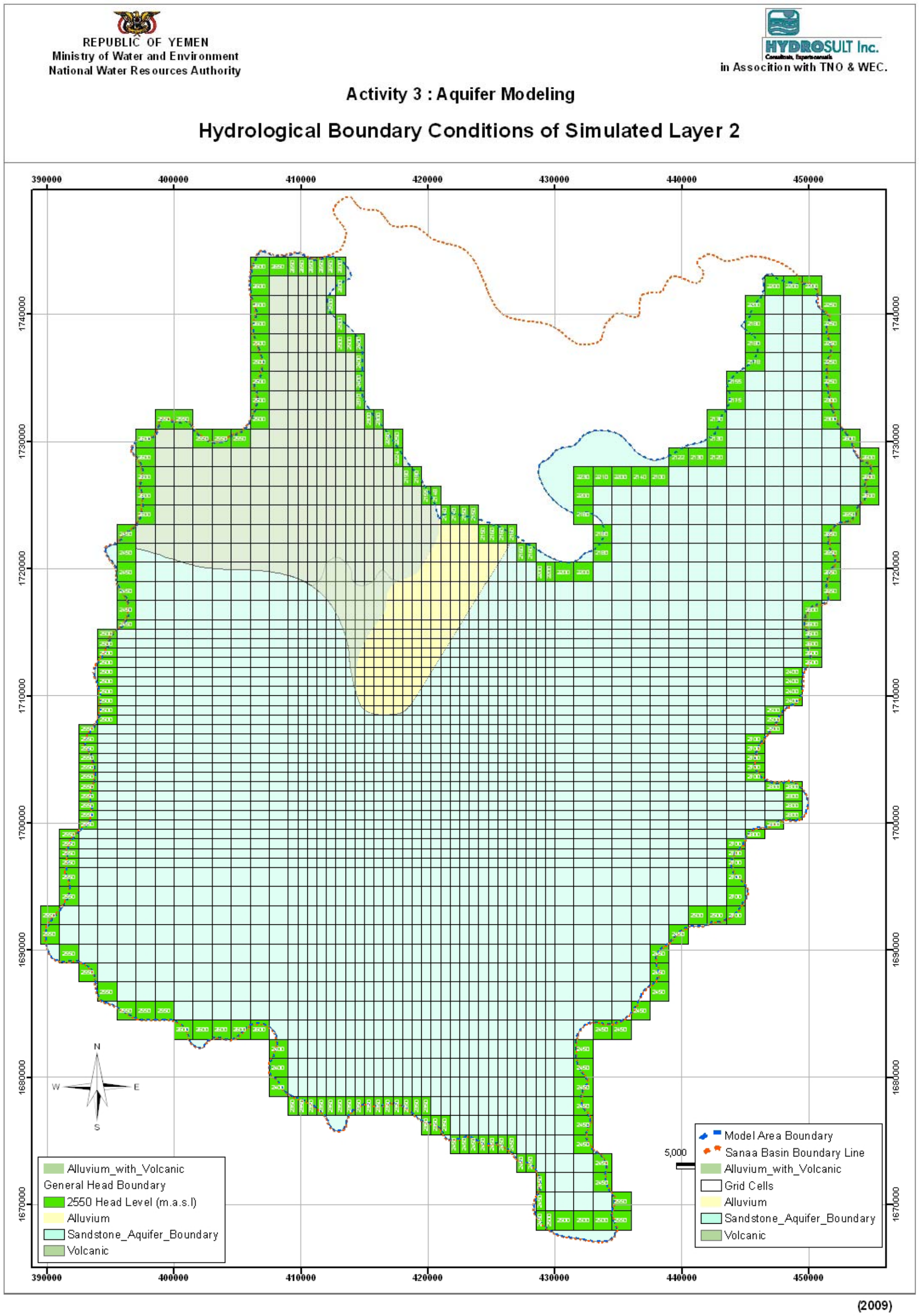


Figure 23: Boundary Condition of Second Simulated Layer

In the of case the Sana'a Basin model, this condition is applied at the nodes where there are hydraulic contacts between the different layers, whether the contact in x-direction, y-direction or z-direction (considering the horizontal conductance, or vertical conductance). Therefore, it is applied at the boundary of the adjacent layers (Quaternary Alluvium, Tertiary and Quaternary Volcanic Group, and Cretaceous Sandstone formations).

The model solves the head values in the General-Head grid cells, whereas the head values are specified in Constant Head cells. The information needed for the General-Head grid cell (boundary head, and conductance) the head is considered as the head of the external source.

7.3 Drain Boundary Conditions (DRN)

Drain Boundary Conditions Module is designed to simulate the effects of features such as agriculture drains, or sewage infiltration, which remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head and elevation. The drain module has no effect if the head falls below the fixed head of the drain.

A huge quantity of sewage infiltration was expected under Sana'a City, and accordingly the water table would rise. Therefore, the water could flow on the surface. Thus, drainage cells are simulated in layer (1).

The Drain Boundary Conditions Module requires the following information as input for each cell simulating the DRN condition:

- Head Elevation: drain head of the free surface of water within the drain. The drain is assumed to run only partially full, so that the head within the drain is approximately equal to the median elevation of the drain.
- Bottom Elevation: the elevation of the bottom of the drain, (this value is not obligatory for Sana'a Basin case).
- Conductance per unit length or area: The conductance value per unit length/area of the drain grid cell.
- Conductance: A numerical parameter representing the resistance of flow between the boundary head and the model domain. This value can be automatically computed applying the following formula;

$$COND = DX * DY * SCOND$$

Where;

COND	the conductance
SCOND	the conductance per unit area
DX	the length of each grid cell in the X-direction
DY	the length of each grid cell in the Y-direction

7.4 Permeable Boundary Condition

The fault-lines in the Sana'a Basin model are considered as relatively permeable boundaries. However, in the Sandstone aquifer, the fault-line in the Wadi as Sirr, at Ratikh and Qa`As-Salahi areas (as projected in the Hydrogeological cross sections F – F` and H – H`), is dividing both sides of the fault with two variable conductivity values. Therefore, this fault-line was simulated as relatively highly permeable boundary in the second simulated layer.

7.5 Closed Boundary Condition (no flow boundary)

This boundary has been simulated in the model by inactive cells; those are outside the model domain. Also, in Sana'a Basin model, the North boundary, where the Amran outcrops, is considered as a no-flow boundary. The hydraulic parameters of the Amran Limestone (kx, ky, and kz) are assigned of very low value. Thus, the complex of the different formations is lying over an almost impervious bed of Amran limestone formations.

7.6 Recharge Boundary Conditions (RCH)

The Project (Activity 2) carried out the hydrological studies on rainfall, evapotranspiration, surface water and groundwater for the improvement of the estimation of the water balance of the Sana'a Basin and its sub-basins.

The average groundwater recharge in each of the 22 sub-basin was determined. The recharge value for each sub-basin was estimated from reservoir, catchments runoff and direct rainfall, and return flow from demand sites. The value of recharge depends on many factors including; the surface topography (slope), the soil cover material, and the predominant landuse and vegetation type.

The recharge from the reservoir varies according to the geology and the shape of the reservoir. When the reservoir site is located on sandstone and volcanic areas, the geology is favorable for recharge occurring in significant amounts.

The direct recharge is calculated from rainfall by soil moisture water balance method and from direct rainfall by a rare phenomenon occurring only during high intensity rainfalls where the soil field capacity is exceeded by the amount of water percolating.

The soil moisture balance was applied (in the study of Activity 2), to estimate a component of water balance, and mainly the groundwater recharge, as the residual of all other fluxes that can be measured or estimated more easily (Lerner et al., 1990). The general relation fluxes (i.e. precipitation (P), surface runoff (Q), evapotranspiration (ET) groundwater recharge (R) and change in water storage in the saturated and unsaturated zones (∂S)) can be represented by the following equation:

$$P = Q + ET + R \pm \partial S$$

Table 1: Recharge abstraction WEC 2002, Hydrosult 2007

No	Catchment Area	Rainfall	Recharge	Recharge	Abstraction WEC, 2002	Abstraction WEC, 2002	Water Balance	Water Balance (mm)
1	76.5	171.0	0.6	7.5	11.1	0.9	-0.3	-3.6
2	211.5	191.0	1.6	7.6	13.8	2.9	-1.3	-6.2
3	136.7	191.0	1.3	9.5	24.6	3.4	-2.1	-15.1
4	111.5	185.0	0.8	7.4	23.9	2.7	-1.8	-16.5
5	210.2	229.0	3.9	18.7	33.0	6.9	-3.0	-14.3
6	75.9	229.0	1.9	25.5	27.9	2.1	-0.2	-2.4
7	64.6	191.0	0.3	4.8	32.8	2.1	-1.8	-28.0
8	120.7	187.0	1.0	8.5	143.8	17.4	-16.3	-135.3
9	322.4	242.0	15.9	49.3	188.8	60.9	-45.0	-139.5
10	77.6	191.0	0.7	8.7	41.9	3.3	-2.6	-33.2
11	219.1	202.0	8.5	38.7	178.3	39.1	-30.6	-139.6
12	45.8	242.0	0.3	6.8	296.9	13.6	-13.3	-290.1
13	204.4	187.0	2.6	12.8	85.4	17.5	-14.8	-72.6
14	364.8	279.0	11.6	31.7	45.3	16.5	-4.9	-13.6
15	63.7	217.0	0.6	8.7	117.3	7.5	-6.9	-108.6
16	179.6	210.0	1.0	5.7	197.1	35.4	-34.4	-191.4
17	95.4	223.0	1.9	19.7	92.5	8.8	-6.9	-72.8
18	236.9	202.0	6.6	27.8	43.9	10.4	-3.8	-16.1
19	143.8	210.0	2.4	16.8	29.4	4.2	-1.8	-12.6
20	69.8	249.0	0.7	9.8	42.4	3.0	-2.3	-32.6
21	80.5	249.0	1.1	13.9	39.4	3.2	-2.1	-25.5
22	125.4	173.0	2.3	18.7	67.3	8.4	-6.1	-48.6
Total	3236.8	___	67.7	358.6	1776.8	270.0	-202.3	-1,418.3

km^2 : Kilometer square
mm/y : Millimeter per year
Mm^3/y : Million cubic meters per year

The results of the study carried out through Activity 2 can be summarized as following;

- Average annual rainfall in Sana'a Basin is 663 Mm^3 which is about 205 mm over an area of 3239 km^2.
- Average annual runoff leaving the basin at the outlet is about 8.7 Mm^3
- The average annual total groundwater recharge is:

  * 51.2 Mm^3 from Surface runoff and direct precipitation.

  * 21.3 Mm^3 from return flow of demand sites including Sana'a City

  * 5.5 Mm^3 from the reservoirs in Sana'a Basin

It was determined that the minimum recharge value is of 6.8 million cubic meters per year in Wadi Beni Hwat, and the maximum of 25.3 million cubic meters per year in Wadi A'sir. The total recharge value for the 22 sub-basins was estimated of about 70 million cubic meters per year.

The Visual MODFLOW allows recharge values to be assigned to layer (1), and will set the recharge to be applied to the upper-most active wet layer of the model for each vertical column of grid cell. The recharge zones were assigned according to the sub-basins which are located inside the boundary of the model domain.

Table 1 shows the recharge values for each sub-basin in mm/yr. Therefore, the distribution of property data for each recharge zone was imported to the model.

According to the available data, the recharge rate values were considered constant with respect to time factor. The model can simulate variable values of the recharge rate considering the effect of aridity and climate change.

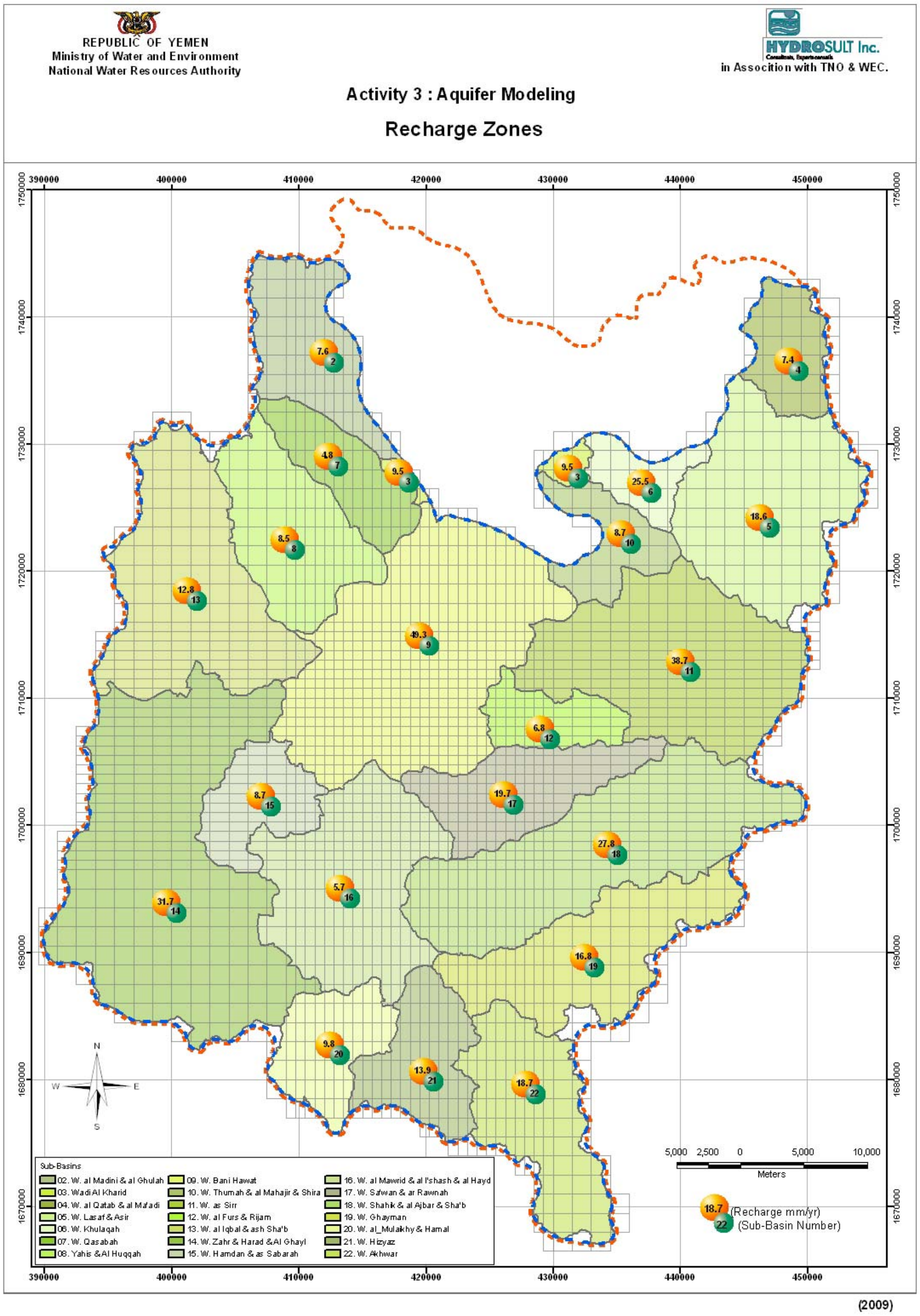


Figure 24: Recharge Rate Distribution

8. GIS INPUT DATA FOR STEADY AND UNSTEADY RUNS

The validation of the different inputs related to the available hydrological and information including; the water level with respect to date, the hydraulic parameters, pumped water, recharge, etc. have to be checked. Then, the model input has to be modified in the GIS database, confirming with the accepted forms of the applied software, “Visual MODFLOW Premium Version 4.2’.

8.1 Validation of the Input Data:

The available hydrogeological and hydrological data were collected and compiled through Activity 1, including the results of the surveys carried out by different organizations and institutions, mainly from the following sources:

- ITALCONSULT survey for alluvial aquifer (296 wells - 1972).
- Russian survey for alluvial aquifer (136 wells – 1985), and for Volcanic aquifer (275 wells, 1985).
- SAWAS survey for alluvial aquifer (610 wells – 1993), and for Tawilah Sandstone (70 wells, 1993).
- NWAS survey for (20 wells, 2000 & 2004).
- WEC complete survey for alluvial aquifer (1282 well, 2002), and for Tawilah Sandstone (1410 wells, 2002).
- NAWRA survey Alluvial, Tawilah Sandstone, and Amran Limestone (33 well, Jan – Sep – 2004 – 2005, 2006).
- HYDROSULT: December 2006, Feb 2007, March 2007, for the proposed observation network).

It was essential to select representative observation wells, which have data on the water levels and the hydraulic parameters. Observation wells were monitored only for the specific defined aquifer. Such input data for the model was validated and used for running the model or for the calibration processes. The following procedures were followed:

- The X-co-ordinate, the Y-co-ordinate, and the top level elevation according to the applied unified DEM map were determined.
- The absolute level of the bottom of the well and the penetrated formations were defined.
- The thickness of the penetrated aquifers at the location of the well.
- The screen level in the well.

The representative observation wells were selected according to the following criteria:

- The filter or screen of the well penetrates one layer only, and the well represents this layer.
- The well is located in the defined delineation boundary of the represented layer.
- The co-ordinates of the well are defined with a permissible accuracy and within the unified applied DEM map system.
- The absolute level of the screen is determined and the measured water level represents the pressure head at this location in the aquifer.
- The observation well is not under any hydrological effect, such as pumping stress.

- The observation wells are not localized in one area, but distributed according to the variation of the initial values of the hydraulic parameters.
- The date of the measured water level is recorded.

Therefore, the available data was validated and the representative observation wells were selected. Also, the Water Table Maps were constructed consistent with the hydrogeological cross sections and the boundary conditions of Sana'a Basin

8.2 Wells

8.2.1 Pumping Wells

WEC, in 2001, carried out a complete hydrogeological survey for all the wells in Sana'a Basin. This survey included the inventory of the hydrogeological data for 13,426 water points. This survey covered mainly type of well; well location; well depth; year of construction; depth to water; pumping rate at dry and wet season.

Since 2001there has been no estimation made of the abstracted water. Therefore, there is no available updated information on the present abstracted water from the Sana'a Basin. With reference to the field survey remarks, it was noted that the dried wells were compensated by other wells. To give an idea of the present hydrogeological conditions of the Sana'a Basin, it was considered that the same rate and distribution of the abstracted water as in 2001 were extended to the year 2008.

Therefore, the scheme of the water abstraction from the Basin was subdivided into the seven main periods;

- in 1972
- from 1973 to 1980
- from 1981 to 1988
- from 1989 to 1993
- from 1994 to 1997
- from 1998 to 2000
- from 2001 to 2008

According to the analysis of the WEC survey data, the pumped wells were defined with respect to the type and construction date.

Table 2: Total Basin Abstraction Rate

YEAR	Total no. of wells	Start Time (d)	Total Pumping (M m^3)/yr
1972	442	0	21.2
1980	835	2,920	35.9
1988	2,834	5,840	115.6
1993	3,800	7,665	153.6
1997	4,655	9,125	184.6
2000	5,553	10,220	211.0
2002	5,965	10,950	227.2
2008	5,965	10,950	227.2

Meanwhile, by reviewing the different studies, the values of the yearly total pumping were adjusted to conform with the projected water balance for the Basin. The transient period is considered at the end of year 2008.

The Excel files were developed according to the MODFLOW Software forms as follows;

1- Well Name
2- X co-ordinate
3- Y co-ordinate
4- Screen ID (no of screen intervals)
5- Top elevation of the Screen
6- Bottom elevation of the Screen
7- Screen Radius
8- Casing Radius
9- Stop Time when pumping rate is appreciable

The co-ordinates and the values of top elevation, top elevation of the screen, and bottom elevation of the screen for each were defined according to WEC survey 2001, and the unification of the projection data was carried out according to the projection modules applying the DEM map.

Each time period requires a valid Start time, End time, and pumping rate. The Start time of one time period is equal to the End time of the previous time period. Negative pumping rate values are used for extraction wells

Four input files were developed for the years 1972, 1980, 1988, 1993, 1997, 2000, 2002, and 2007. As no recent complete surveys has been carried out, according to the general surveys carried out for Activity 1, Activity 2, and Activity 4, the value of the total groundwater abstraction in the last years has not changed. Some wells became dry due to the continuous over-pumping. These wells were replaced, and the value of total groundwater abstraction from the basin has almost kept the same value during the period 2002 to 2008.

The values of screen radius and the casing radius are not obligatory when applying the MODFLOW 2000 engine. The attached volume for Database Sana'a Basin includes the complete information on the pumping wells data in Visual MODFLOW format.

8.2.2 Head Observation Points:

The criteria for selecting representative observation points were considered as follows:

- The well filter penetrates one layer only and the well represents this layer.
- The well is located in the defined delineation boundary of the represented layer.
- The co-ordinates of the well are defined with a permissible accuracy and within the unified applied DEM map system.
- The absolute level of the screen is determined and the measured water level represents the pressure head at this location in the aquifer.
- The observation well is not under any hydrological effect, such as pumping stress.
- The observation wells are not located in one area, but are distributed according to the variation of the initial values of the hydraulic parameters.
- The date of the measured water level has to be known.

Also, available data must be validated and thoroughly reviewed according to the above-mentioned criteria. Also, the Water Table Maps are constructed in consistency with the hydrogeological cross-sections and the hydrological boundary conditions of Sana'a Basin.

A distinguished effort was made to develop the files of Head Observation Points from the different studies: ITALCONSULT (1972), Russian survey (1985), SAWAS survey (1993), NWAS survey (2000, 2004), WEC (2002), and HYDROSULT (2007, 2008). These existing water level data from different surveys during different periods were reviewed.

Meanwhile, new water levels were recorded for some selected observation wells through the implementation Activities 1, 2 and4. These wells are monitored periodically by the Project. Observation Wells were verified with the defined layers delineation (location of the screen within the top and bottom elevation of the specified well location in the layer). Also, maps were established to define the distribution of wells penetrating each water formation for the first and second simulated layers.

The Head observation well data required by Visual MODFLOW format includes: Well Name, X co-ordinate, Y co-ordinate, Screen I.D., Screen Elevation The attached volume for Database Sana'a Basin includes the complete information on the observation wells data in Visual MODFLOW format. These data were applied for the simulation in the transient calibration run.

8.3 Hydraulic Parameters (Flow Properties)

8.3.1 Conductivity:

The pumping tests data were compiled from the past studies carried out by NWSA and SWEP, and were evaluated within Activity 1 of the current Project. The re-analysis of some pumping tests data generated by Italconsult, 1972, Dar Al Handasah Consultants (Shair and Partners), 1980, and Howard Humphry and Sons, 1981 were undertaken. The priority was given to wells that are located in the highly exploited areas in the Basin and that represent different hydraulic properties of the aquifer. The majority of deep wells developed in Tawilah Sandstone Formation and some wells in the Volcanic Formation, and Alluvial Formation were selected. Different methods of analysis were applied.

