DEVELOPING RENEWABLE GROUND WATER RESOURCES IN ARID LANDS

PILOT CASE: THE EASTERN DESERT OF EGYPT

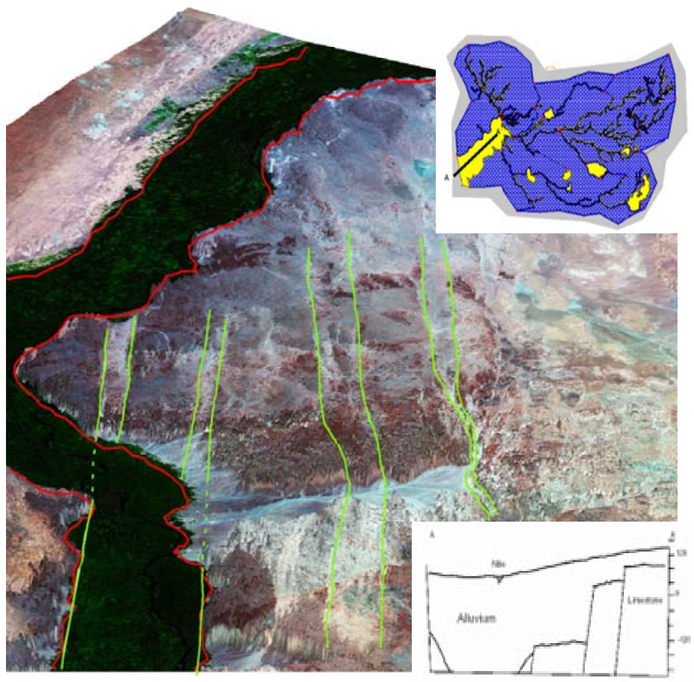
EDP
EASTERN DESERT PROJECT

SUSTAINABLE DEVELOPMENT OF WADY ASUITY: *A GROUND WATER FLOW MODEL*

UNDP

GEF

Cairo University



Prepared by

International Consultant, EDP

Eugene Yan, Environmental Research Division, Argonne National Lab, USA
Mohamed Sultan, Head**,** Dept. Geosciences, Western Michigan University, MI, USA

Project Director, EDP

Ahmad Wagdy, Irrigation and Hydraulics Dept, Engineering, Cairo University

GW- 201- Nov. 2004

TABLE OF CONTENTS

1	**Acknowledgments**	**2**
2	**Abstract**	**3**
3	**Introduction**	**4**
4	**Geologic Setting**	**6**
5	**Geochemical Affinities of the Nubian Aquifer Groundwater**	**8**
6	**Locating Nubian aquifer groundwater residing in alluvial aquifers**	**10**
7	**Assessment of Nubian Aquifer groundwater residing in alluvial aquifers: Wady Asuity**	**13**
	7.1 Conceptual Model	**13**
	7.2 Model Construction	**14**
	7.3 Model Calibration	**16**
	7.4 Simulation Results	**17**
8	**Potential Sustainable Groundwater Production**	**19**
9	**References Cited**	**21**

1. ACKNOWLEDGMENTS

We thank the scientists and administration of the Ministry of Water Resources and Irrigation for their valued efforts in all aspects pertaining to this project and for the administration of Cairo University for their continued support. The activities for this project were supported by the United Nations Developing Program and the Global Environmental Facility International Water Program.