Different methods of analysis of pumping test data are used according to the hydraulic conditions of each test such as, the location of the pumping well in an aquifer of relatively infinite areal extent ; the aquifer homogeneity; isotropic or uniform thickness over the area influenced by the pumping test; the rate of pumping is constant or variable; fully penetrated or partially penetration; steady state or unsteady state condition. Accordingly, the proper method of analysis was applied (Theis's, Chow's, Jacob, Theis's recovery, Hantush , Boulton, Cooper-Jacob's method, or others).

The Conductivity parameter includes;

- Kx; Hydraulic conductivity in the direction of the model X-axis.
- Ky; Hydraulic conductivity in the direction of the model y-axis, as initial values was considered the same value of Kx.
- Kz; Hydraulic conductivity in the direction of the model z-axis, as initial values was considered 10% of the value of Kx.

The statistical analysis was conducted for depicting spatial and lateral changes in aquifer parameters, and thus allowed a better understanding of the characterization of the aquifers. Furthermore, new pumping test in several locations of the Sana'a Basin were carried out through the Project. The analysis of the data generated by the new pumping tests provided further information on the characteristics of the Tawilah sandstone Formation and the alluvial aquifer in different locations in the Sana'a Basin.

The analyses carried out by Activity 1 can be summarized as follows:

- The Tawilah sandstone is the main aquifer in the Sana'a Basin;
- The statistical study of hydrodynamic characteristics showed that the Tawilah sandstone aquifer is highly anisotropic and heterogeneous in relation with the structural events that affects this formation;
- There is no correlation between different hydrodynamic parameters of the Sandstone aquifer such as depth versus transmissivity and thickness of aquifer versus transmissivity;
- The transmissivity of the Volcanic aquifer depends mainly on the degree of fracturing ;
- Analysis of pumping test curves shows that there is a recharge effect from the same aquifer at a long distance;
- The geological structure, such as a dyke, constitutes a boundary effects and limits the hydraulic relation between wells in the sandstone aquifer;
- 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 another area;
- The results of new pumping test carried out in the alluvial aquifer in different area of the basin showed a relatively high transmissivity for this aquifer.

The results of the analyses of pumping tests are considered as initial values for running the model for steady state calibration. After reviewing the available results and considering the hydrogeological conditions for each pumping test, the method of analysis and the following outputs were selected as initial input values for running the model for steady state calibration case. Tables 3, 4, and 5 are imported to the model after assigning them in the Visual MODFLOW accepted format.

Naaman (2004) in his modeling studies for Sana'a Basin, used one horizontal permeability value of 0.05 m/d, and one vertical hydraulic conductivity of 0.005 m/d for the Alluvium aquifer. The Volcanic aquifer applied two horizontal hydraulic conductivity values; Sana'a Basin floor of 0.02 m/d, and outside basin floor of 0.002m/d. The Quaternary Volcanic applied one value of 1 m/d. Also, the vertical hydraulic conductivity of 0.00006 m/d for the Volcanic, and for the Sandstone aquifer considered one value of 0.001m/d.

Table 3: Conductivity Parameter for Alluvium Formations
(Input Visual MODFLOW Format)

Well No	East	North	Kx	Ky	Kz
734	420500.00	1717500.00	0.18	0.18	0.02
L1	416500.00	1688500.00	3.11	3.11	0.31
867	415500.00	1715500.00	15.77	15.77	1.58
126	421500.00	1684500.00	0.08	0.08	0.01
1-P	413680.00	1697830.00	0.35	0.35	0.35
734	420500.00	1717500.00	0.18	0.18	0.02

Table 4: Conductivity Parameter for Volcanic Formations
(Input Visual MODFLOW Format)

Well No	East	North	Kx	Ky	Kz
O125	433500	1689500	0.036916	0.036916	0.003692
O128	431500	1688500	0.046930	0.046930	0.004693
47	431500	1674500	0.036099	0.036099	0.0036099
261	402500	1695500	0.003536	0.003536	0.0003536
25	414500	1678500	0.016075	0.016075	0.016075
160	432500	1699500	0.006625	0.006625	0.000625
Salm	418600	1688800	0.191941	0.191941	0.019194
707	403500	1694500	0.282059	0.282059	0.028206
48	415500	1681500	0.004616	0.004616	0.000462
1126	413500	1691500	0.255000	0.255000	0.025500
5-p	413510	1698910	0.013840	0.013840	0.001384
SE-4	414850	1695300	0.211515	0.211515	0.021152
EXP-2	409230	1692457	0.133230	0.133230	0.013323
EXP-1	403801	1695406	0.139879	0.139879	0.013988
AS1	411220	1696100	0.024590	0.024590	0.002459
HZ	419766	1685107	0.039846	0.039846	0.003985
H3R	413296	1703296	0.419886	0.419886	0.041989
ST-3	417700	1692750	0.020750	0.020750	0.002075
1P	413688	1697813	0.096105	0.096105	0.009611
2P	420603	1679475	0.000393	0.000393	0.000039
3P	403700	1697944	0.009559	0.009559	0.000956

Table 5: Conductivity Parameter for Sandstone Formations (Input Visual MODFLOW Format)

Well No	East	North	Kx	Ky	Kz
c	410938	1696367	0.34	0.34	0.034
ASR	410938	1696367	0.50	0.50	0.050
P8R	413000	1705000	0.10	0.10	0.010
SA-1	413594	1696222	1.16	1.16	0.116
P26	414109	1700607	0.19	0.19	0.019
EX-S	414157	1691674	0.11	0.11	0.011
TP1	415350	1701200	1.89	1.89	0.189
W	416205	1700850	0.35	0.35	0.035
SS	416413	1701152	8.22	8.22	0.0822
N3	416455	1700970	0.87	0.87	0.087
M4	416665	1698207	1.27	1.27	0.127
T	417885	1701005	0.80	0.80	0.080
E	418005	1703262	5.20	5.20	0.052
M16	418080	1700347	1.34	1.34	0.0134

8.3.2 Specific Yield (Sy)

Specific Yield is known as the storage term for an unconfined aquifer. It is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area per unit decline in the water table level. For sand and gravel aquifers, specific yield is generally equal to the porosity. The values of the storage coefficient and specific yield are computed mainly from the analyses of pumping tests for unsteady state or non-equilibrium flow. Unfortunately, only a few storage coefficients were computed from pump tests where observation wells were used during the test. By reviewing the available results from the studies of Activity 1, some values were selected for use in the model as initial values for calibration of the transient run.

Table 6: Storage Coefficient for Alluvium Aquifer

Well No	East	North	Ss
HS 51	440585	1711095	8.00E-03
HS 66	440783	1710542	4.00E-04
HS A19	416322	1715307	1.35E-03
HSA26	421921	1713997	1.00E-03
HSA30	422810	1716400	1.10E-03
HSA31	423079	1717230	9.00E-03
HSA 36	423334	1719743	8.70E-03
HSs 3	425228	1701002	3.30E-03
HSA54	416612	1717630	4.90E-04
HSA55	416631	1717743	9.00E-03
HSZ 12	416473	1689675	7.80E-02
HAS 61	416062	1714747	3.00E-03
HAS 62	414799	1715584	1.00E-02

Table 7: Storage Coefficient for Sandstone Aquifer

Well No	East	North	Ss
P17	400656	1708837	2.07E-03
P15	409405.26	1709557.5	9.30E-04
P8	413047.74	1704606.37	2.08E-04
P16	413945.58	1701124.8	6.10E-04
P17 (OW)	400656	1708837	1.86E-03
SE-1 (OW)	414930	1701500	1,8 E-4
SE-2 (OW)	414930	1701490	3.84E-04
SE-3 (OW)	420860	1707950	7.52E-04
ST7 (OW)	412400	1704800	7.65E-03
HS 50	427222	1711226	2.40E-04
HS 56	431087	1715023	9.57E-04
HS 63	420466	1707697	4.13E-05

Results of the transient state calibration of the Naaman Model (2004) showed that the estimated value of specific yield for the alluvium and Tertiary volcanic aquifer, (value of 0.2), is lower than the specific yield of the sandstone aquifer (value of 0.005). However the sandstone aquifer is known to be the main aquifer in Sana'a Basin, and the Quaternary volcanic is characterized by fissures and fractures.

The value of the Storage Coefficient for the volcanic aquifer was estimated at 3.74E-7, and for the sandstone aquifer at 0.908E-04.

The same procedure as that applied for the conductivity coefficient for the steady state calibration was applied for the transient calibration for the values of the Specific Yield and the Storage Coefficient. The values obtained from the pumping test analyses, plus the general values obtained from the Naaman Model (2004) were introduced as initial values.

9. MODEL RUN SETTING

9.1 Time Steps

The model was operated for the steady state and unsteady state conditions. The steady state run was mainly to calibrate the aquifer conductivity parameter and its variation for both the first and second simulated layers. In the early seventies, the Basin was not affected by heavy pumping and overexploitation. In 1972, Italconsult carried out a survey on the water resources in Sana'a Basin. The available data, compiled by Italconsult can be considered as the Basic available data for the steady state calibration.

The unsteady state calibration run covered the period from 1972 to 2008. According to the available data compiled from the different studies carried out in the basin, the following stress periods are considered:

- 1985 (reference to the Russian studies)
- 1993 (reference to the SAWAS studies)
- 2002 (reference to the WEC survey)
- 2007 (reference to the HYDROSULT studies)

The computation for the time step is considered as 365 days (one year). The Visual MODFLOW automatically merges all the different time periods defined for all pumping wells and boundary conditions to conform to the uniform stress period format required by MODFLOW. The stress period is defined as a time period in which all the stresses (boundary conditions, pumping rates, etc.) on the system are constant. Therefore, the number of stress periods and the length of each stress period can be defined automatically.

The time step Multiplier is the factor used to increment the time size within each stress period, (i.e. it is the ratio of the value of each time step to that of the proceeding time step). The value of the time step Multiplier is considered 1.2, which produces smaller time steps in a simulation resulting in a better representation of the changes of the transient flow field.

9.2 Layer Type Setting (LAYCON) & Numeric Engine (LAYAVG)

The type for each of the three simulated layers has been defined as follows (LAYCON):

The first simulated layer (Alluvial and Volcanic) is defined as unconfined, is considered as type 1, where the transmissivity of the layer varies, and is calculated from the saturated thickness and hydraulic conductivity.

The second layer, mainly Sandstone, is considered as type 3, where the transmissivity of the layer varies and is calculated from the saturated thickness and hydraulic conductivity. The storage coefficient may alternate between confined and unconfined values.

The method of Log-arithmetic mean interblock transmissivity (value 20), is assigned as the numeric engine (LAYAVG) to be applied in the Visual MODFLOW.

The Layer type setting is assigned as follows:

- Layer 1 Alluvial & Volcanic Type(21) Logarithmic Mean Unconfined
- Layer 2 Sandstone Type (23) Logarithmic mean Confined/Unconfined, variable T&S

9.3 Solver Settings

The WHS Solver is selected because it uses a Bi-Conjugate Gradient stabilized acceleration routine, implemented with Stone incomplete decomposition for preconditioning of the groundwater flow partial differential equations. This solver approaches the solution of a large set of partial differential equations iteratively through an approximate solution. The applied solver parameters for the WHS are a strongly implicit procedure and applying over-relaxation method.

The WHS works on a two-tier approach to a solution at one time step. An Outer Iteration is where the hydrogeologic parameters of the flow system are updated in the factorized set of matrices. Inner Iterations are used to iteratively solve the matrices created in the outer iterations.

After every outer iteration is completed, the solver checks for the maximum change in the solution for each cell. If the maximum change in the solution is below the defined tolerance value (The Head Change Criterion for Convergence), then the solution has converged and the solver stops, otherwise a new outer iteration is started.

While the head change criterion is used to judge the overall convergence, the Residual Criterion is used to judge the convergence of the inner iterations of the solver. If the change in successive inner iterations is less than the tolerance specified (Residual Criterion), then the solver will proceed with the next outer iteration.

The parameter used to make a non–convergent (oscillating or divergent) solution process more stable so that the solution can be achieved, is known as a Damping Factor. This factor is similar to “acceleration parameters” used in other solvers.

Another method of checking for convergence of the inner iteration is to use a parameter known as the Relative Residual Criterion. Once the most recent inner iteration residual is below the initial inner iteration residual times the Relative Residual Criterion, the current outer iteration is completed and a new outer iteration will be started.

There are also two “levels” of Factorization for the application of the WHS solver; 0 and 1. Level 0 requires more outer iterations but less memory. Level 1 requires less outer iteration but more memory.

Different tests were applied to determine the proper parameters to obtain a successful convergence for the Sana’a Basin simulation;

- Max Outer Iterations (MXITER) = 75
- Max Inner Iterations (ITERI) = 25
- Head Change Criterion (HCLSE) = 1
- Residual Criterion (RCLOSE) = 0.1
- Damping factor (DAMP) = 1
- Relative Residual Criterion (RSCRRIT) = 0
- Factorization Level = 0

9.4 Re-wetting Setting

The Visual MODFLOW does not allow cells in unconfined layers to become re-saturated if the head dropped below the bottom elevation of the grid cell during the course of simulation or during the solution iterations. Instead, these cells were simply made inactive until the end of simulation. The Block-Centered Flow package (BCF) allows for the re-wetting of these “dry” cells during the simulation runs. The wetting of a dry cell is triggered by the head values in adjacent grid cells. The wetting threshold is used to determine if the dry cell needs to be wetted. For a dry cell to become wet, the head in the adjacent cells must be greater than the elevation of the bottom of the dry cell plus the Wetting threshold value. The wetting method module to control the cell wetting has two options:

- From below (WETDRY < 0) will use only the head in the grid cell directly below the dry cell.
- Wet cells from the side and below (WETDRY > 0) will use the head in all four adjacent grid cells and the grid cell directly below the dry cell, to determine if the dry cell should be wetted. This option has been assigned for the Sana’a Basin model.

The wetting head was calculated from neighbors:

Head = Zbot + Wetting factor * (Neighboring head – Zbot)

Where;

Zbot : the bottom elevation of the current cell

9.5 Zone Budget

Seven zones were edited; four located at the first simulated layer (Fig. 25), and three zones at the second simulated layer (Fig. 26). These zones were defined to get the complete water balance components for each water flow system zone, and for each aquifer formation. Meanwhile, the water balance for the whole Basin can be displayed. The water balance components cover the details of flow rates (both inflow to and outflow from the zone) at the end of each Stress Period and Time Step.

The report of each zone budget for both input and output forms include the main following flow components: Constant Head, General Head Boundaries, Wells, Drains, Recharge, Evapotranspiration, as well as the flow rates between zones (whether lateral flow or vertical flow). Also, the discrepancy in percentage between the total inflow and the outflow is defined.

9.6 Anisotropy Setting

Horizontal anisotropy is the ratio of transmissivity or hydraulic conductivity along a column to its component value along each row. Visual MODFLOW provides two options for determining the Anisotropy Factor; Anisotropy by layer and Anisotropy as specified. For the Sana’a Basin simulation model, the Anisotropy as specified has been selected, where the Kx and Ky values defined for each property zone. This feature allows spatially variable anisotropy within a layer.

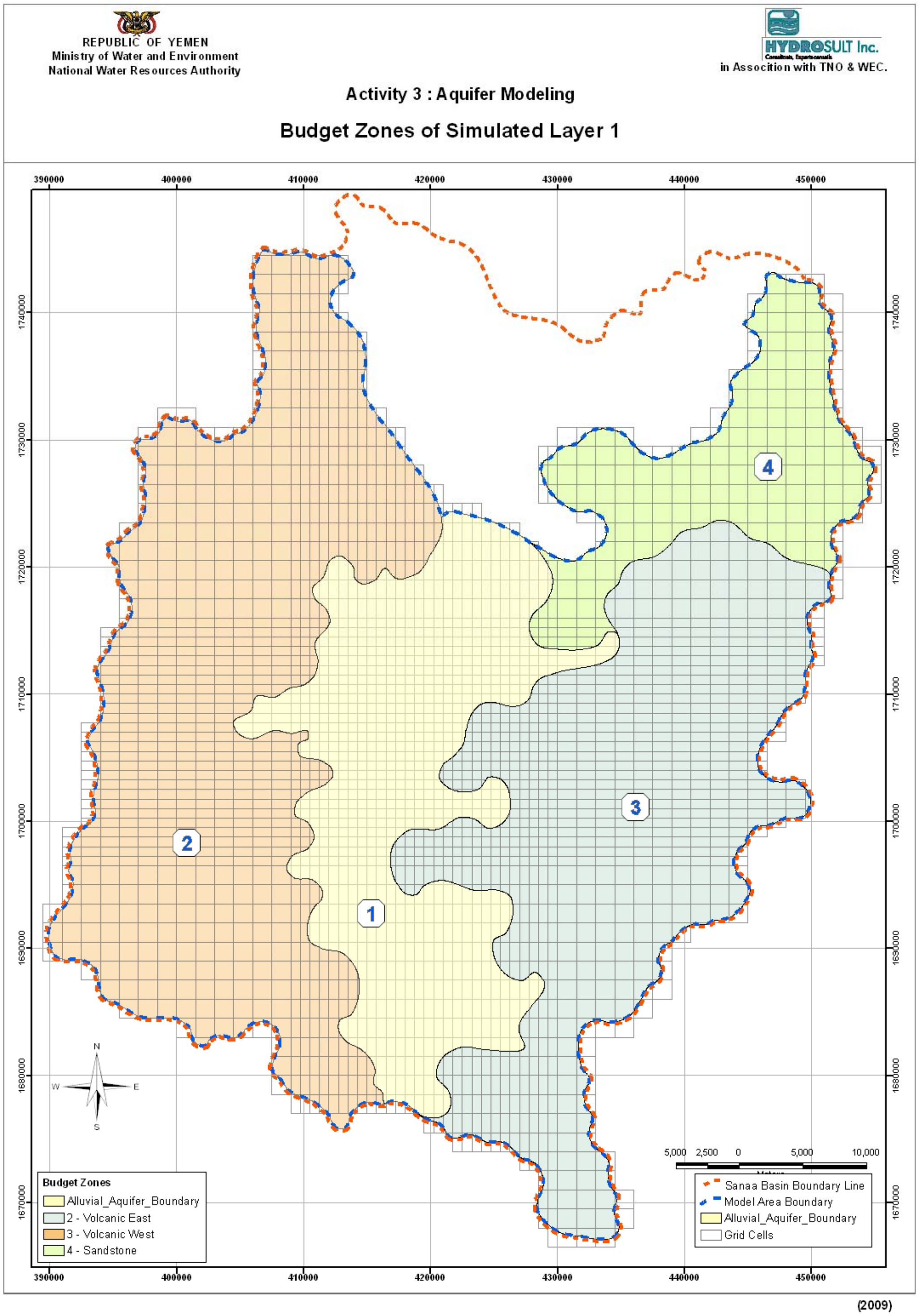


Figure 25: Budget Zones of Simulated Layer 1

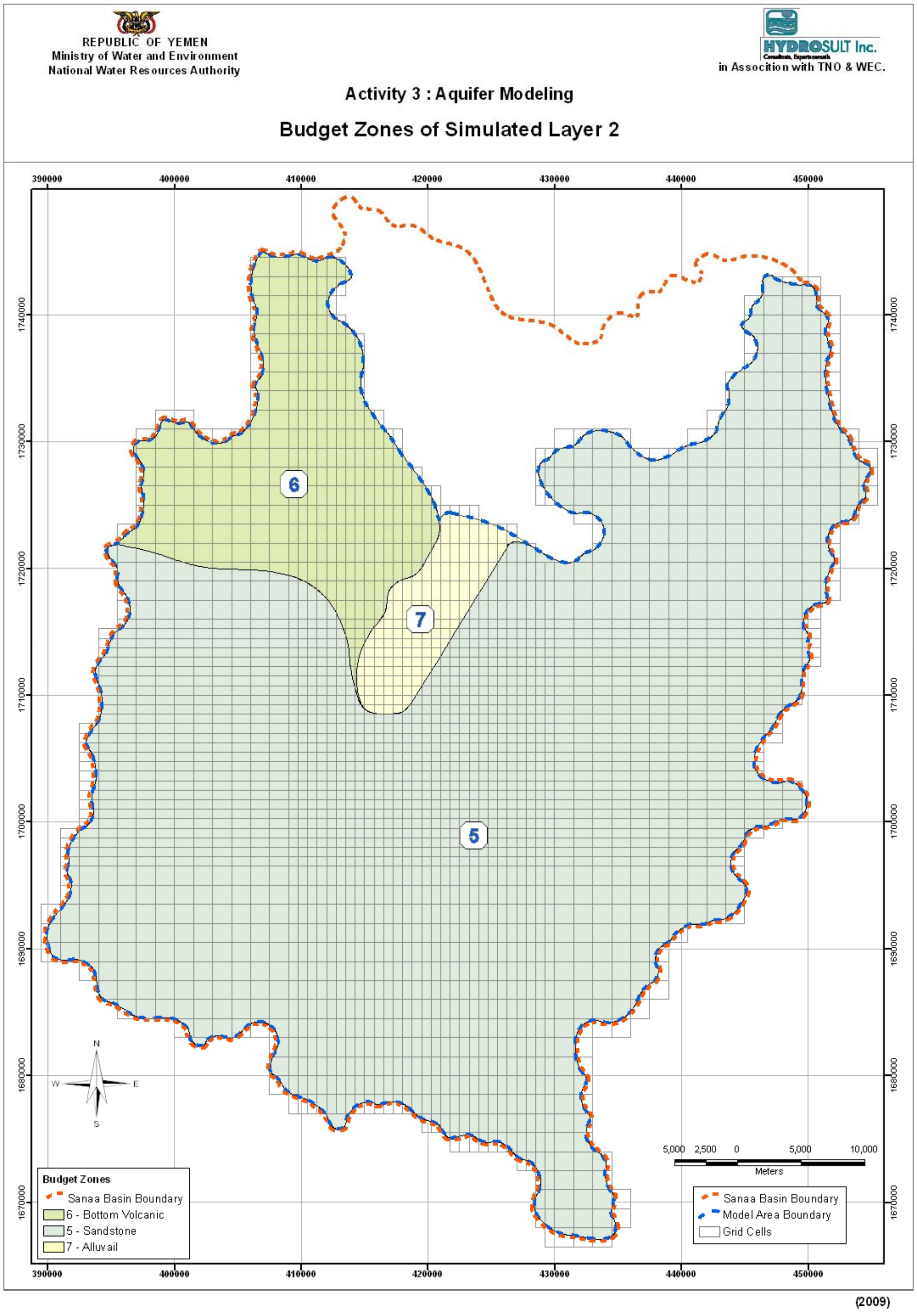


Figure 26: Budget Zones of Simulated Layer 2

10. STEADY STATE CALIBRATION RUN

The steady state run was carried out for year 1972, which is considered as the base year. The computation of the steady state calibration run can be summarized by the following main outputs:

- The initial head values for the transient model.
- The initial values for the time invariable hydraulic conductivity parameters (Kx,Ky,Kz).
- The water balance at the start period (1972).

10.1 Input Pumped Water

Pumped well data was compiled from studies on record which were carried out mainly by ITALCONSULT 1972. The WEC Hydrogeological survey carried out in 2002, generated the basic data, and the basic information required for the MODFLOW input Format. These pumped well data were documented in soft (PDF and SHP files Format) and hard copy in the attached Database Sana'a Basin media.

The intensity of pumped water was determined according to the summation of the rate of the pumped wells located in each grid cell. The intensity gives the depth of pumped water at each active modeling cell (Fig. 26). The intensity was distributed in zones from less than 100 mm/yr/m^2 to more than 1,000 mm/yr/m^2. The map gives the distribution of pumped water in 1972. It shows the pumped water in 1972 was not extensive, except in a few locations. This map is also documented in soft (PDF and SHP files format) and the hardware copy was prepared in the attached media for the modeling studies.

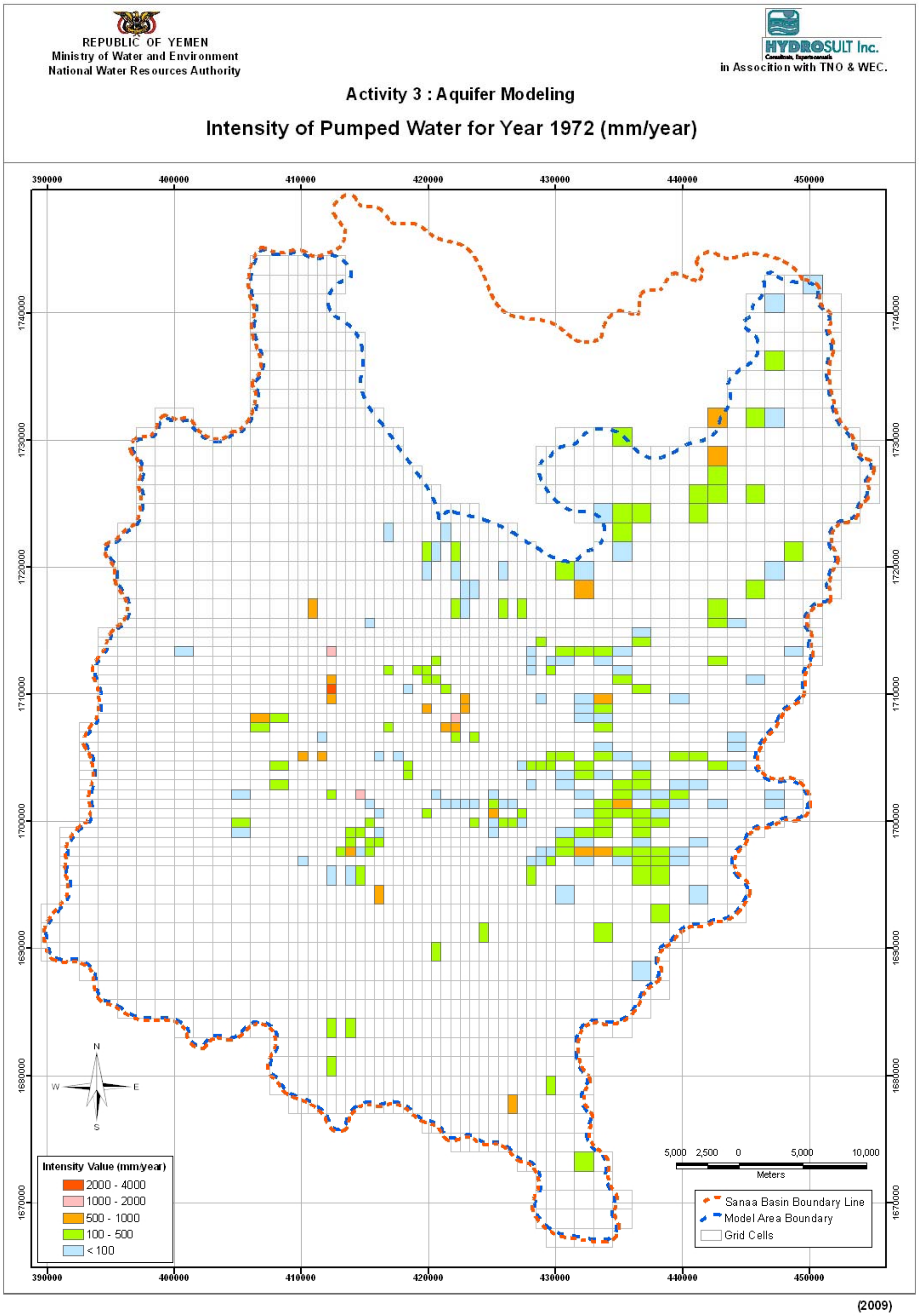


Figure 27: Intensity of Pumped water for Year 1972 (mm/year/m2)

10.2 Running procedure

The following engines were applied: MODFLOW 2000, Zone Budget, and Pest. The MODFLOW engine can be run by itself without any requirement from any other engines, and can apply the above-mentioned selected WHS Solver. The Zone Budget engine requires a valid .BGT file to be present in the project folder. This file will be automatically created. If MODFLOW and Zone Budget are mutually selected, the user–defined zones are created in the input data of the model (Fig. 25, Fig. 26). The Zone Budget program reads the MODFLOW output and calculates the water budget between user-defined in calibration of the model. Visual MODFLOW automatically creates zone budget zones for the various conductivity zones and boundary conditions.

The PEST mode is used in running in Estimation Mode or Prediction Mode. Estimation Mode is used to estimate the selected parameter values required to optimize (minimize) the objective function. The indirect solution to the inverse problem uses a least square statistical framework, gradient search solution, and a Gauss-Newton solution procedure. There is a limit on the amount by which parameter values may change; parameter adjustments could regularly "overshoot" their optimal values, causing prolongation of the estimation process at best, and instability with consequential estimation failure at worst. The concerns are greatest for highly non-linear problems. The automated inverse models are criticized because of problems with non-uniqueness and instability (Mary Anderson, William Woessner, 1999).

The limit of the total number of adjustable parameters in Pest and the lack of information about variation of aquifer parameters over all Sana'a Basin, were motivation for the aquifer parameters to be calibrated by trial and error manually. The different runs were carried out to adjust the water budget components and to minimize the difference between computed and recorded head in the observation points.

10.3 Calibrated Conductivity values for First Simulated layer

The horizontal and vertical conductivity values were calibrated for the different water bearing formations. Figure 27 shows the areal distribution of the horizontal hydraulic conductivity parameter. **Table 9** represents the legend of the conductivity distribution. The results of the calibrated values can be summarized as follows:

- The area of the upper part of the Alluvial aquifer where Volcanic and Sandstone are absent - represented by Zone1 in the Water Flow System map (Fig. 12);

Kx = 5 m/d

Ky = 4 m/d

Kz = 0.05 m/d

- The area of the Alluvial aquifer where Volcanic is absent - represented by Zone5 in the Water Flow System map (Fig. 10);

Kx = 10 m/d

Ky = 10 m/d

Kz = 0.005 m/d

- The Upper Part of the Quaternary Volcanic;

Kx from 0.02 m/d to 1 m/d

Ky from 0.01 m/d to 1 m/d

Kz from 0.0002 m/d to 0.001 m/d

- The east and West Tertiary Volcanic;

Kx from 0.0002 m/d to 0.4 m/d

Ky from 0.0002 m/d to 0.4 m/d

Kz from 5E-5 m/d to 0.002 m/d

- The Complex of Alluvial and Volcanic (represented by Zone 7 in the Water Flow System map (Fig. 10);

Kx from 0.0002 m/d to 5 m/d

Ky from 0.0001 m/d to 5 m/d

Kz from 0.2 m/d to 0.002 m/d

- The fault Zone

Kx = 0.005 m/d

Ky = 0.005 m/d

Kz = 0.0027 m/d

10.4 Calibrated Conductivity values for Second Simulated layer

The horizontal and vertical conductivity values were also calibrated for the different water bearing formations of the second simulated layer. Figure 28 shows the areal distribution of the horizontal hydraulic conductivity parameter. Also, Table 9 represents the legend of the conductivity distribution. The results of the calibrated values can be summarized as follows:

- The area of the lower part of the Alluvial aquifer where Volcanic and Sandstone are absent (represented by Zone 1 in the Water Flow System map (Fig. 28);

Kx = 2.0 m/d

Ky = 2.0 m/d

Kz = 0.02 m/d

- The lower Part of the Quaternary Volcanic;

Kx = 0.2 m/d

Ky = 0.1 m/d

Kz = 0.005 m/d

- The Sandstone has been subdivided to many zones;

Kx	from	0.2	m/d	to	3.97	m/d
Ky	from	0.1	m/d	to	4.77	m/d
Kz	from	0.002	m/d	to	0.0718	m/d

- The West fault Zone from North to South,

Kx	=	0.0045	m/d
Ky	=	0.0045	m/d
Kz	=	2.7E-5	m/d

- The Permeable Boundary from North-East to South-West,

Kx	=	0.2	m/d
Ky	=	0.1	m/d
Kz	=	0.002	m/d

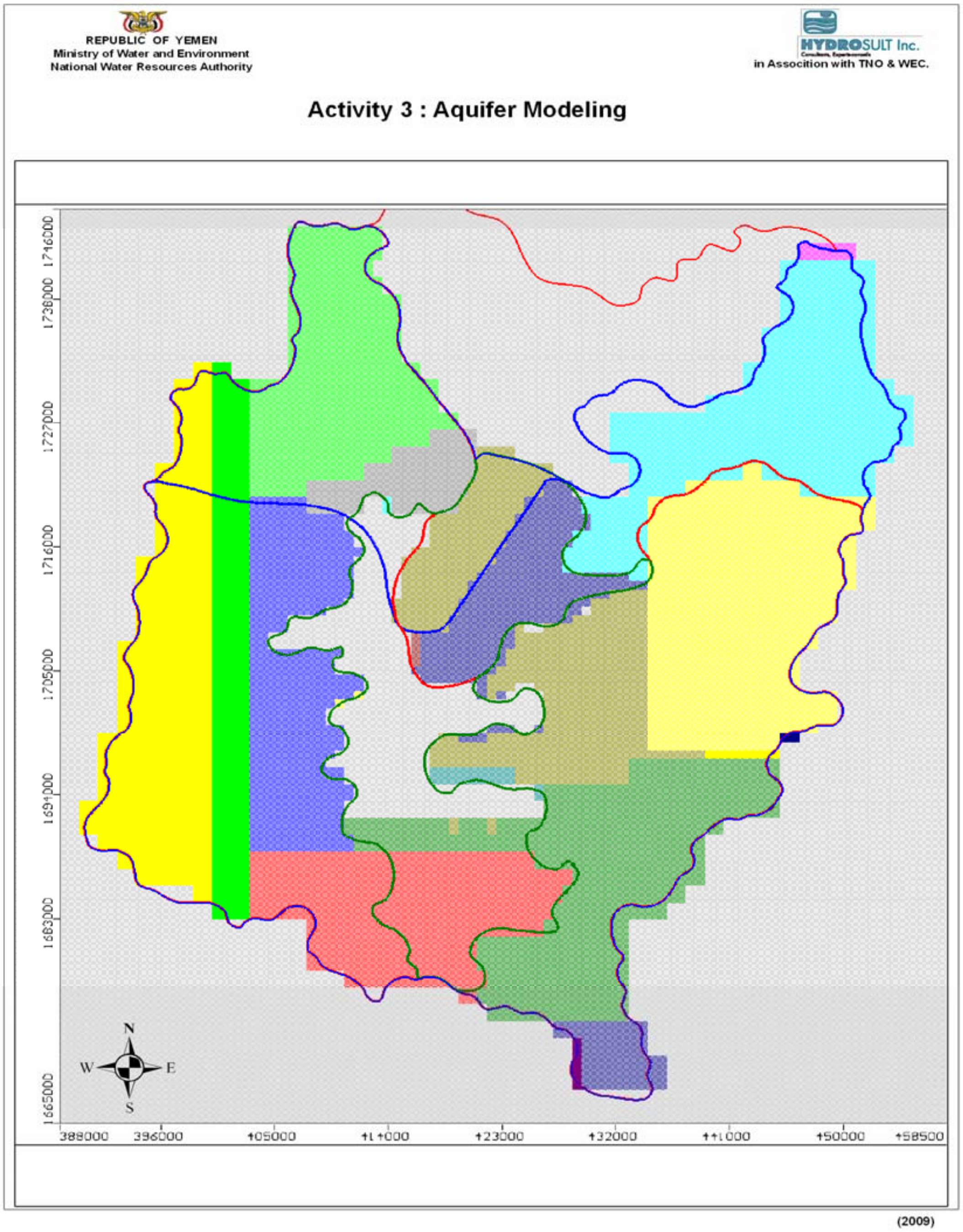


Figure 28: Steady State Calibrated Conductivity Parameters Distribution in First Layer

Legend shown in Table (8)

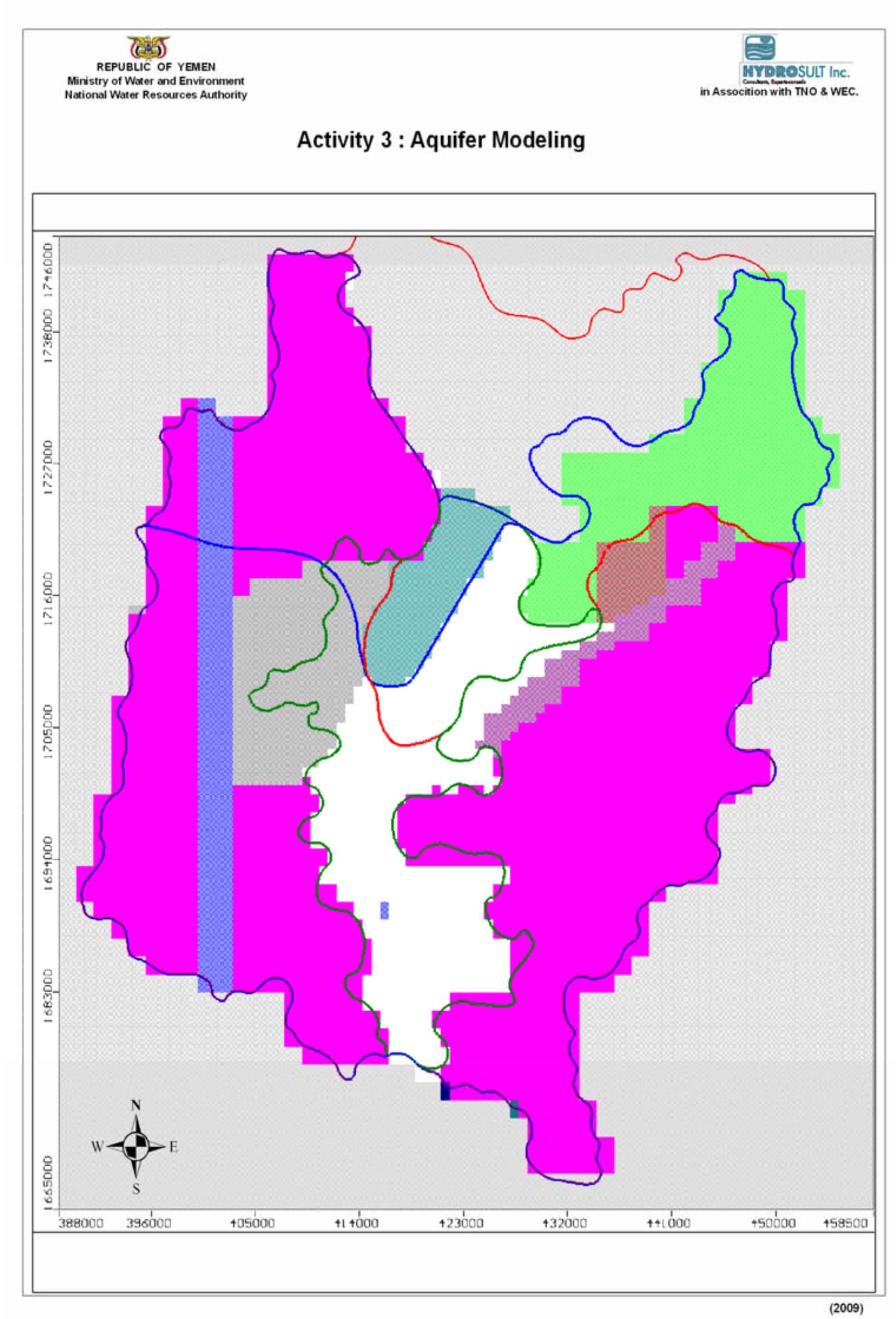


Figure 29: Steady State Calibrated Conductivity Parameters Distribution in Second Layer – *Legend shown in Table (8)*

Table 8 Calibrated Conductivity Values Legend

Conductivity

Zone	Kx [m/d]	Ky [m/d]	Kz [m/d]
1	1	1	1
2	0.02	0.01	2E-7
3	0.021	0.01	2E-7
4	0.021	0.01	1E-7
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	1
10	1	1	1
11	0.005	0.005	0.0027
12	0.02	0.01	0.002
13	0.2	0.1	0.002
14	0.05	0.05	0.005
15	10	5	0.04
16	1	0.05	0.0008
17	0.2	0.1	5E-6
18	0.002	0.001	5E-5
19	0.09	0.06	0.04
20	0.2	0.1	5E-5
21	0.09	0.06	0.04
22	10	10	1
23	10	10	0.005
24	2	2	0.2
25	5	5	0.5
26	0.02	0.01	0.0002
27	1	1	0.001
28	0.0002	0.0001	0.002
29	0.02	0.01	0.0002
30	1	1	0.001
31	0.0002	0.0001	0.002
32	0.001	0.001	0.0005
33	0.07	0.07	0.007
34	0.4	0.4	0.004
35	2	2	0.02
36	3	3	0.03
37	0.2	0.1	0.002
38	5	5	0.01
39	5	5	0.05
40	0.02	0.01	0.0002
41	0.09	0.06	0.004
42	0.001	0.001	0.0004
43	0.001	0.001	0.0004

10.5 Sensitivity Analysis

The purpose of a sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters. Uncertainties are quantified by calculating the magnitude of change in heads from the calibrated model caused by the change of the value of the parameters. The results of the sensitivity analysis indicate the uniqueness of the calibrated model and provide a better understanding of the performance of the model (Anderson and Woessner, 1992).

The sensitivity analyses were carried out by running the model with the conductivity coefficient changed by 20%. The effect on the calculated groundwater in each aquifer is recorded. It was found from the results of the sensitivity analyses, that there are three categories of sensitivities, defined as follows:

- Low sensitivity where the change in levels does not exceed one meter, in the aquifers. This is encountered where the following of wells are located: ITL6, ITL8, ITL9, ITL10, ITL13, and ITL14. Mainly, these wells are located in Quaternary Alluvium and in some parts of the Quaternary Volcanics.
- Medium sensitivity where the change in levels ranges from one to two meters, in the aquifers. This is encountered where the following wells are located: ITL7, ITL12, and ITL18. Mainly, these wells are located in the Tertiary Volcanics.
- Very sensitive where the change in levels exceeds two meters. This is encountered where the following wells are located: ITL2, ITL4, ITL5, ITL16, ITL17, and ITL20. Mainly, these wells are located in he second simulated aquifer, mainly in the Tawilah Sandstone. The same sensitivity was observed for changes of values of anisotropy.

Accordingly, the calibrated values for the hydraulic parameters can be accepted, and can be applied for the modeling simulation procedures.

10.6 Calibrated Flow Balance Graph

The water balance components for each budget zone were computed, and a graph was plotted (Fig. 30). The graph shows the value of the total inflow and total outflow for each defined budget zone. The discrepancy value is negligible with respect to the total inflow and the total outflow.

10.7 Calibrated Values for the Water Balance Components

The Water Balance was computed using cell-by-cell for each Defined Budget Zone. Each table includes the details of the results of the zone budget calculations. The details of flow rates (both inflow to and outflow from the Zone) for each of the following items: Storage, Constant Heads, Wells, drains, Recharge, and General Head Boundaries. Also, the output includes the flow rates between zones. The percent discrepancy between the total IN and OUT is defined in each Zone Budget Output.

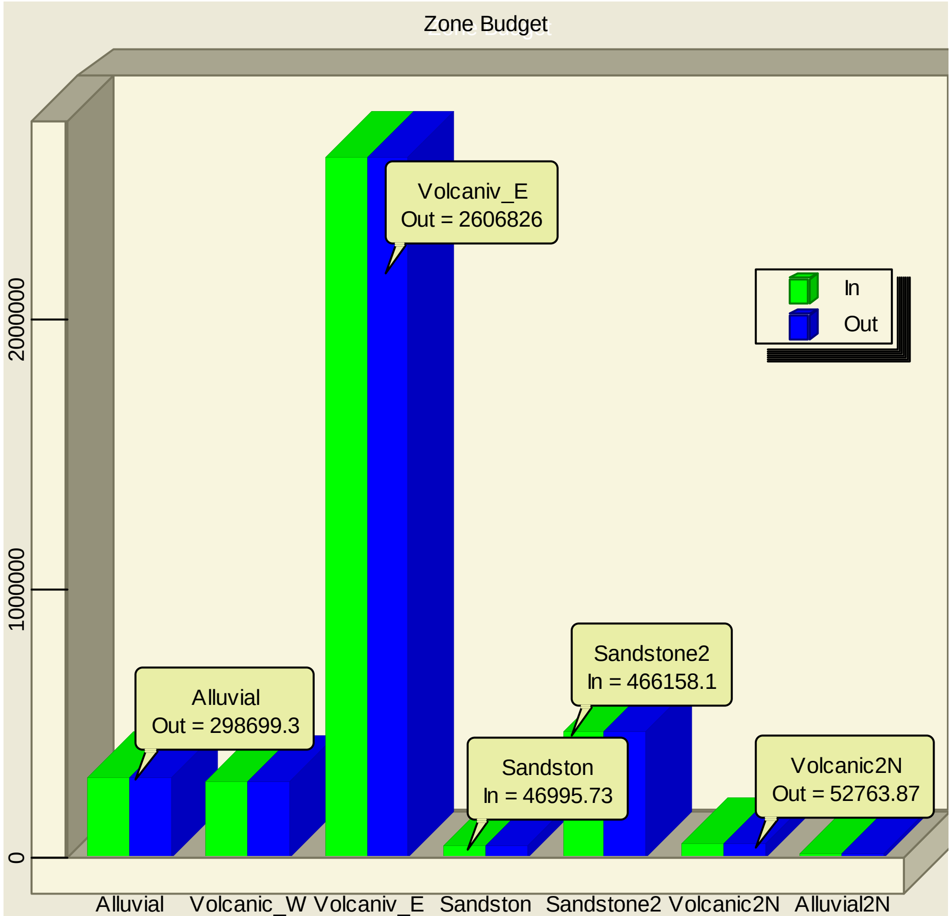


Figure 30: Flow Balance Graph

The following tables show the complete output of the Sana'a Basin Steady State Calibrated Run for each of the defined Budget Zones. Verification was carried out for some values such as the total abstraction from the two simulated layers. Total abstraction was confirmed with the input values of the pumped water from the different aquifers, and equals to 24.8 Mm^3 /yr. Also, the value of the total recharge rate was confirmed with the input value. It was found that the percent discrepancy between the total IN and OUT for the whole basin does not exceed 1.4.