2. ABSTRACT

Rising demands for fresh water supplies in arid lands is leading to excessive exploitation and unsustainable mining of non-renewable fossil groundwater in these areas. Using the Nubian Aquifer of Saharan Africa as a test site, we demonstrate an integrated approach to identify areas of discharge that could have gone undetected, and to model extraction that is sustained by natural discharge. Using geochemical (stable and radiogenic isotope geochemistry), field, and remote sensing data we show that discharge of the Nubian aquifer is occurring on a larger scale, primarily through deep seated fault systems and that ascending groundwater discharge into the relatively thick alluvial aquifers proximal to the fault complex that define, the River Nile and the Gulf of Suez. Following the identification of the targeted alluvial aquifers, we develop a hydrologic model to assess the discharge and to constrain sustainable extraction in one of the identified discharge areas along the River Nile, the Asuity area and to demonstrate a replicable model for similar reservoirs along the Nile and the Gulf. A two-dimensional groundwater flow model was constructed (hydrologic parameters extracted from 77 production wells) and calibrated against head data from 19 wells. Results point to a significant contribution to the Asuity groundwater system from rising Nubian groundwater (3.19 x 10^7 m^3/year: 75% of discharge) and a modest contribution (1.08 x 10^7 m^3/year: 25% of discharge) from surface runoff. Approximately 7 x $10^6 m^3$/year of groundwater could be used in a sustainable matter in Asuity. Assuming geologic settings and discharge rates similar to those of the Asuity, we estimate that 200 x $10^6 m^3$/yr of groundwater is available for sustainable development in similar settings around the River Nile and the Gulf of Suez.

3. INTRODUCTION

Demand for fresh water supplies in arid and semi-arid countries world-wide is on the rise from increasing populations and limited water supplies. These problems are exemplified in countries of Saharan Africa (North Africa) and the Middle East where scarcity of water resources contributes to political instabilities, disputes, and conflicts. Studies have shown that the number of countries unable to meet their water needs to be self-reliant in food production were 12 in 1993, are 16 in the year 2000, and will be 18 by 2025;. by 2025, only Iraq, Lebanon, and Mauritania will have enough water in this area, and the average availability will have dropped to 535m^3 per capita year, less than one half of what is considered necessary (IN-WARDAM, 1990). Sources of fresh water supplies in these areas include: surface runoff (e.g., Nile River in Egypt and Sudan) that generally originates from allochthonous precipitation over distant mountains located in wetter climates, and groundwater resources that originated as autochthonous precipitation that recharged the aquifers in previous wet climatic periods (e.g., Nubian Aquifer in Egypt, Sudan, Libya). Anthropic controls on hydrologic systems in these areas are largely related to: (1) environmental and hydrologic consequences of engineering efforts intended to expand and to exploit water resources, largely involving impoundments of surface waters; and (2) excessive exploitation of non-renewable fossil groundwater without a clear understanding of these hydrologic systems. Nowadays, the Nubian aquifer is being tapped extensively for irrigation in the oasis and lowlands of the Western Desert of Egypt (e.g., Kharga, Dakhla, Farafra), eastern Libya (e.g., Kufra Basin), and northern Chad. As a consequence, the naturally flowing springs in many of these oases and lowlands have dried up and groundwater levels have been dropping for decades due to excessive pumping. It is estimated that by the year 2070, deep drawdown cones will form, and the extensive and interconnected basins that exist nowadays within the aquifer will be dissected by interleaving dry areas (Soliman et al., 1998). These development scenarios are typical for similar setting elsewhere; often the case development efforts are largely localized in areas that are more suited for settlement of communities. In the case of the Nubian aquifer, development is largely concentrated in the lowlands for obvious reasons: (1) natural discharge and/or shallow groundwater, (2) rich soils (clay deposits from old playas), (3) mild climatic conditions, etc. Such problems could be alleviated (at least in part) through the identification and sustainable development in areas where natural discharge occurs. In this manuscript, we demonstrate that many of the discharge areas may have gone undetected in the Nubian aquifer and demonstrate examples for sustained development of such systems.