ZONEBUDGET version 2.00
Program to compute a flow budget for sub regions of a model using
Cell-by-cell flow data from the USGS Modular Ground-Water Flow Model
The cell-by-cell budget file is: HYDROSULT_SANAA.BGT
3 layers 67 rows 61 columns
Zone Budget - BATCH
The zone file is: HYDROSULT_SANAA.ZBI

Table 9: Flow Budget for Zone 1 [Alluivial]

Output Time Step 1, Stress Period 1, Time (days): 3650

Budget Term Flow (L**3/T) (m3/day)

Input Report

Storage = 0.00 m^3/day
Constant Head = 1598.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 45647.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 2 to 1 = 67229.00 m^3/day
Zone 3 to 1 = 105620.00 m^3/day
Zone 4 to 1 = 8395.30 m^3/day
Zone 5 to 1 = 69664.00 m^3/day
Zone 6 to 1 = 59.05 m^3/day
Zone 7 to 1 = 696.99 m^3/day

Total IN = 298910.00 m^3/day

Output Report

Storage = 0.00 m^3/day
Constant Head = 0.97 m^3/day
Wells = 10952.00 m^3/day
Drains = 143450.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 14585.00 m^3/day
Zone 1 to 2 = 29898.00 m^3/day
Zone 1 to 3 = 57375.00 m^3/day
Zone 1 to 4 = 11723.00 m^3/day
Zone 1 to 5 = 20359.00 m^3/day
Zone 1 to 6 = 936.24 m^3/day
Zone 1 to 7 = 9417.30 m^3/day

Total OUT = 298700.00 m^3/day

Difference: IN - OUT = 207.5 m^3/day

Percent Discrepancy = 0.07%

Table 10: Flow Budget for Zone 2 at Time Step 1 of Stress Period 1

Zone 2 [Volcanic_W] [Zone2]

Output Time Step 1, Stress Period 1, Time (days): 3650

Input Report

Storage = 0.00 m^3/day
Constant Head = 182910.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 48515.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 320.36 m^3/day
Zone 1 to 2 = 29898.00 m^3/day
Zone 5 to 2 = 18923.00 m^3/day
Zone 6 to 2 = 3792.90 m^3/day
Zone 7 to 2 = 0.00 m^3/day

Total IN = 284360.00 m^3/day

Output Report

Storage = 0.00 m^3/day
Constant Head = 61.54 m^3/day
Wells = 917.49 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 4645.90 m^3/day
Zone 2 to 1 = 67229.00 m^3/day
Zone 2 to 5 = 174340.00 m^3/day
Zone 2 to 6 = 37007.00 m^3/day
Zone 2 to 7 = 104.77 m^3/day

Total OUT = 284300.00 m^3/day

Difference:
IN - OUT = 56.388 m^3/day

Percent Discrepancy = 0.02%

Table 11: Flow Budget for Zone 3 [Volcanic_E]

Output Time Step 1, Stress Period 1, Time (days): 3650

Input Report

Storage = 0.00 m^3/day
Constant Head = 217700.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 51198.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 1 to 3 = 57375.00 m^3/day
Zone 4 to 3 = 745.94 m^3/day
Zone 5 to 3 = 7015.50 m^3/day

Total IN = 334034.44 m^3/day

Output Report

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 21444.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 3 to 1 = 105620.00 m^3/day
Zone 3 to 4 = 833.30 m^3/day
Zone 3 to 5 = 206140.00 m^3/day

Total OUT = 334037.3 m^3/day

Difference:
IN - OUT = -2.86 m^3/day

Percent Discrepancy = 0%

Table 12: Flow Budget for Zone 4 [Sandstone]

Output Time Step 1, Stress Period 1, Time (days): 3650

Input Report

Storage = 0.00 m^3/day
Constant Head = 3845.90 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 14346.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 471.72 m^3/day
Zone 1 to 4 = 11723.00 m^3/day
Zone 3 to 4 = 833.30 m^3/day
Zone 5 to 4 = 14175.00 m^3/day

Total IN = 45396.00 m^3/day

Output Report

Storage = 0.00 m^3/day
Constant Head = 65.20 m^3/day
Wells = 2082.50 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 19674.00 m^3/day
Zone 4 to 1 = 8395.30 m^3/day
Zone 4 to 3 = 745.94 m^3/day
Zone 4 to 5 = 14430.00 m^3/day

Total OUT = 45393.00 m^3/day

Difference:
IN - OUT = 2.3272 m^3/day

Percent Discrepancy = 0%

Table 13: Flow Budget for Zone 5 [Sandstone _2]

Output Time Step 1, Stress Period 1, Time (days): 3650

Input Report

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 ^3/day
General-Head = 44233.00 m^3/day
Zone 1 to 5 = 20359.00 m^3/day
Zone 2 to 5 = 174340.00 m^3/day
Zone 3 to 5 = 206140.00 m^3/day
Zone 4 to 5 = 14430.00 m^3/day
Zone 6 to 5 = 5513.10 m^3/day
Zone 7 to 5 = 1144.20 m^3/day

Total IN = 466160.00 m^3/day

Output Report

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 20667.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 334570.00 m^3/day
Zone 5 to 1 = 69664.00 m^3/day
Zone 5 to 2 = 18923.00 m^3/day
Zone 5 to 3 = 7015.50 m^3/day
Zone 5 to 4 = 14175.00 m^3/day
Zone 5 to 6 = 574.16 m^3/day
Zone 5 to 7 = 592.96 m^3/day

Total OUT = 466180.00 m^3/day

Difference:
IN - OUT = -22.969 m^3/day

Percent Discrepancy = 0%

Table 14: Flow Budget for Zone 6 [Volcanic _2N]

Output Time Step 1, Stress Period 1, Time (days): 3650

Input Report

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 14198.00 m^3/day
Zone 1 to 6 = 936.24 m^3/day
Zone 2 to 6 = 37007.00 m^3/day
Zone 5 to 6 = 574.16 m^3/day
Zone 7 to 6 = 52.03 m^3/day

Total IN = 52767.00 m^3/day

Output Report

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 21.95 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 41589.00 m^3/day
Zone 6 to 1 = 59.05 m^3/day
Zone 6 to 2 = 3792.90 m^3/day
Zone 6 to 5 = 5513.10 m^3/day
Zone 6 to 7 = 1788.30 m^3/day

Total OUT = 52764.00 m^3/day

Difference:
IN - OUT = 3.5631 m^3/day

Percent Discrepancy = 0.01%

Table 15: Flow Budget for Zone 7 [Alluvial _2N]

Output Time Step 1, Stress Period 1, Time (days): 3650

Input Report

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 1 to 7 = 9417.30 m^3/day
Zone 2 to 7 = 104.77 m^3/day
Zone 5 to 7 = 592.96 m^3/day
Zone 6 to 7 = 1788.30 m^3/day

Total IN = 11903.00 m^3/day

Output Report

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 908.22 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 9086.40 m^3/day
Zone 7 to 1 = 696.99 m^3/day
Zone 7 to 2 = 0.00 m^3/day
Zone 7 to 5 = 1144.20 m^3/day
Zone 7 to 6 = 52.03 m^3/day

Total OUT = 11888.00 m^3/day

Difference:
IN - OUT = 15.483 m^3/day

Percent Discrepancy = 0.13%

10.8 Calculated and Observed Scatter Graph

The observation wells were edited as model input according to the MODFLOW format. The Calibration Package saves the calculated head at the locations of the specified observation wells for every time step. For the Steady State run, the values of the head were edited for the recorded observation head in 1972 (Italconsult, 1972). Fig 30 shows the distribution of the observation wells.

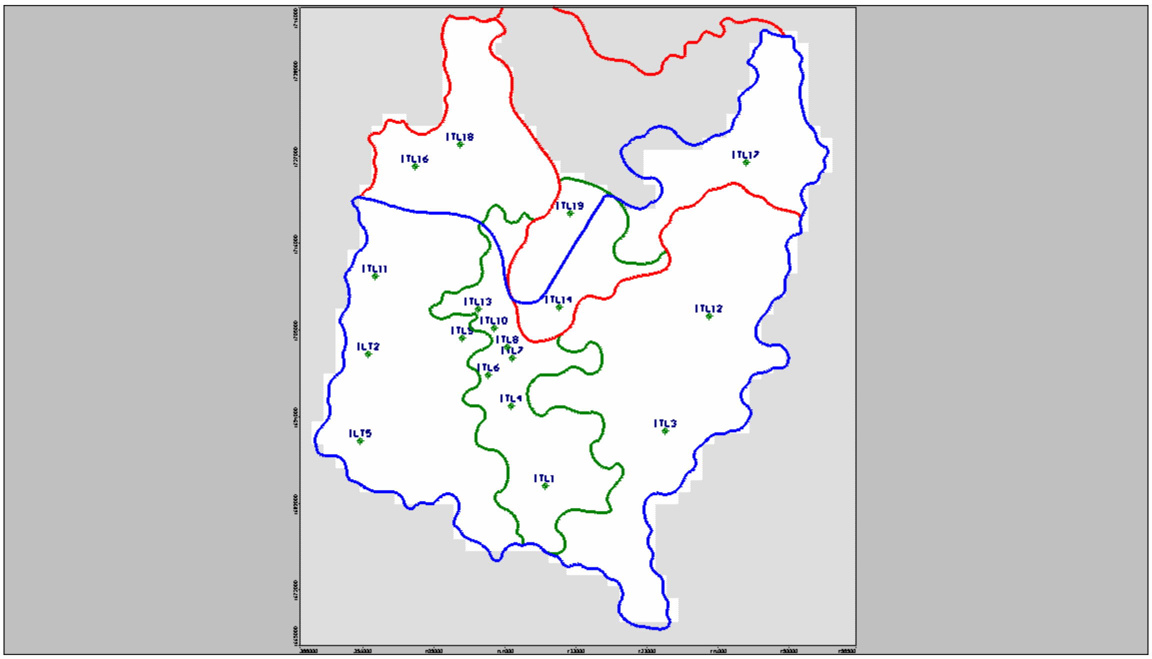


Figure 31: Observation Wells Distribution for Steady State Calibration Run (1972)

In Sana'a Basin, the total head difference is about 1,000 m (from 1,800 to 2,800 m asl.), if a value of 5% of the ratio of error to the total head difference is acceptable, then errors up to 50 m are acceptable (Fopen 2004). Therefore, the output of the Calibrated Steady State Run can be completely accepted.

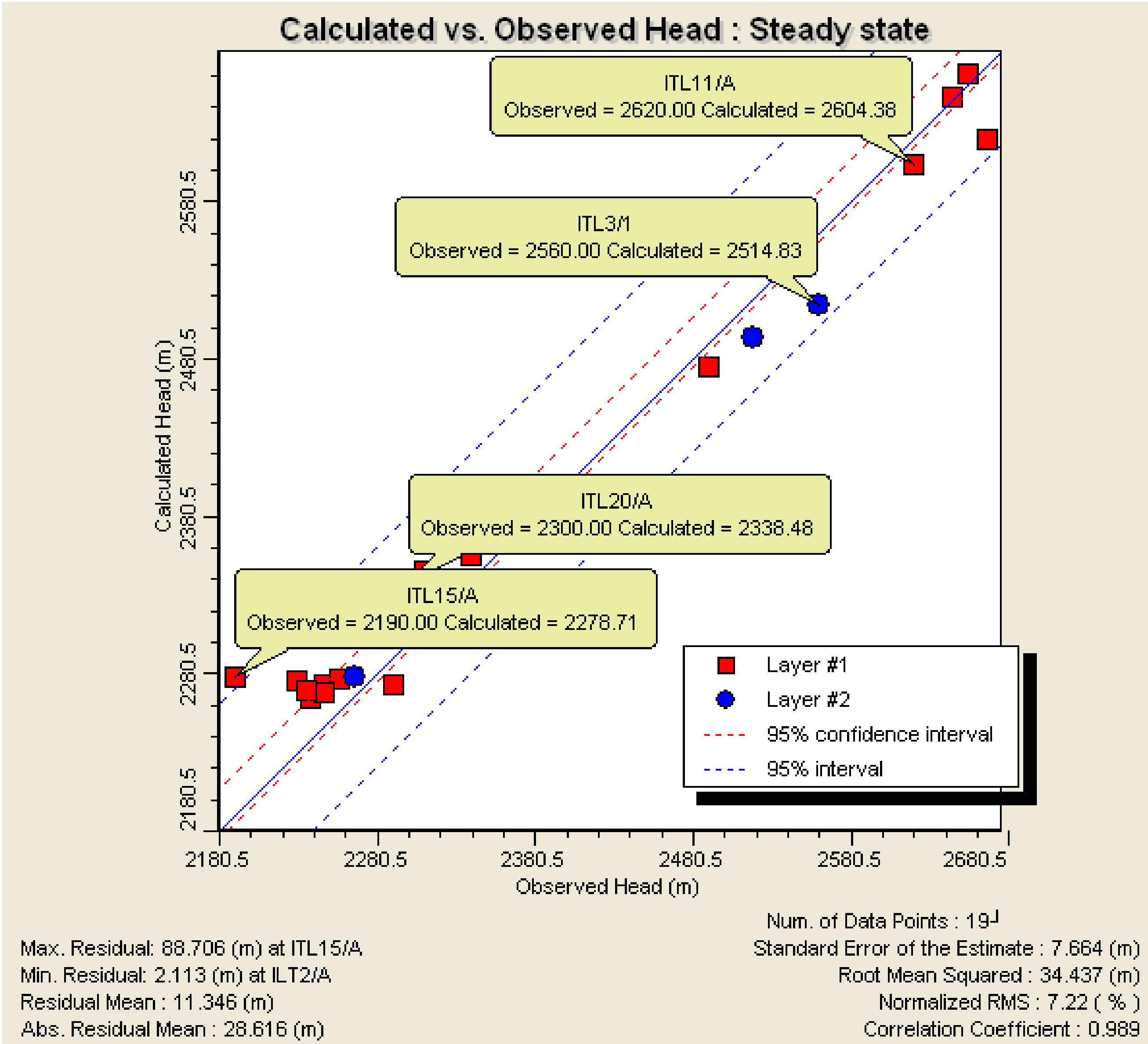


Figure 32: Scatter Graph of Calculated versus Observed Head (Steady State Calibration Output)

The interpolated data compares the value calculated at the observation point against the value observed at the observation point. The value calculated at the observation point is obtained by interpolating calculated values from surrounding cells to the observation point location. The calculated data compares the value calculated at the cell center against the value observed at the observation point.

The Scatter Graph of Calculated versus Observed values represents a snap-shot in time of the comparison between the values calculated by the model (Y-axis), and the values observed or measured in the field (X-axis). Figure 32 shows the goodness of fit of observed heads in the aquifer and the calculated heads, where most of the data points intersects the 45 degrees line on the graph where X=Y.

It was found that,

- Max. Residual = 88.706 (m) at Well ITL15/ 1
- Min. Residual = 2.113 (m) at Well ITL2 /1
- Residual Mean = 11.346 (m)
- Absolute Residual Mean = 28.616 (m)
- Number of Data Points = 19
- Standard Error of the Estimate = 7.664 (m)
- Root Mean Squared = 34.437 (m)
- Normalized RMS = 7.22 (m)
- Correlation Coefficient = 0.989 %

10.9 Calibration Residuals Histogram

The calibration Residuals Histogram displays the Population, and Relative Frequency of Observations, for specified intervals of the Normalized Calibration Residuals values. Figure 33 shows the Calibration residuals Histogram. The number of groups of observation points is edited for 20 channels.

This Histogram provides a qualitative comparison of the distribution of the normalized calibration residual values against the student distribution curve. The mean value of the residual values was calculated as 37.84641. The curve shows the different value of frequency against the normalized residuals (residual = Calculated value –Observed value) for each channel. For example, for the channel -3.552714E-15 < Residuals < 12.33877 the frequency equals 3. The goodness of the Calibrated values can be accepted, particularly since the available observation point data for 1972 was very poor.

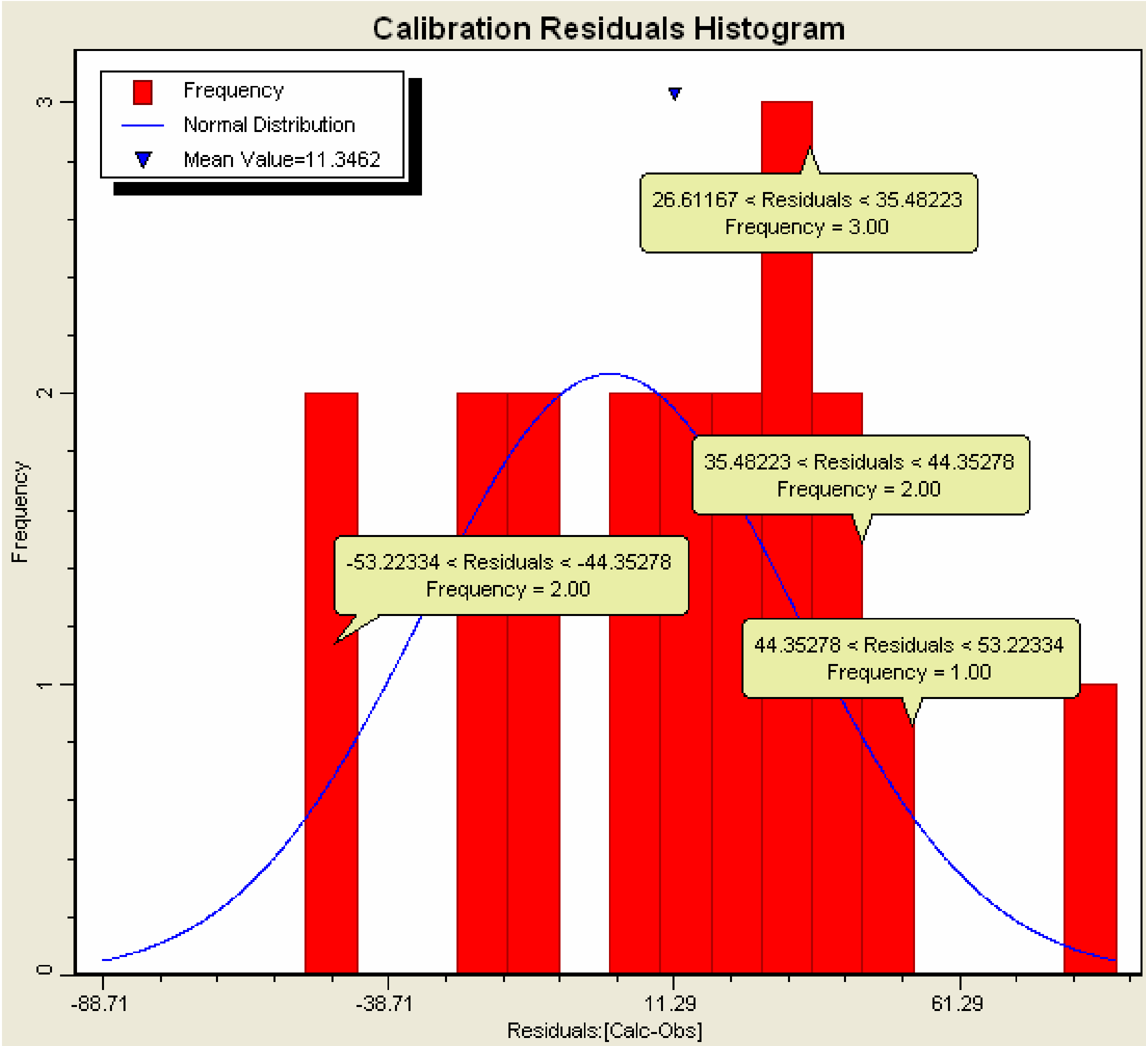


Figure 33: Calibration Residuals Histogram

10.10 Calculated Head Contour Map

The value of the computed head due to the Calibration accepted run for the steady-state conditions, was carried out for each cell. The Contour Groundwater Elevation map was plotted. Figure 33 shows the water table map for the first simulated layer. The groundwater flows from West and East to the Centre of the Basin.

This map will be considered as the initial head for the transient state Calibrations.

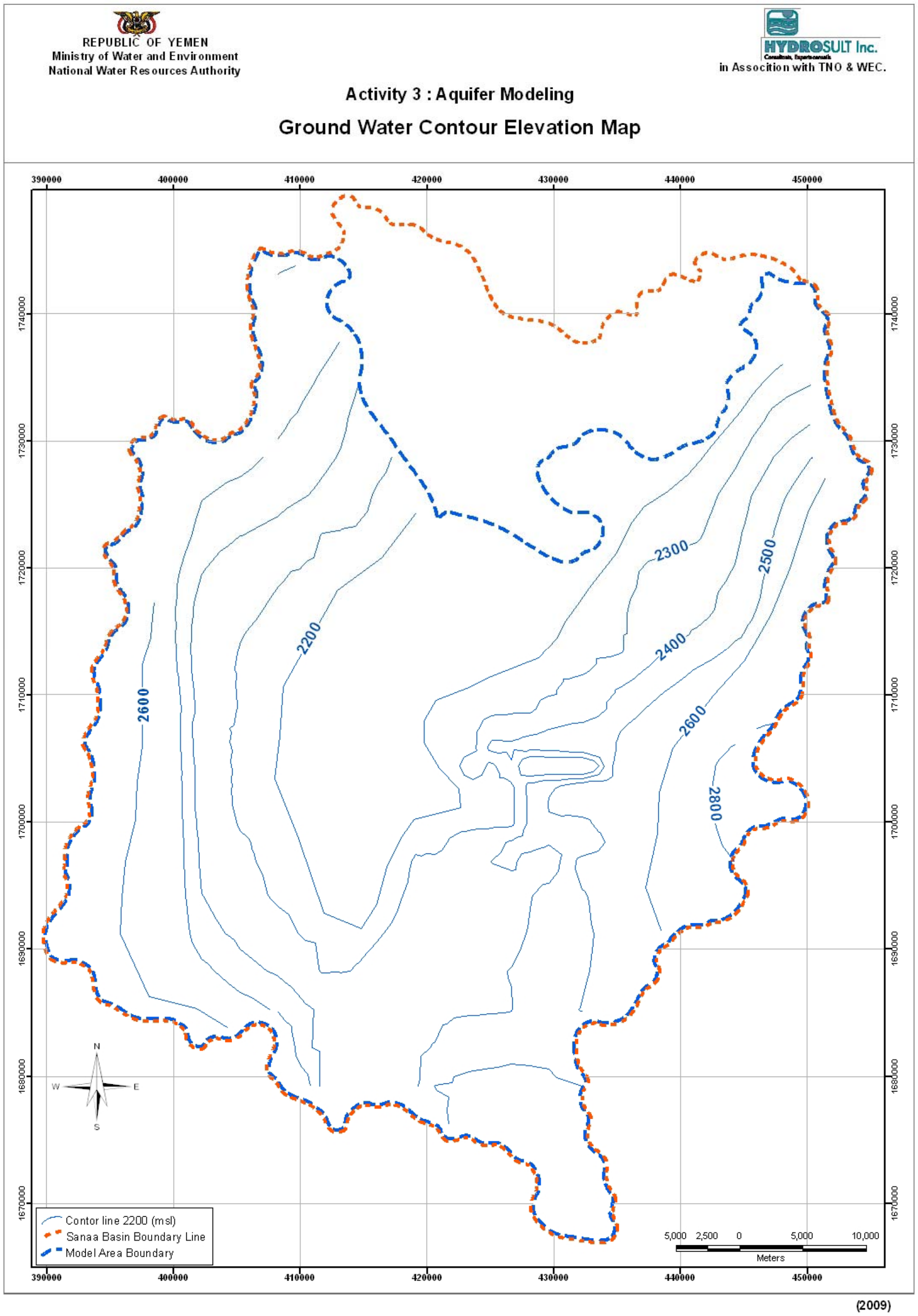


Figure 34: Groundwater Contour Elevation Map

11. Transient (Unsteady-State) Calibration Run

11.1 Simulation of Abstracted Groundwater

Table 16 shows the great increase in groundwater abstraction in 1981, as recorded by the WEC survey, from about 36 Mm^3/yr to more than two hundred million cubic meters per year, a mere two decades later. Of course the number of pumped wells increased from approximately 835 in 1980 to about 6,000 wells in 2000. It means that the abstracted groundwater increased fivefold in twenty years.

Table 16: Total Abstraction for different Periods

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
2003-2008	----	5965	10950	13140	16,2	227.2

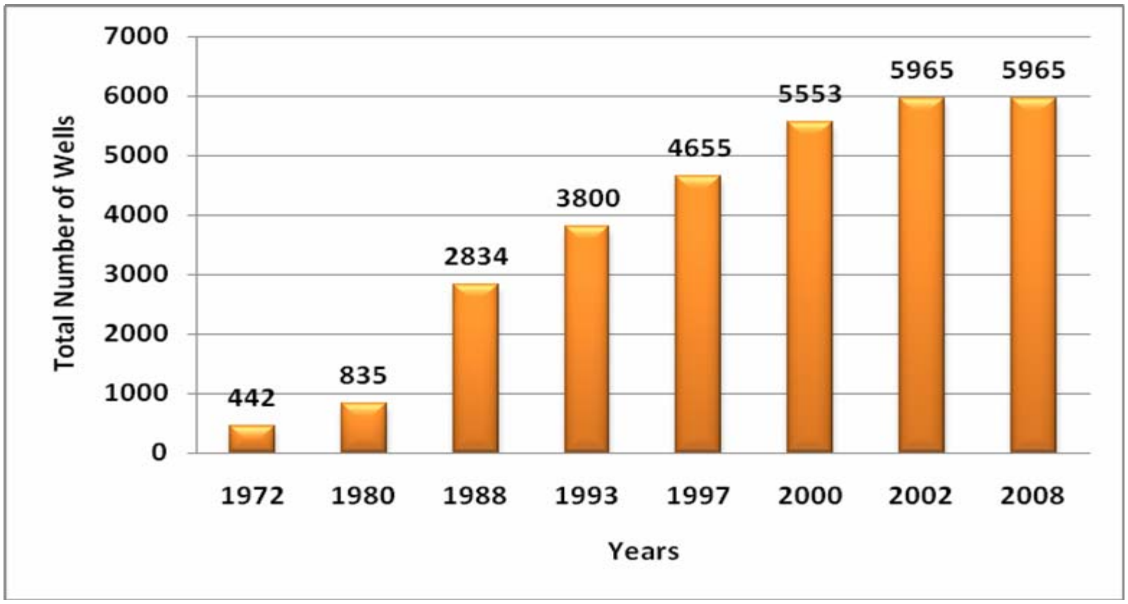


Figure 35: The Pumped Wells in the last century

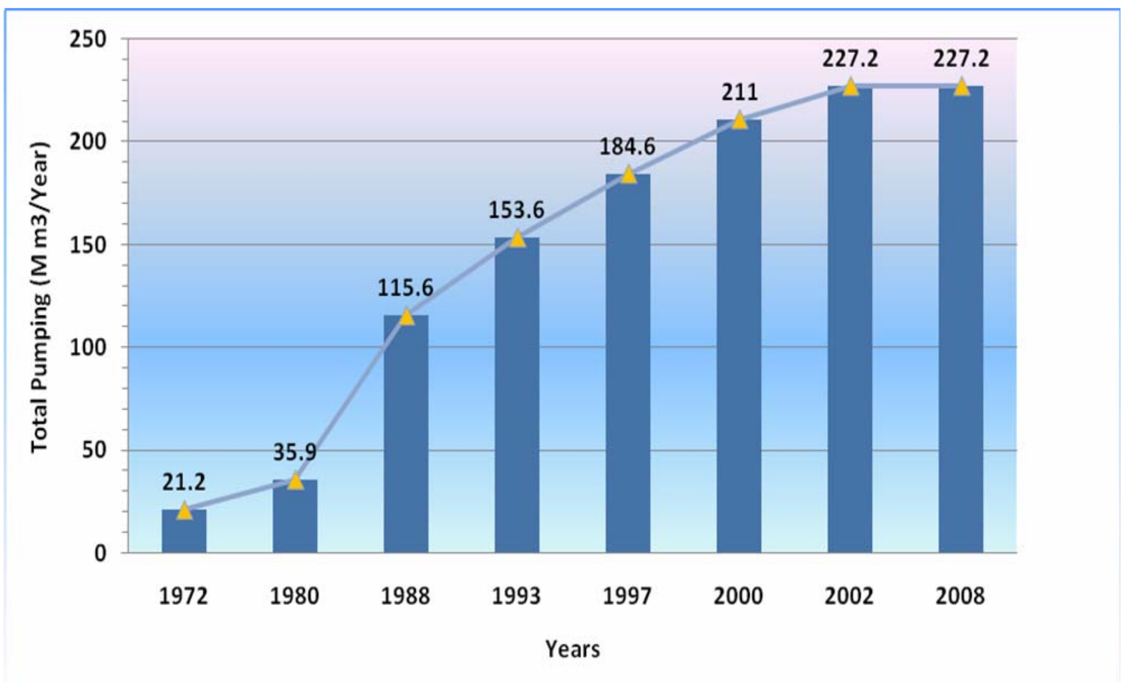


Figure 36: The Groundwater Abstraction in the last century

Complete information about the pumped wells were prepared in Visual MODFLOW form, including the coordinates, screen ID, the absolute level of top and bottom of the screen, starting time, stop time, and the 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 intensity maps of pumped water per square meter were constructed and documented in special media attached to the Modeling Studies documents.

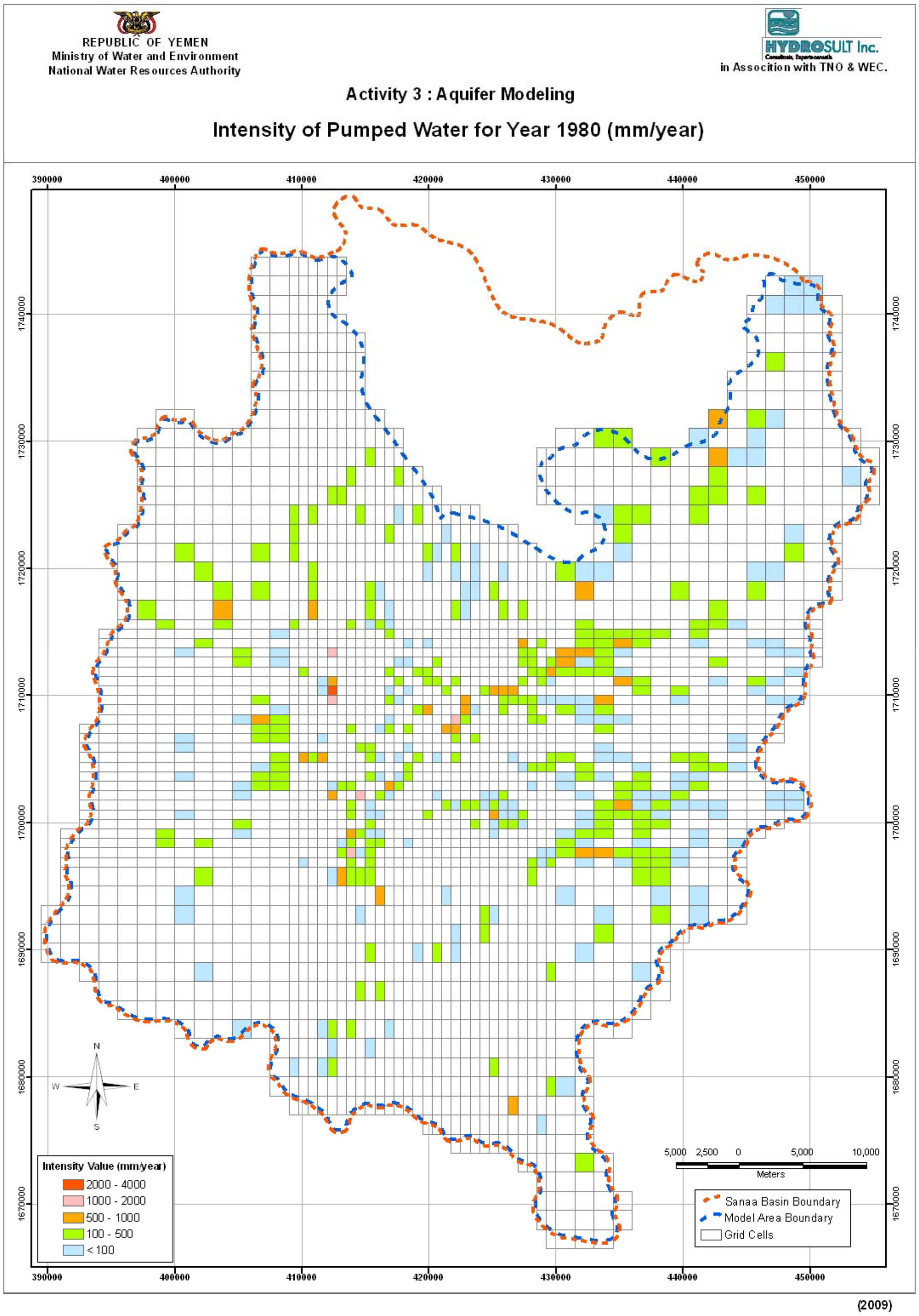


Figure 37: Intensity of Pumped water for Year 1980 (mm/yr/m^2)

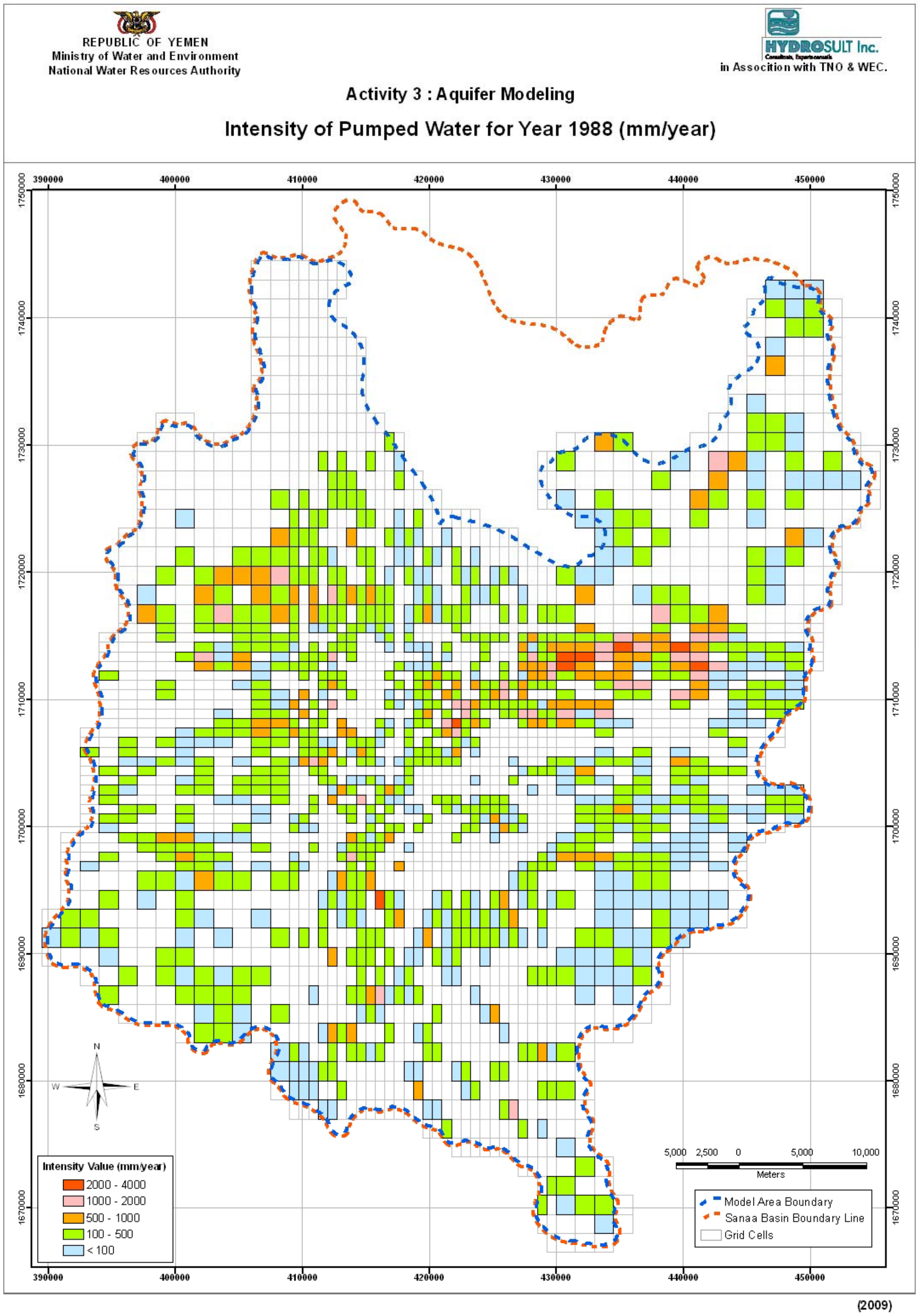


Figure 38: Intensity of Pumped water for Year 1988 (mm/ yr/m^2)

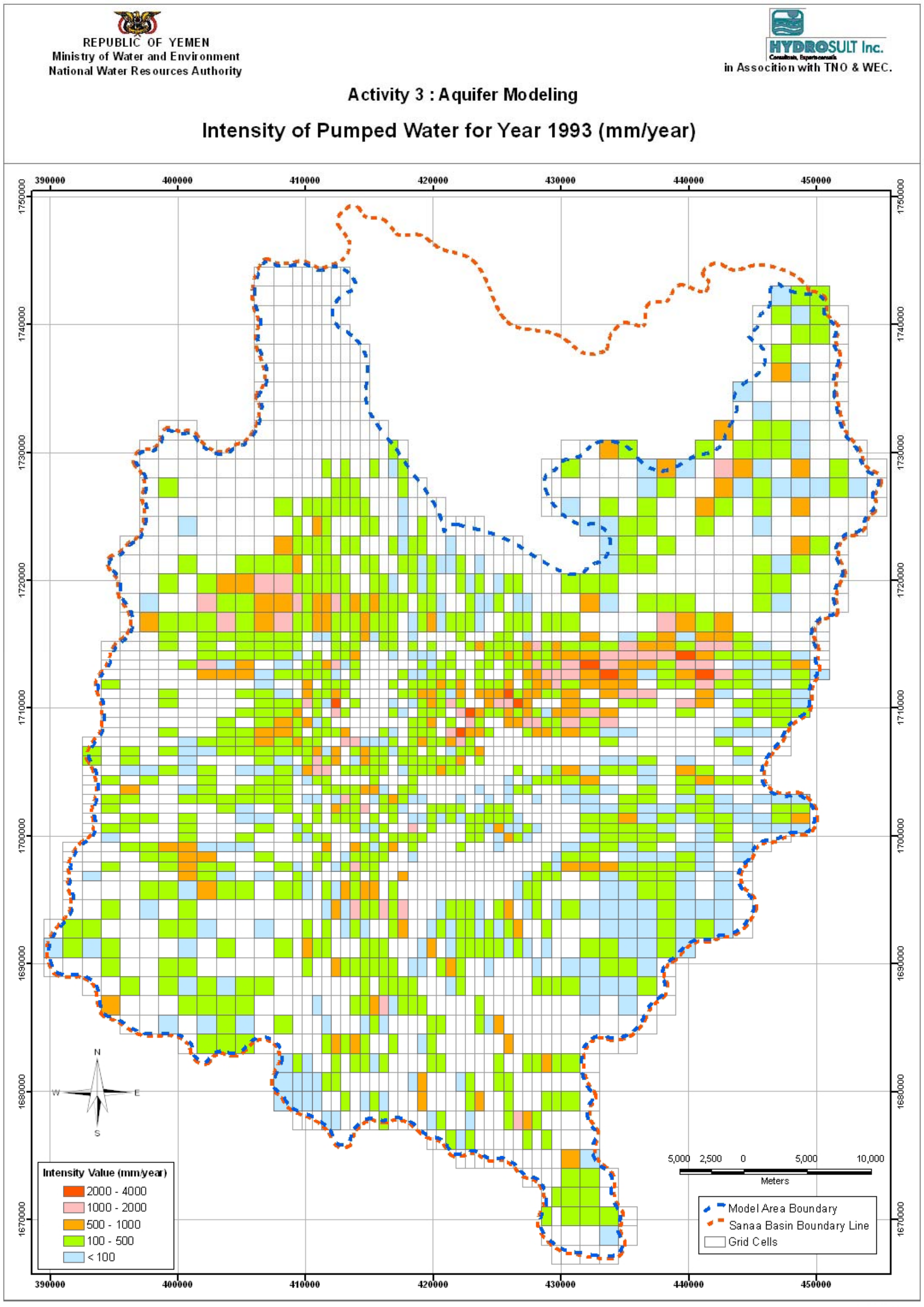


Figure 39: Intensity of Pumped water for Year 1993 (mm/ yr/m^2)

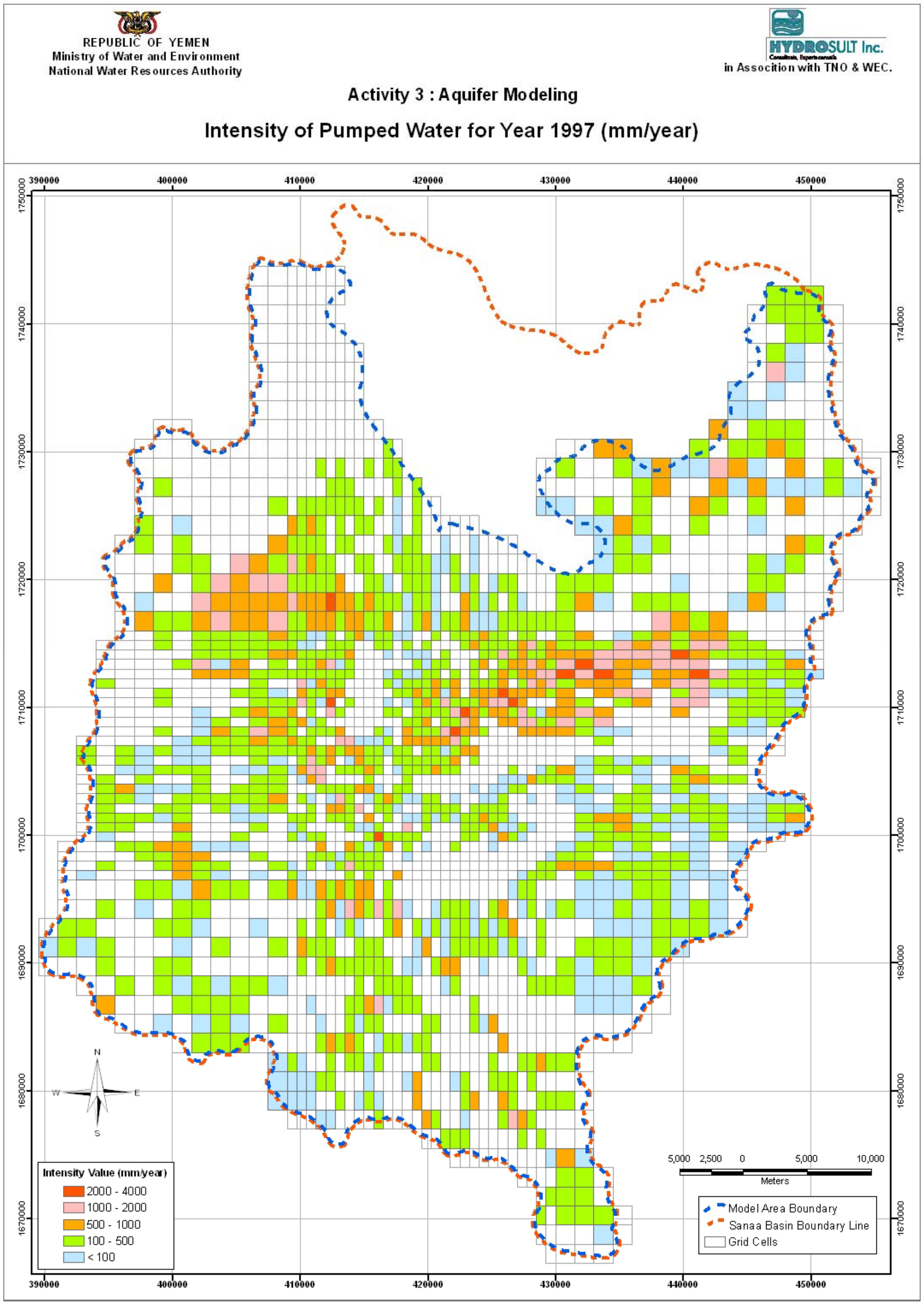


Figure 40: Intensity of Pumped water for Year 1997 (mm/ yr/m^2)

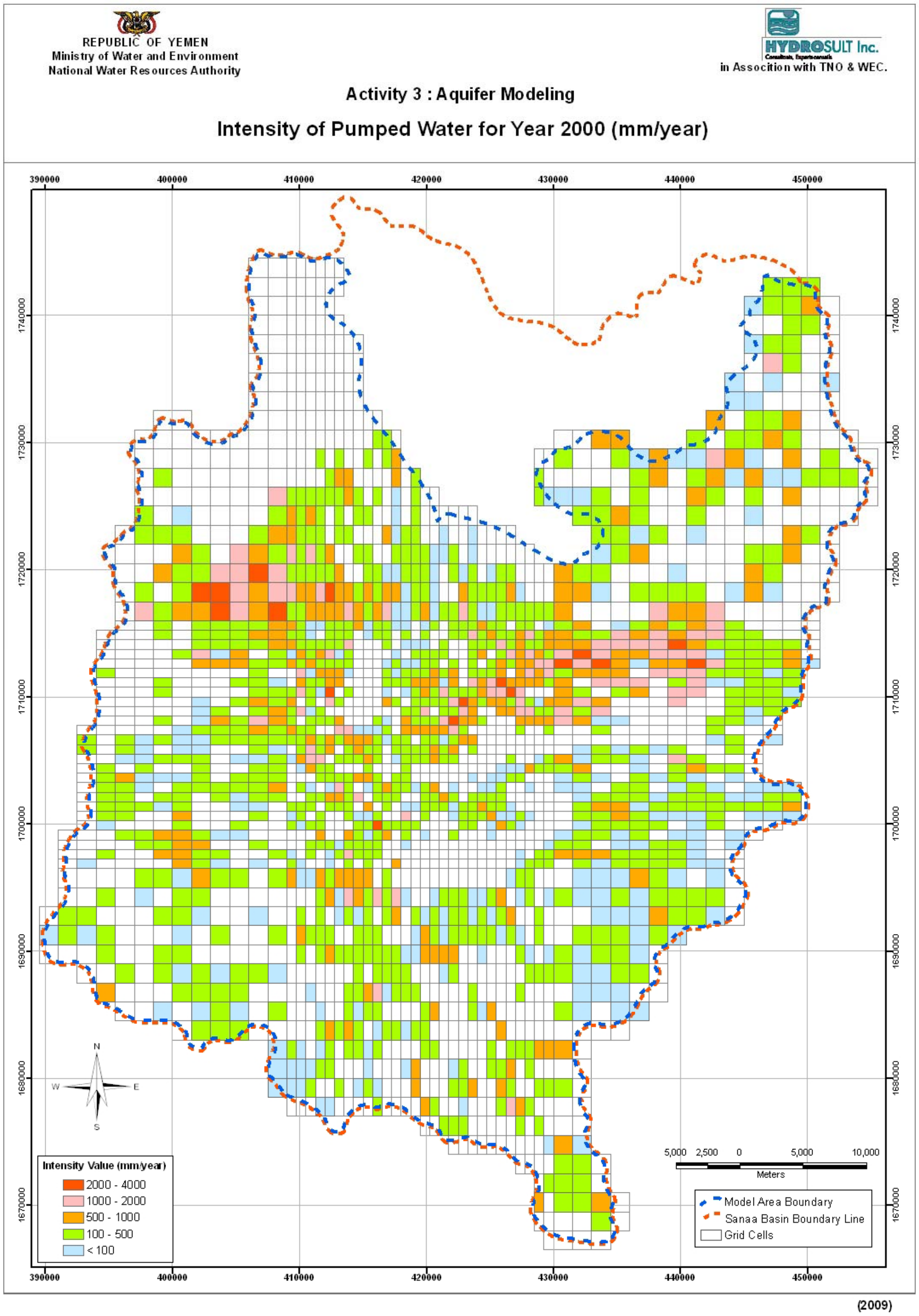


Figure 41: Intensity of Pumped water for Year 2000 (mm/ yr/m^2)

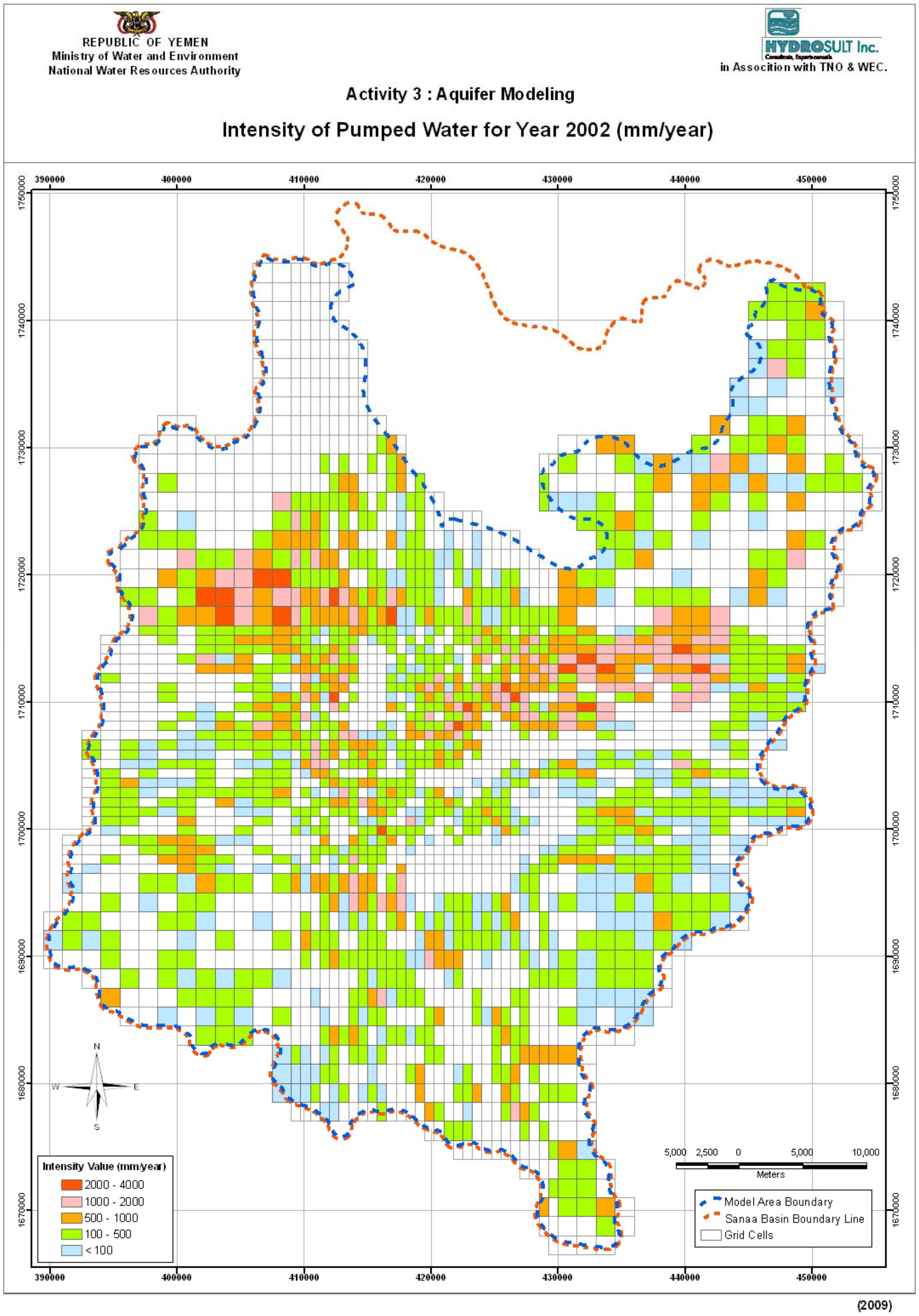


Figure 42: Intensity of Pumped water for Year 2002 (mm/ yr/m^2)

11.2 Measured Water Levels for Transient Calibration

The data from observation wells were compiled from the different studies carried out since 1972. As mentioned, 1972 is considered as the base year for the steady state calibration. The data were collected from the following survey documents;

- Russian survey in 1983 for Alluvial and Volcanic formations.
- SAWAS Survey in 1994 for volcanic group.
- WEC survey in 2002 for Alluvial, Volcanic, and Sandstone Formations.
- NWRA surveys in 2004, and 2006.
- HYDROSULT in 2007, and 2008.

These data were compiled in the Visual MODFLOW format; including the X and Y co-ordinates, screen ID (number of aquifers penetrated by the well screen.), Screen Elevation, Observed Date and the corresponding Observed Head Value. All these data were documented in the Database attached to the Sana'a Basin Modeling studies documents, in software (EXCEL sheets), and in hard copy.

Different procedures were applied for filtering and verification of the available data;

- The transfer of all available well data on a unified geographic coordination system (X, Y, and Z). The digital elevation model (DEM) was applied as it represents GIS delineation process, starts with a grid representation of topography. The (DEM) map was adapted from the Shuttle Radar Topographic mission (STRM). STRM consisted of a specially modified radar system that flew onboard the Space Shuttle during an 11-day mission in February of 2000. Accordingly, the available data relating the geographic coordination was unified.
- Referring to the complete hydrogeological survey carried by WEC in 2002, the observed wells by the different studies were projected to determine the well depth. Accordingly the penetrated aquifer has been defined, and the screen elevation for each observation well is estimated.
- GIS modules were provided for data automation, mapping, viewing spatially varying information layers, and spatially analysis of information layers. The water table maps were constructed according to the measured water level in the observation wells. The observed Heads were connected hydraulically with the values of the defined head at the hydrological boundaries (Constant Head Boundary, and General Head Boundary). Head Contour Map has been constructed for each time stress as a GIS layer. The different layers representing the defined stress periods are overlapped, and verified. The extraordinary values and discrepancies in water head values were deleted. The projected observed head values, representing the different water formations, were selected. These values were used in the Unsteady State Calibration runs for reaching the actual piezometric values under the different variable stresses of groundwater abstraction.

Tables 17 shows the filleted observation wells including the water levels measured by Russian in 1983 and the corresponding nearby wells (in the same cell location) measured by WEC in 2001. Also Table 19 shows the observation wells measures by SAWAS in 1993 and the corresponding nearby observation wells measured by WEC in 2001. These observed values were applied for the transient calibration run.

Table 17: Observations Wells (Russian - 1983) & Nearby Observation Wells (WEC -2001)

Well_N	X_Coord	Y_Coord	Screen_ID	Screen_Elev	Observ_Time	Head
Rus36	415521	1718281	1	1904	4015	2144
Rus95	419627	1718154	1	2055	4015	2125
Rus43	423315	1718420	1	1974	4015	2124
Rus72	420363	1716381	1	1988	4015	2138
Rus74	420736	1719393	1	2085	4015	2130
Rus67	420334	1712167	1	2111	4015	2159
Rus73	420087	1716119	1	1975	4015	2125
Rus69	420719	1712142	1	2065	4015	2155
Rus62	420161	1712727	1	2104	4015	2156
WECF-1389	415489	1718329	1	1930	10585	2066
WECF-1382	419266	1718300	1	2093	10585	2095
WECA-1948	422982	1718356	1	2020	10585	2097
WECA-2046	420409	1716299	1	2022	10585	2118
WECA-1931	420462	1719442	1	2115	10585	2114
WECC-2317	420215	1712364	1	2141	10585	2147
WECA-2045	420124	1716260	1	2023	10585	2116
WECC-2316	420378	1712436	1	2100	10585	2147
WECC-2336	420218	1712822	1	2133	10585	2153

Table 18: Observations nearby Wells (SAWAS - 1993) & Observation Wells (WEC -2001)

Well No	X_Coord	Y_Coord	Screen_ID	Screen_Elev	Observ_Time	Head
S50	441400	1712730	1	2042	7665	2326
S49	442560	1714890	1	1941	7665	2350
S53	445140	1711160	1	2055	7665	2376
S49	442560	1714890	1	2111	7665	2350
S53	445140	1711160	1	1985	7665	2376
S45	436620	1714270	1	2064	7665	2230
S42	432960	1715830	1	2165	7665	2233
S51	445160	1712640	1	2054	7665	2365
S29	426600	1713790	1	1975	7665	2125
S53	445140	1711160	1	2005	7665	2376
WBS-0786	441795	1712770	1	2042	10585	2190
WBS-0983	442409	1715208	1	1947	10585	2241
WBS-0701	445537	1711279	1	2040	10585	2269
WBS-0985	442322	1714648	1	2110	10585	2259
WBS-0915	442674	1714603	1	2089	10585	2260
WBS-0665	444885	1710861	1	1980	10585	2287
WE-0871	436227	1714096	1	2033	10585	2190
WE-0781	433111	1715540	1	2168	10585	2208
WBS-0484	445027	1712589	1	2023	10585	2348
WC-1761	426507	1714200	1	1971	10585	2110
WBS-0666	444924	1710818	1	2400	10585	2370

11.3 Adaptive Time Stepping

The Visual MODFLOW provides great robustness and efficiency in Transient flow simulations, and provides improved and control of simulation output. The initial time step size, a minimum and maximum time step size, a time step multiplier, and a time step reduction factor for each stress period were defined. With these parameters, automatic generation of time steps take place and the time steps are dynamically determined during the iterations by cutting the time step size when the convergence becomes difficult, and increasing it when the difficulty passes.

Table 19: Adaptive Time-Stepping Table

YEAR	Period	Start Time (d)	Stop Time (d)	Time Steps	Multiplier	Total Pumping Mm^3/yr
1972	1	0	1314	10	1.2	21.2
1980	2	1314	2920	10	1.2	35.9
1988	3	2920	5840	10	1.2	115.6
1993	4	5840	7665	10	1.2	153.6
1997	5	7665	9125	10	1.2	184.6
2000	6	9125	10220	10	1.2	211.0
2002	7	10220	10950	10	1.2	227.2
2008	8	10950	13140	10	1.2	227.2

Visual MODFLOW automatically merges all of the different time period data defined for each pumping well and boundary conditions into the uniform stress period format required by the MODFLOW. This creates a time-dependent flow solution, as the model is being run with different inputs at different times. As mentioned for Steady State Calibration Run the numeric engine MODFLOW-2000 is also selected for the transient run.

11.4 Output of the Transient Calibration Run

The transient run was carried out for 8 periods starting from the base year 1972 to the year 2008. Each period covered 10 time steps (as the time multiplier is taken to a value of 1.20.

The results of year 1972 were shown in details for the Steady State Calibration Run. The Water Balance Components for the Budget Zones outputs were selected to give an idea about the rate of variation of the hydrgeological conditions of the Basin in the last 36 years. It is emphasized on the Period 8 representing the present status (year 2008) of groundwater abstraction of about 227 million cubic meters per year from the whole Basin extension.

The primary storage coefficient is calculated by Visual MODFLOW to be equal to the specific storage multiplied by the layer thickness (Specific Storage x thickness = Storage Coefficient). The storage parameter is using by Visual MODFLOW the constant property values. The main property areas are as follows:

- Property area (1) covering the Volcanic aquifer at the North –West of the Basin, representing Zone 2 in the Flow Water System Map (Figure 10). The specific storage equals 3.7E-7 1/m.
- Property area (2) covering the Sandstone aquifer at the North –East of the Basin, representing Zone (3) in the Flow Water System Map (Figure 10). The specific storage equals 9E-6 1/m.
- Property area (3) covering the main aquifer complex at the Center of the Basin, representing Zones 6 & 7 in the Flow Water System Map (Figure 10). The specific storage equals to 9E-7 1/m.
- The mean value of the specific yield for unconfined aquifer (specific value) varies between 1.00E-2 1/m, and 5E-4 1/m.

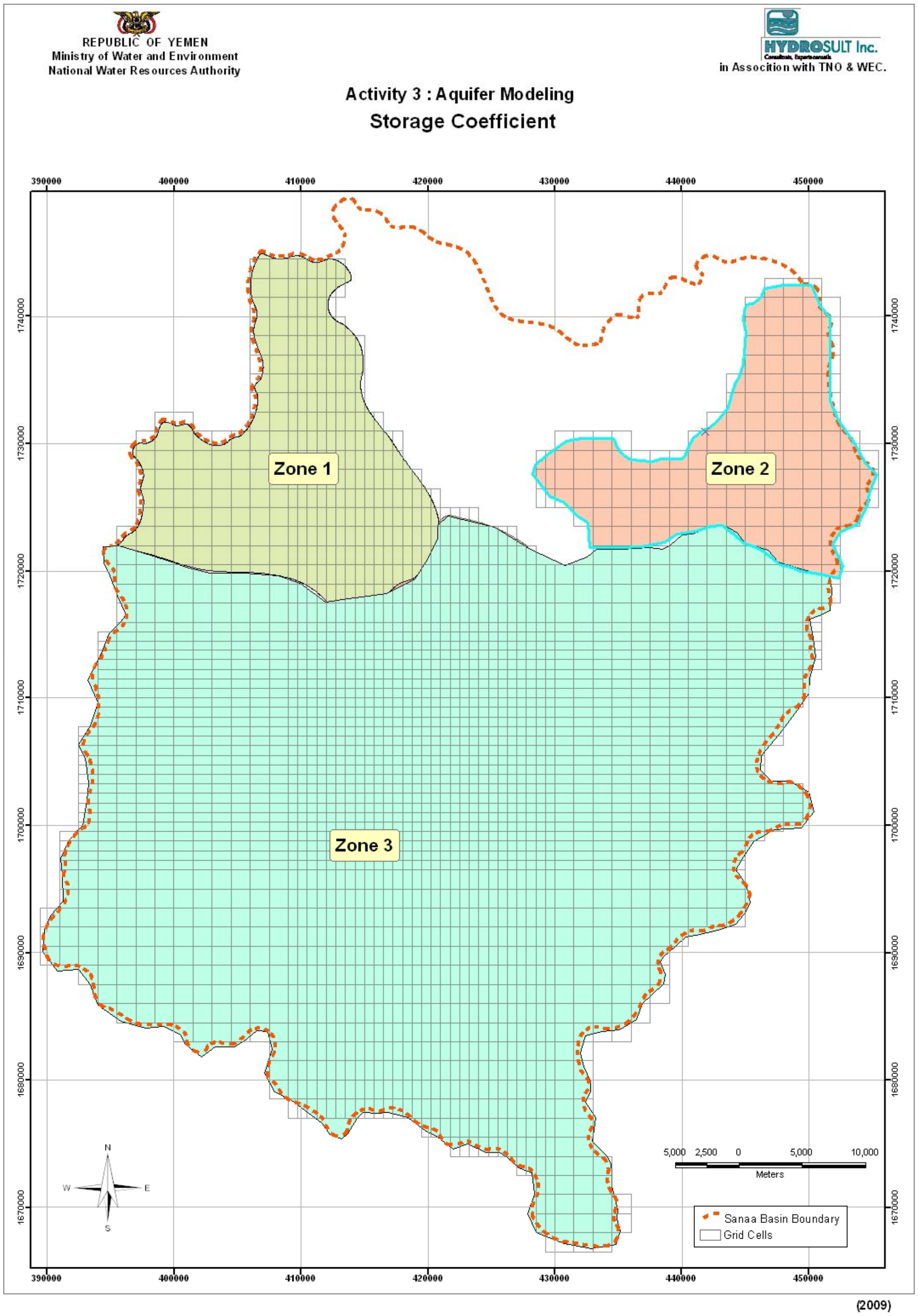


Figure 43: Computed Storage Coefficient for Transient Calibration Ru

11.5 Assessment of the Present Status

11.5.1 Budget Zone Calibration Water Balance Components

(Output of the Transient Calibration Run for Year 2008)/

ZONEBUDGET version 2.00
Program to compute a flow budget for sub regions of a model using
Cell-by-cell flow data from the USGS Modular Ground-Water Flow Model
The cell-by-cell budget file is: HYDROSULT_SANAA.BGT
3 layers 67 rows 61 columns
Zone Budget - BATCH
The zone file is: HYDROSULT_SANAA.ZBI

Table 20: Flow Budget for Zone 1 [Alluvial]

Output Time Step 10 of Stress Period 8 Time (days): 13140

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 1780.40 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 39935.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 1935.50 m^3/day
Zone 2 to 1 = 56185.00 m^3/day
Zone 3 to 1 = 94358.00 m^3/day
Zone 4 to 1 = 4187.90 m^3/day
Zone 5 to 1 = 68333.00 m^3/day
Zone 6 to 1 = 2004.50 m^3/day
Zone 7 to 1 = 849.02 m^3/day

Total IN = 269570.00 m^3/day

Output Report

Constant Head = 0.00 m^3/day
Wells = 58610.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 196.10 m^3/day
Zone 1 to 2 = 51633.00 m^3/day
Zone 1 to 3 = 61859.00 m^3/day
Zone 1 to 4 = 2564.30 m^3/day
Zone 1 to 5 = 84900.00 m^3/day
Zone 1 to 6 = 1845.60 m^3/day
Zone 1 to 7 = 7677.40 m^3/day

Total OUT = 269290.00 m^3/day

Difference:
IN - OUT = 282.45 m^3/day

Percent Discrepancy = 0.1%

Table 21: Flow Budget for Zone 2 [Volcanic_W]

Output Time Step 10 of Stress Period 8 Time (days): 13140

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 190960.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 40558.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 321.35 m^3/day
Zone 1 to 2 = 51633.00 m^3/day
Zone 5 to 2 = 19973.00 m^3/day
Zone 6 to 2 = 2194.90 m^3/day
Zone 7 to 2 = 0.00 m^3/day

Total IN = 305640.00 m^3/day

Output Report

Constant Head = 60.97 m^3/day
Wells = 33752.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 3458.90 m^3/day
Zone 2 to 1 = 56185.00 m^3/day
Zone 2 to 5 = 172680.00 m^3/day
Zone 2 to 6 = 39201.00 m^3/day
Zone 2 to 7 = 306.47 m^3/day

Total OUT = 305640.00 m^3/day

Difference:
IN - OUT = -0.45719 m^3/day

Percent Discrepancy = 0%

Table 22: Flow Budget for Zone 3 [Volcanic_E]

Output Time Step 10 of Stress Period 8 Time (days): 13140

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 2518600.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 44703.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 1 to 3 = 61859.00 m^3/day
Zone 4 to 3 = 824.17 m^3/day
Zone 5 to 3 = 3303.60 m^3/day

Total IN = 2629300.00 m^3/day

Output Report

Constant Head = 2254900.00 m^3/day
Wells = 55611.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 3 to 1 = 94358.00 m^3/day
Zone 3 to 4 = 302.21 m^3/day
Zone 3 to 5 = 224160.00 m^3/day

Total OUT = 2629300.00 m^3/day

Difference:
IN - OUT = 7.7008 m^3/day

Percent Discrepancy = 0%

Table 23: Flow Budget for Zone 4 [Sandstone]

Output Time Step 10 of Stress Period 8 Time (days): 13140

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 6291.30 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 11603.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 7078.00 m^3/day
Zone 1 to 4 = 2564.30 m^3/day
Zone 3 to 4 = 302.21 m^3/day
Zone 5 to 4 = 5126.30 m^3/day

Total IN = 32965.00 m^3/day

Output Report

Constant Head = 1367.90 m^3/day
Wells = 4775.30 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 3628.40 m^3/day
Zone 4 to 1 = 4187.90 m^3/day
Zone 4 to 3 = 824.17 m^3/day
Zone 4 to 5 = 18178.00 m^3/day

Total OUT = 32962.00 m^3/day

Difference:
IN - OUT = 3.2175 m^3/day

Percent Discrepancy = 0.01%

Table 24: Flow Budget for Zone 5 [Sandstone]

Output Time Step 10 of Stress Period 8 Time (days): 13140

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 62711.00 m^3/day
Zone 1 to 5 = 84900.00 m^3/day
Zone 2 to 5 = 172680.00 m^3/day
Zone 3 to 5 = 224160.00 m^3/day
Zone 4 to 5 = 18178.00 m^3/day
Zone 6 to 5 = 9295.50 m^3/day
Zone 7 to 5 = 3041.10 m^3/day

Total IN = 574960.00 m^3/day

Output Report

Constant Head = 0.00 m^3/day
Wells = 194280.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 280580.00 m^3/day
Zone 5 to 1 = 68333.00 m^3/day
Zone 5 to 2 = 19973.00 m^3/day
Zone 5 to 3 = 3303.60 m^3/day
Zone 5 to 4 = 5126.30 m^3/day
Zone 5 to 6 = 196.40 m^3/day
Zone 5 to 7 = 2995.00 m^3/day

Total OUT = 574780.00 m^3/day

Difference:
IN - OUT = 177.3 m^3/day

Percent Discrepancy = 0.03%

Table 25: Flow Budget for Zone 6 [Volcanic-2N]

Output Time Step 10 of Stress Period 8 Time (days): 13140

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 14786.00 m^3/day
Zone 1 to 6 = 1845.60 m^3/day
Zone 2 to 6 = 39201.00 m^3/day
Zone 5 to 6 = 196.40 m^3/day
Zone 7 to 6 = 3941.00 m^3/day

Total IN = 59970.00 m^3/day

Output Report

Constant Head = 0.00 m^3/day
Wells = 5616.50 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 39836.00 m^3/day
Zone 6 to 1 = 2004.50 m^3/day
Zone 6 to 2 = 2194.90 m^3/day
Zone 6 to 5 = 9295.50 m^3/day
Zone 6 to 7 = 1011.80 m^3/day

Total OUT = 59959.00 m^3/day

Difference:
IN - OUT = 11.303 m^3/day

Percent Discrepancy = 0.02%

Table 26: Flow Budget for Zone 7 [Sandstone]

Output Time Step 10 of Stress Period 8 Time (days): 13140

Budget Term Flow (L**3/T) (m3/day)

Input Report

_Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 414.37 m^3/day
Zone 1 to 7 = 7677.40 m^3/day
Zone 2 to 7 = 306.47 m^3/day
Zone 5 to 7 = 2995.00 m^3/day
Zone 6 to 7 = 1011.80 m^3/day

Total IN = 12405.00 m^3/day

Output Report

Constant Head = 0.00 m^3/day
Wells = 4357.40 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 181.82 m^3/day
Zone 7 to 1 = 849.02 m^3/day
Zone 7 to 2 = 0.00 m^3/day
Zone 7 to 5 = 3041.10 m^3/day
Zone 7 to 6 = 3941.00 m^3/day

Total OUT = 12370.00 m^3/day

Difference:
IN - OUT = 34.623 m^3/day

Percent Discrepancy = 0.28%------

12. EVALUATION OF THE PRESENT STATUS

12.1 The Prevailing Hydrological Conditions

The computed groundwater contour was constructed according to the Visual MODFLOW run for the year 2008 (Fig. 43). It confirmed the drop in water levels during the last decades. The contour map was also constructed for the depth to groundwater from the ground surface. It indicates that the water level has dropped extensively in some locations (Fig. 44).

The result of over-exploitation for decades is shown in the contour drawdown of groundwater. The map reflects the locations affected by long term over-pumping (Fig. 45). It shows two main zones, one to the East and the other to the West. The area of the East zone is approximately 205 square kilometers, and the West zone is approximately 205 square kilometers. There are also some small locations where the effect of the heavy and continuous pumping is obviously noted.

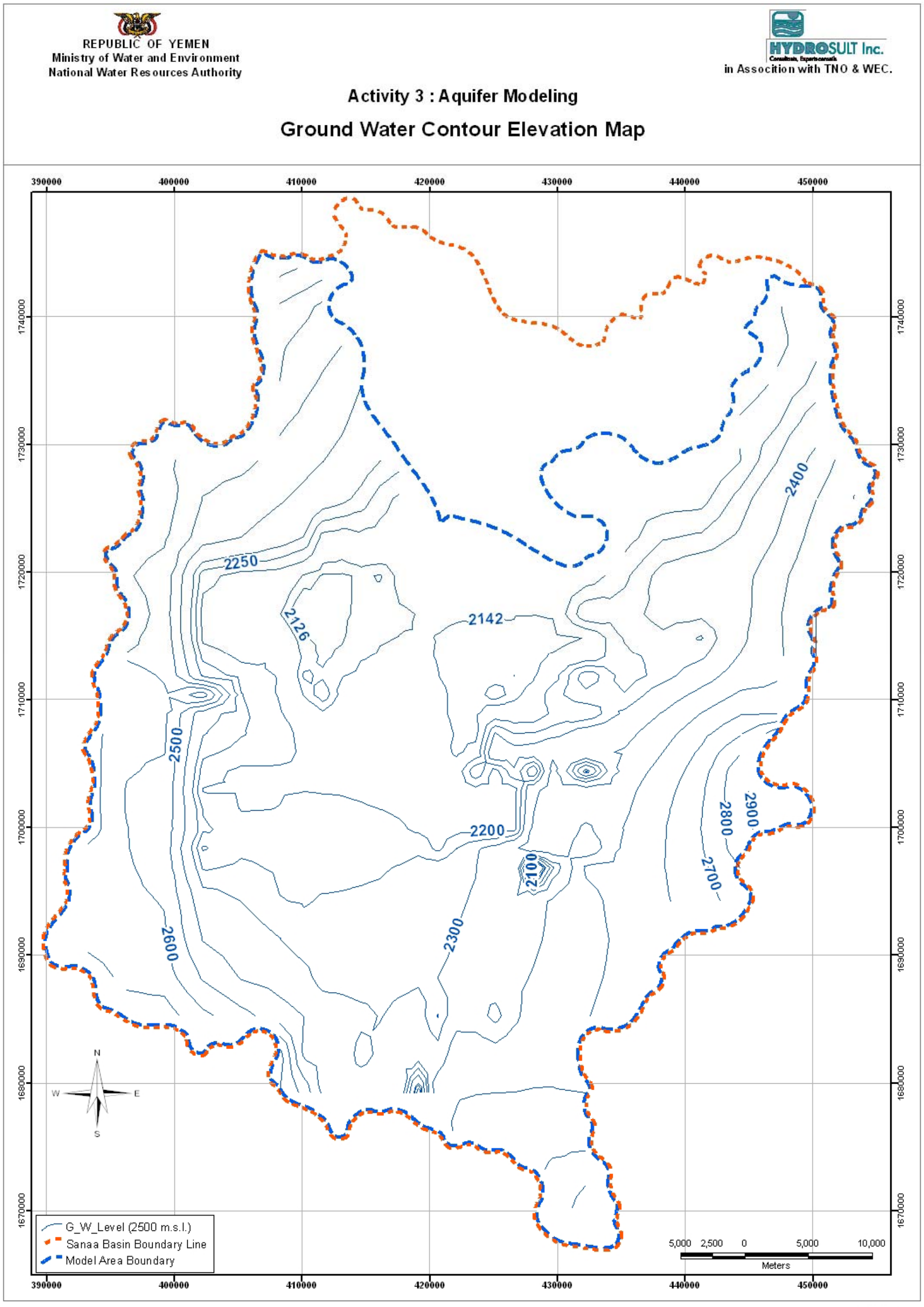


Figure 44: Computed Groundwater Contour Elevation Map

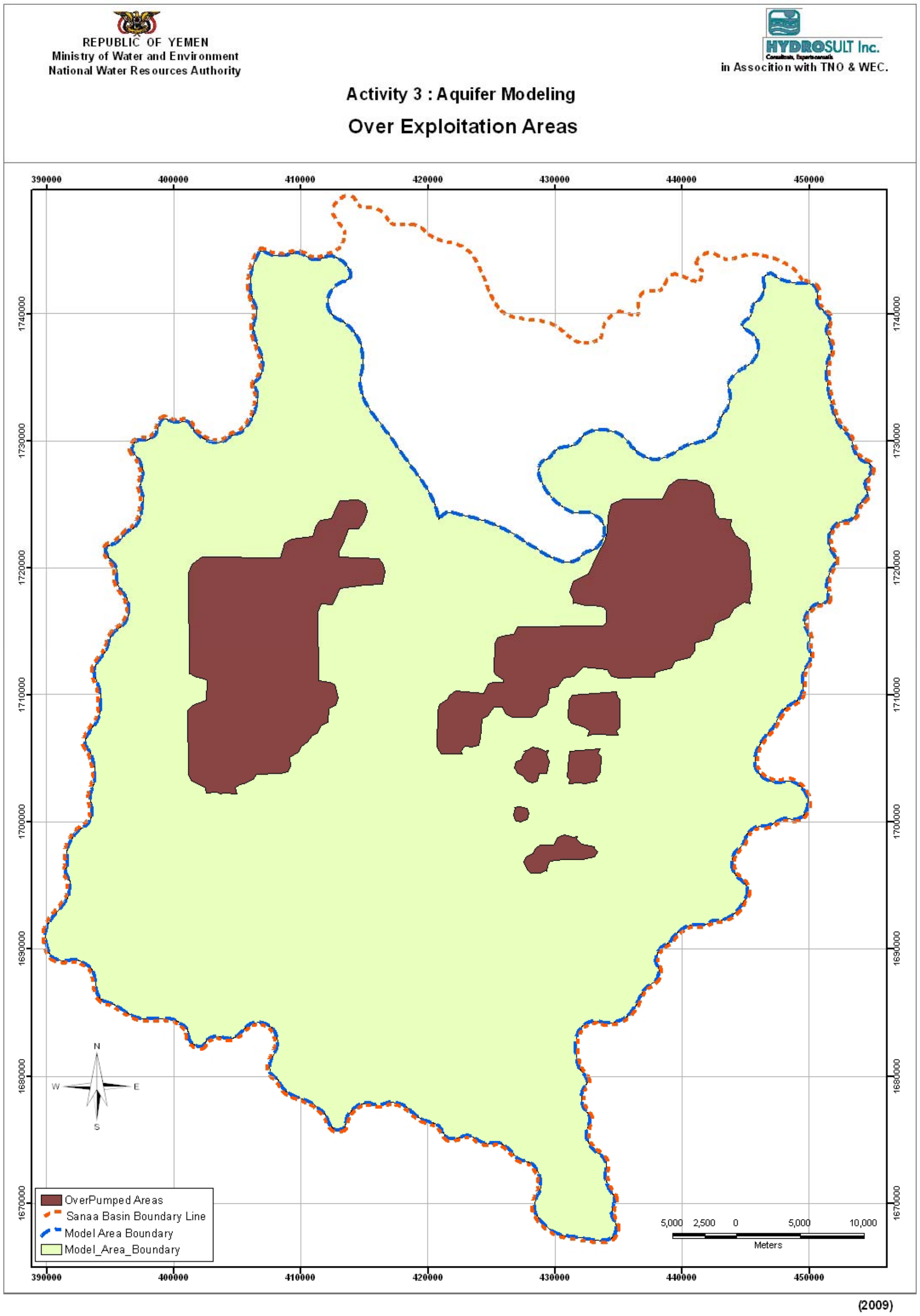


Figure 45: Over-Exploited Areas

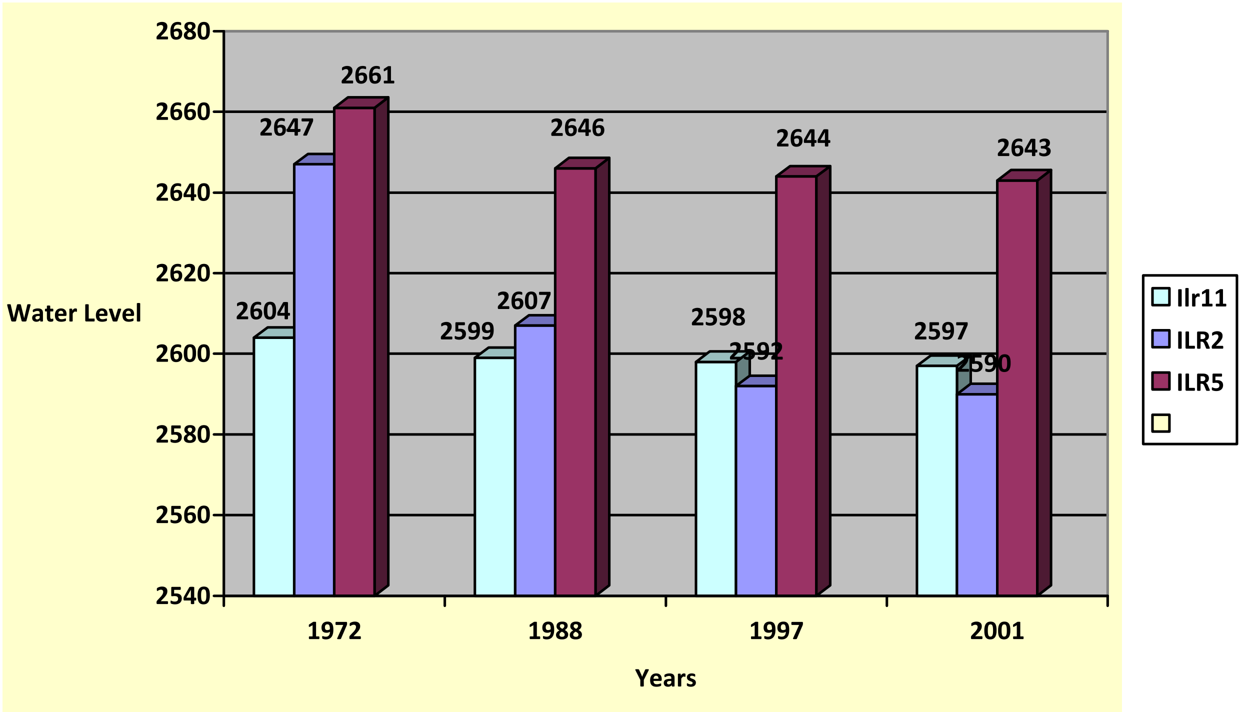


Figure 46: Computed Groundwater Level (m.s.l.) West Volcanic Group (Zone 6_W)

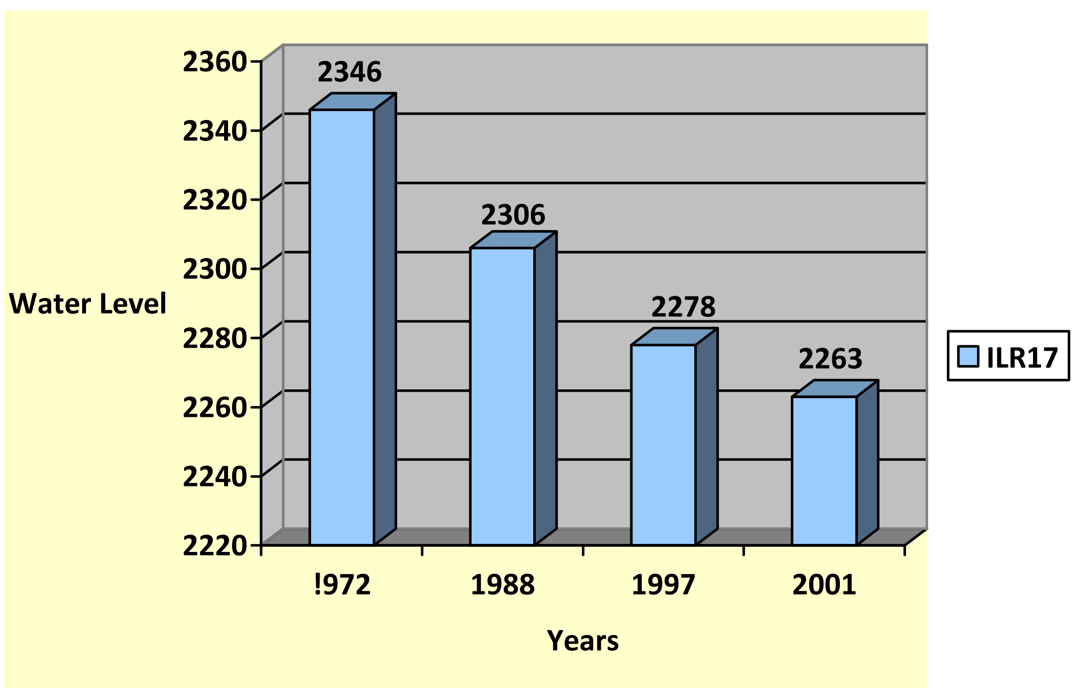


Figure 47: Computed Groundwater Level (m.s.l.) Sandstone formations (Zone 3)

12.2 Proposed Plan for Management

It is quite clear from the assessment of the present status that Sana'a Basin is under heavy pumping stress. The water level in many areas has severely dropped. Also, some locations have dried. Figure 45 shows the locations affected by extensive groundwater over-exploitation. It is proposed to adopt proper management measures and the development plan simultaneously. Priority action must be undertaken for the two most deteriorated areas. It is proposed that the management plan be implemented as soon as possible which considers the practical measures to achieve integrated management, and to adopt a holistic and participatory approach in the planning and management of the water resources.

It is essential to use mathematical modeling techniques as an effective means in the management of water resources. There should be continuous measurements taken for water level and quantities to ensure that there are no discrepancies between actual values encountered during the implementation of the proposed investment plans and the values predicted by the model. It should be noted that the use of the mathematical modeling techniques are not only for planning aspects, but also for follow-up, and management processes.

Without information and data bases, there can be no sound scientific planning, developing, and management of water resources. Therefore, continuous monitoring coupled with a computerised GIS database is a powerful tool with which proper planning can be updated.

The water development plan can be implemented by improving and increasing the groundwater potentialities. The artificial recharge can be carried out through dams, hafir and infiltration ponds and injection wells. The sub-surface flow collection for water augmentation can be implanted via Aflaj, Kahriz, infiltration galleries and hand-dug wells. Some technologies have proved useful and have recently been developed and are now being propagated. The available potential to use water harvesting methods in Sana'a Basin is very encouraging. Yemen has to use and develop their traditional technique taking into account the progress achieved in this field.

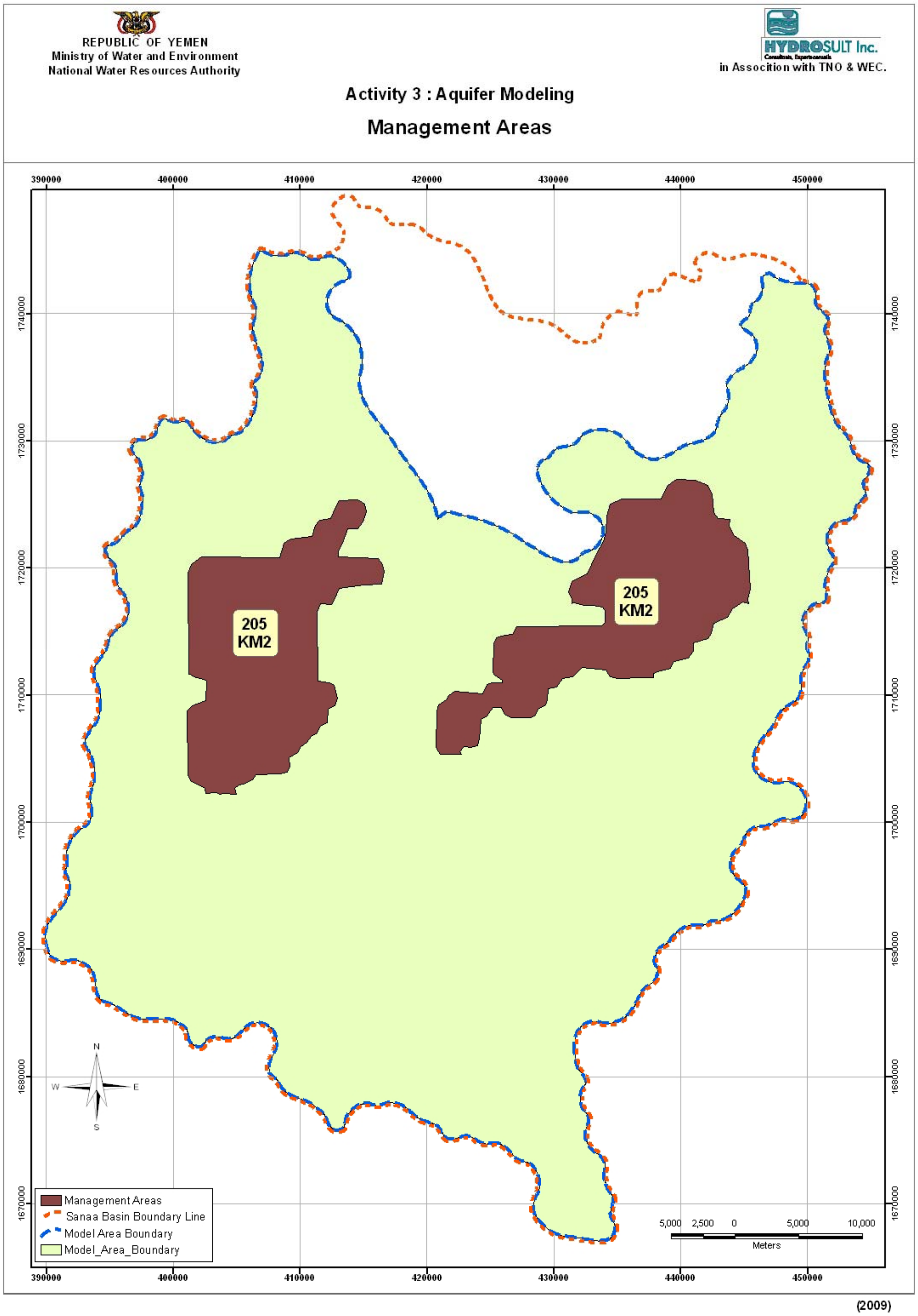


Figure 48: Priority Areas for Management

13. SIMULATION OF GROUNDWATER DEVELOPMENT STRATEGIES

Referring to the assessment of the present status, the Sana'a Basin is experiencing conditions of severe depletion. Many cells were dried, and the groundwater level in different locations in the first simulated layer dropped dramatically. The proposed strategy mainly emphasizes the application of a proper management scheme and groundwater development plan. The proposed scenario is to test the application of water augmentation strategy for the Basin, to improve the present groundwater status, and to increase the groundwater potentiality.

The scenario of increasing the groundwater recharge was simulated. It was proposed to increase the value of groundwater recharge for the different sub-basins by 50%. From a practical stand-point, such an amount can be increased by applying different means of water augmentation, particularly since the hydrological conditions of the Basin are suitable and encouraging. The predicted water balance components for the different budget zones were determined. Also the effect of the proposed scenario on the water flow system was computed. The expected drawdown contour map was established.

13.1 Water Balance Components for the Proposed Scenario

Recharge Distribution Increased by 50%

Table 27: Flow Budget for Zone 1 [Alluvial]

Output Time 1 of Stress Period 1 Time (days): 3650

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 1735.70 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 67150.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 437.67 m^3/day
Zone 2 to 1 = 61350.00 m^3/day
Zone 3 to 1 = 101920.00 m^3/day
Zone 4 to 1 = 4089.60 m^3/day
Zone 5 to 1 = 64509.00 m^3/day
Zone 6 to 1 = 1531.20 m^3/day
Zone 7 to 1 = 263.36 m^3/day

Total IN = 302990.00 m^3/day

Output Report

Constant Head = 0.00 m^3/day
Wells = 66727.00 m^3/day
Drains = 8788.30 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 2762.20 m^3/day
Zone 1 to 2 = 54576.00 m^3/day
Zone 1 to 3 = 66163.00 m^3/day
Zone 1 to 4 = 2593.80 m^3/day
Zone 1 to 5 = 89276.00 m^3/day
Zone 1 to 6 = 2027.20 m^3/day
Zone 1 to 7 = 10062.00 m^3/day

Total OUT = 302980.00 m^3/day
Difference:
IN - OUT = 15.266 m^3/day

Percent Discrepancy = 0.01%

/

Table 28: Flow Budget for Zone 2[Volcanic_W]

Output Time 1 of Stress Period 1 Time (days): 3650

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 186450.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 63590.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 306.92 m^3/day
Zone 1 to 2 = 54576.00 m^3/day
Zone 5 to 2 = 17736.00 m^3/day
Zone 6 to 2 = 2619.20 m^3/day
Zone 7 to 2 = 0.00 m^3/day

Total IN = 325280.00 m^3/day

Output Report

Constant Head = 85.22 m^3/day
Wells = 35652.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 3845.90 m^3/day
Zone 2 to 1 = 61350.00 m^3/day
Zone 2 to 5 = 183620.00 m^3/day
Zone 2 to 6 = 40478.00 m^3/day
Zone 2 to 7 = 257.29 m^3/day

Total OUT = 32290.00 m^3/day

Difference:
IN - OUT = -9.9969 m^3/day

Percent Discrepancy = 0%

Table 29: Flow Budget for Zone 3[Volcanic_E]

Output Time 1 of Stress Period 1 Time (days): 3650

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 2509500.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 71235.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 1 to 3 = 66163.00 m^3/day
Zone 4 to 3 = 837.56 m^3/day
Zone 5 to 3 = 3152.20 m^3/day

Total IN = 2650800.00 m^3/day

Output Report

Constant Head = 2260000.00 m^3/day
Wells = 60061.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 3 to 1 = 101920.00 m^3/day
Zone 3 to 4 = 232.78 m^3/day
Zone 3 to 5 = 228580.00 m^3/day

Total OUT = 2650800.00 m^3/day

Difference:
IN - OUT = -5.9333 m^3/day

Percent Discrepancy = 0%

Table 30: Flow Budget for Zone 4[Sandstone]

Output Time 1 of Stress Period 1 Time (days): 3650

Budget Term Flow (L**3/T) (m3/day)

Input Report

Storage = 0.00 m^3/day
Constant Head = 6021.20 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 19756.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 3924.30 m^3/day
Zone 1 to 4 = 2593.80 m^3/day
Zone 3 to 4 = 232.78 m^3/day
Zone 5 to 4 = 4638.70 m^3/day

Total IN = 37167.00 m^3/day

Output Report

Constant Head = 1472.00 m^3/day
Wells = 6089.90 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 5006.60 m^3/day
Zone 4 to 1 = 4089.60 m^3/day
Zone 4 to 3 = 837.56 m^3/day
Zone 4 to 5 = 19671.00 m^3/day

Total OUT = 37166.00 m^3/day

Difference:
IN - OUT = 0.66031 m^3/day

Percent Discrepancy = 0%

Table 31: Flow Budget for Zone 5[Sandstone_2]

Output Time 1 of Stress Period 1 Time (days): 3650

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 54456.00 m^3/day
Zone 1 to 5 = 89276.00 m^3/day
Zone 2 to 5 = 183620.00 m^3/day
Zone 3 to 5 = 228580.00 m^3/day
Zone 4 to 5 = 19671.00 m^3/day
Zone 6 to 5 = 12213.00 m^3/day
Zone 7 to 5 = 2250.60 m^3/day

Total IN = 590070.00 m^3/day

Output Report

Constant Head = 0.00 m^3/day
Wells = 204940.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 292810.00 m^3/day
Zone 5 to 1 = 64509.00 m^3/day
Zone 5 to 2 = 17736.00 m^3/day
Zone 5 to 3 = 3152.20 m^3/day
Zone 5 to 4 = 4638.70 m^3/day
Zone 5 to 6 = 252.31 m^3/day
Zone 5 to 7 = 1969.70 m^3/day

Total OUT = 590010.00 m^3/day

Difference:
IN - OUT = 57.246 m^3/day

Percent Discrepancy = 0.01%

Table 32: Flow Budget for Zone 6 [Volcanic_2N]

Output Time 1 of Stress Period 1 Time (days): 3650

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 14944.00 m^3/day
Zone 1 to 6 = 2027.20 m^3/day
Zone 2 to 6 = 40478.00 m^3/day
Zone 5 to 6 = 252.31 m^3/day
Zone 7 to 6 = 4001.10 m^3/day

Total IN = 61703.00 m^3/day

Output Report

Constant Head = 0.00 m^3/day
Wells = 4205.50 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 40460.00 m^3/day
Zone 6 to 1 = 1531.20 m^3/day
Zone 6 to 2 = 2619.20 m^3/day
Zone 6 to 5 = 12213.00 m^3/day
Zone 6 to 7 = 668.85 m^3/day

Total OUT = 61699.00 m^3/day

Difference:
IN - OUT = 4.2498 m^3/day

Percent Discrepancy = 0.01%

Table 33: Flow Budget for Zone 7 [Alluvial_2N]

Output Time 1 of Stress Period 1 Time (days): 3650

Budget Term Flow (L**3/T) (m3/day)

Input Report

Constant Head = 0.00 m^3/day
Wells = 0.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 1 to 7 = 10062.00 m^3/day
Zone 2 to 7 = 257.29 m^3/day
Zone 5 to 7 = 1969.70 m^3/day
Zone 6 to 7 = 668.85 m^3/day

Total IN = 129 58.00 m^3/day

Output Report

Constant Head = 0.00 m^3/day
Wells = 4357.40 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
Surface Leakage = 0.00 m^3/day
General-Head = 2083.50 m^3/day
Zone 7 to 1 = 263.36 m^3/day
Zone 7 to 2 = 0.00 m^3/day
Zone 7 to 5 = 2250.60 m^3/day
Zone 7 to 6 = 4001.10 m^3/day

Total OUT = 12956.00 m^3/day

Difference:
IN - OUT = 2.3038 m^3/day

Percent Discrepancy = 0.02%

13.2 The Effect of Increasing Recharge on Groundwater Level

The predicted Groundwater Contour Elevation Map due to applying the strategy of increasing the groundwater recharge by 50%, was constructed (Figure 51). The groundwater elevation was raised with different values. The expected increase of the groundwater level in the different zones, (defined in the above-mentioned water flow system map in Figure 10), can be summarized as follows:

- The groundwater rises from about 14 meters (ITL18) to about 42 meters (ITL18), in Quaternary and Tertiary Volcanic Group, located in Zone 2.
- The groundwater rises about 14 meters (ITL17), in Cretaceous Sandstone, located in Zone 3.
- The groundwater rises about 33 meters (ITL14), in Quaternary Alluvium in Zone 5.
- The groundwater rises from about 11 meters (ITL16), in the North to about 22 meters (ITL2) at the South, in the West area of the Basin, in Quaternary and Tertiary Volcanic Group, located in Zone 6_W.
- The groundwater rises from about 14 meters (ITL6), in the South to about 24 meters (ITL10) at the North, in the in Quaternary Alluvium, Quaternary and Tertiary Volcanic Group, located in Zone 7. Also, a rise in the Sandstone aquifer to about 12 meters (ITL 4) was noted.

Not only did the values of the drawdown decrease by applying this scenario, but also the extension of the deteriorated areas under severe over-exploitation conditions, was reduced from about 30% to 40 %. Figure 52 shows the resulted drawdown areas after considering the increase of groundwater recharge.

It can be concluded that the proposed scenario of increasing the groundwater recharge will give a very good response, and the groundwater potentialities will be improved. Therefore, the groundwater recharge can be considered as a technically feasible solution to augment the water supply of Sana'a Basin, besides the integrated management procedures that have to be achieved.

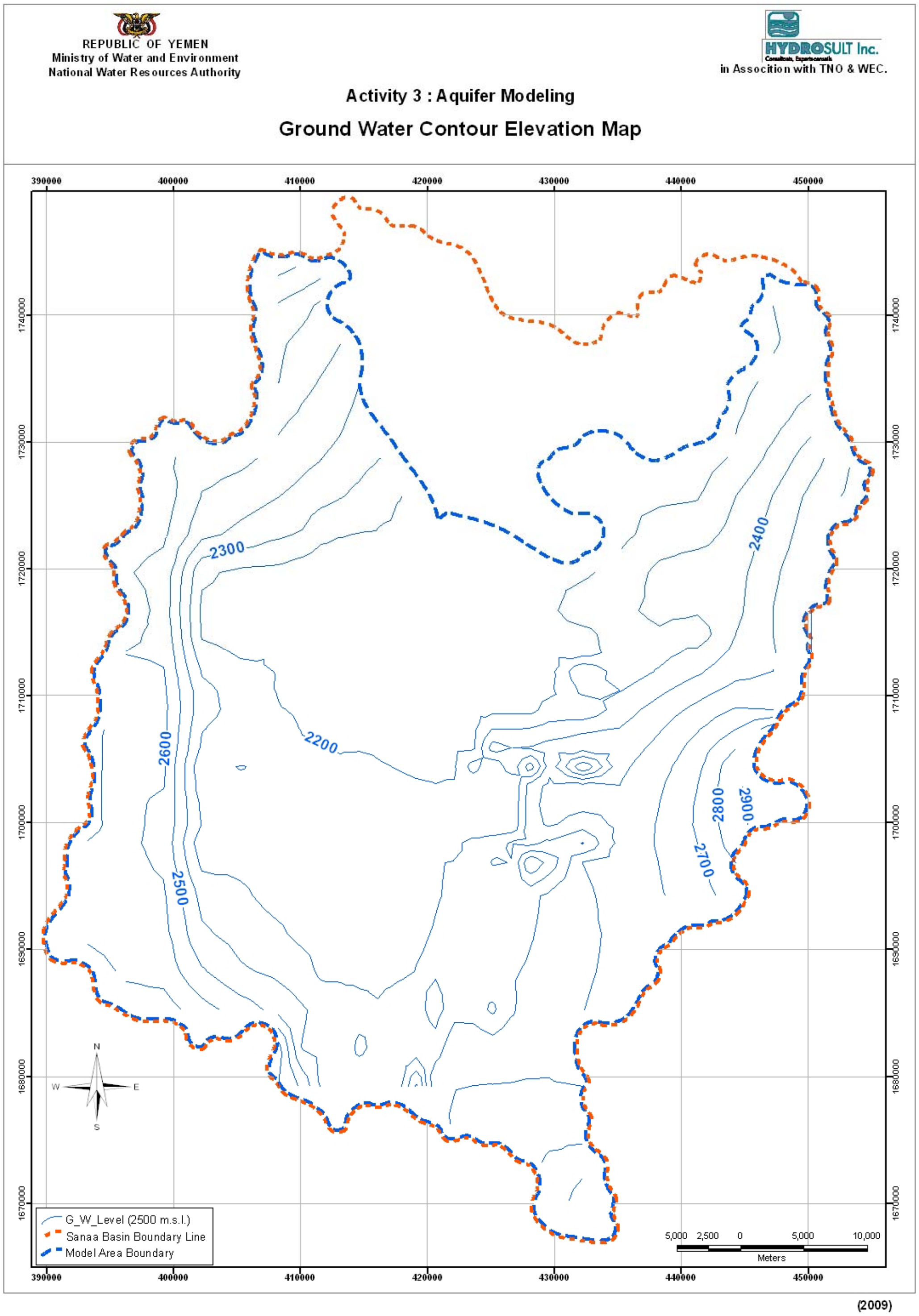


Figure 49: Predicted Groundwater Contour Elevation Map (Scenario Recharge Increase 50%)

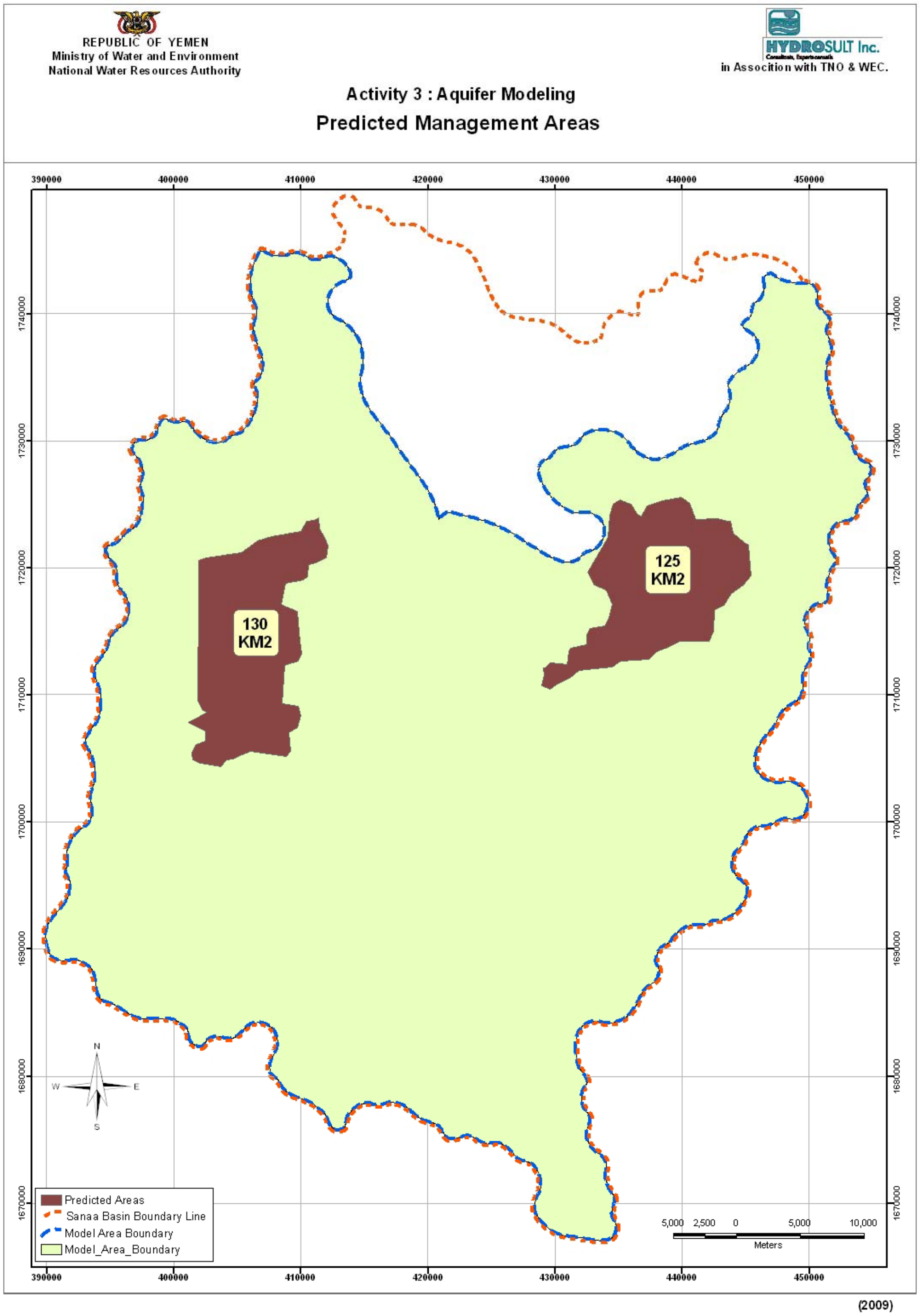


Figure 50: Extension for the Predicted Managed Areas (Applying an Increase of Recharge 50%)

14. CONCLUSIONS & RECOMMENDATIONS

The detailed investigation in Sana'a Basin has shown that the Basin is now within a water deficiency situation. The results of the model showed that the Basin is suffering over-exploitation conditions. 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. The development of the groundwater resources for the Basin is highly recommended where different methods for water augmentation have to be applied.

There are numerous reasons for this Water Problem, which may be summarized as follows:

- Limited water resources and insufficient recharge.
- High rate of population growth and an accelerating rate of social and economic development.
- The continuous improvements in pumping technology and market conditions 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.

Proper Management of Groundwater Resources

It seems that the only recourse for solving this problem or for attenuating its severity is a removal of its causes. Finally, it should be emphasized that it is important to continuously improve the state of knowledge about the available resources. The application of the Modeling Techniques can be considered as an efficient tool for integrated planning and sound management of groundwater resources in Sana'a Basin. This can be achieved by continuous Model Calibration and enhancing the output results. Therefore, periodical accurate measurements of water level, and pumped water quantities are required to ensure that there are no discrepancies between the measured values during the exploitation of groundwater and the predicted values by the model. It should be noted that the use of the mathematical model technique is not only for planning, but also for follow-up (monitoring), and management processes.

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. The Water Resources Database has a great value, where huge amount of data and information are being compiled, collected, updated, and processed. The water resources data is actually a national treasure, and vital for managing and monitoring the water resources in the country. Sana'a Basin recognized the importance of data bases, where it started to document data and information for the Basin, region. Water data is geographical and dynamic. This means that it changes according to time and location. Geographic

Information Systems have to be applied extensively to enable various methods of storage, treatment and linkage of data and its projection in maps by international or national geographic coordinates.

It is beyond doubt that the critical water situation in Sana'a Basin requires special attention to the development of Human Resources in the water sector, as a fundamental measure to achieve sustainable scientific studies. There are good experts in Sana'a Basin in the different related specialities; in Hydrogeology, Hydrology, modelling techniques, GIS, and others. However, there is a need for the continuous gaining of knowledge and this, in turn, requires periodic training to keep up with scientific and technological progress that is moving at a fast pace. It is therefore necessary to expand horizontally in gaining knowledge while emphasising the development of specific practical skills in a team effort.

With regards to the water shortages, there is a need to maximise utilisation of available water, especially as 93% of available resources (Al-Hamdi, 2000) are used in agriculture. It is recommended to improve the irrigation systems and to reduce the losses of the transport and distribution irrigation networks. The exploitation of groundwater in agriculture should be maximized in the integrated production system: plants, soil-water, climate and environment.

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. There should be broad lines of economic aspects, design, and administration and supervision studies to ensure sustainable field irrigation of acceptable efficiency. The studies should cover the integrated fields such as irrigation, soil, hydraulics, type of water, economics, sociology and climate.

The real water needs should be determined, where continuity and fairness should be observed in the regulation of water resources. The allocation of water will be the main distinctive feature of water policy in the Sana'a Basin. It should elaborate short and long- term water strategies and apply laws that would ensure the implementation of these strategies. Therefore, it is essential for Sana'a Basin to give more attention to water Legislation, to ensure sound implementation of water policies and proper management of this important resource. Thus, it is to enact water laws that regulate the utilisation of water within the available resources, protect them against deterioration, assign responsibilities and competence to the administering bodies and regulate the relations between these bodies.

Sana'a Basin Groundwater Development (Fresh Water Augmentation Technologies)

Sana'a Basin must be subjected to groundwater development in addition to the measures to be accomplished for proper management. The inefficient approach for planning and management has led to programs that are not focused on strategies for curbing the waste of huge amounts of water, 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.

With regards to the output of the simulation run of the Groundwater Development Strategies, it was found that the increase of Groundwater Recharge wells response in increasing the groundwater potentiality, and will improve the groundwater present status. It has been proven that the aquifers are highly sensitive to the groundwater recharge and positive results can be achieved. Different methods can be applied for increasing the Groundwater Recharge whither from Reservoir, Catchment Runoff, and Return Flow from demand sites. The available potential to use water harvesting methods in Sana'a Basin is very encouraging. Sana'a Basin should use and develop their traditional techniques taking into account, the progress achieved in this field.

It is essential to develop the technology for developing groundwater resources (water augmentation), and to rationalize the use of water for agriculture, and to enhance the exerted efforts in the domain of water management through integrated strategic planning for water resource and water use.

All of the above falls within the framework of limiting natural conditions of the scarcity of water resources. It is essential to employ a full range of policy instrument, improve the efficient use of water resources and promote their allocation, support the diffusion of technology and capacity-building, facilitate the establishment of public-private partnerships.

15. REFERENCES

Interim report, and progress reports, (2006, 2007), Sana'a Basin Management Project, Hydrogeological and Water Resources Monitoring and Investigations, Component 3(d): REP No. 5/003;

Activity (1) Aquifer Storage Investigations and Assessment.

Activity (2) Water Balance and Sub-Basin Monitoring

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