4. GEOLOGIC SETTING

Beneath the surface of the eastern and Western Deserts of Egypt and adjacent portions of eastern Libya, northeastern Chad, and northwestern Sudan (Fig. 1) lies an immense reservoir (>50,000 km^3) of freshwater in the Nubian Aquifer system (Thorweihe, 1990). This resource resides in two major basins: (1) the Kufra Basin of eastern Libya, and northern Chad, and (2) the Dakhla Basin of western Egypt and northeastern Sudan (Fig. 1). The Aquifer consists mainly of continental sandstones with intercalated shales of shallow marine and deltaic origin, unconformably overlying Proterozoic basement, and reaching a thickness approaching 3,000 m in the center of the basin (Hesse et al., 1987). The Aquifer reaches a thickness approaching 3,000 m in the center of the basin (Hesse et al., 1987). The Aquifer is underlain by Precambrian basement. The sandstone is exposed in NE Chad. North of the 25^{th} parallel, the Nubian Aquifer is confined beneath thick marine shales. North of the 29^{th} parallel, northward groundwater flow is limited by saline water. In the north, where the Aquifer is confined, it is divided into four thick (tens to hundreds of meters thick) horizons of sandstone layers that are separated by relatively thin (meters to tens of meters thick) shale layers. Water in the Dakhla Basin flows from southwest to northeast (gradient 0.5 m/km) and discharges naturally at oases. For a long time, it was realized that the discharge from the Nubian occur in the lowlands or in the depressions of the Western desert of Egypt and of the Libyan desert as well. It is now becoming clearer that the discharge of the Nubian aquifer waters is occurring on a larger scale, primarily through deep seated fault systems that act as pathways for ascending Nubian aquifer groundwater. The most prominent of these systems are those bounding the River Nile and the Gulf of Suez grabens. Figure 2 is a schematic E-W trending cross section (A-A'; Fig. 1) that cross cuts the Eastern Desert of Egypt, the study area. The Eastern Desert of Egypt extends from the Nile River to the Red Sea, covering an area more than 200,000 km^2. In the central part of the Eastern Desert is a mountain range cored by Precambrian basement (550-900 Ma), with prominent peaks formed by granite bodies, and volcano-sedimentary rock units. The mountains are drained by a series of Wadys into the Nile River on the west and the Red Sea on the east. The modern Nile

River valley was excavated and developed as a subsequent stream to the numerous valleys emanating from the elevated Red Sea hills to the east (Said, 1993). The cross section shows a concentration of high angle deep-seated fault systems in the proximity of the Nile and the Gulf of Suez complexes. Should these faults terminate at, or define the distribution of, the relatively thick alluvial aquifers along the Gulf of Suez or the River Nile graben, the rising Nubian aquifer groundwater might ultimately flow through these shallow aquifers before discharging into the Nile or the Gulf. In general, the thickness of alluvial aquifers increases in the proximity of the River Nile and Gulf of Suez grabens. Next, we show that the isotopic affinities of these shallow waters now residing in these alluvial aquifers are indicative of their origin, being largely derived from the fossil water of the Nubian Aquifer.

5. GEOCHEMICAL AFFINITIES OF THE NUBIAN AQUIFER GROUNDWATER

We collected groundwater samples for isotopic analyses (O, H, tritium) from the shallow alluvial aquifers adjacent to the Nile Valley, within the Precambrian terrane, and from the Gulf of Suez and surroundings (Fig. 4). For comparison, we compared our groundwater samples from wells penetrating the underlying Eocene limestone, and from artesian wells tapping the Nubian Aquifer at depth. Additional insights into the origin of the Eastern desert waters were made through comparisons to groundwater from the Western desert and Sinai.

The stable isotope ratios of hydrogen and oxygen are shown in Figure 3, which includes data for samples from the present study as well as: Nubian Aquifer paleowaters from the Gulf of Suez area paleowaters, also from the Nubian Aquifer (Sturchio et al., 1996); shallow aquifers in the Wady Tarfa area (Sultan et al., 2000); and data for modern precipitation from Sidi Barrani (IAEA/WMO, 1998).

The Eastern Desert groundwater samples have a wide range in hydrogen and oxygen isotope ratios, from a relatively depleted composition of $\delta D = -59.2$, $\delta 18O = -7.9$ in Bir Laquita to a relatively enriched composition of $\delta D = +32$, $\delta 18O = +5.2$ at Wady El Sheikh Fadl. Two groups of samples could be identified. The first group (Group I) includes samples that have isotopic compositions similar to those of meteoric precipitation or evaporated precipitation. Examples of these include groundwater samples in fractured basement rocks and the overlying alluvium aquifers (e.g., Sheikh El Shazly, Bir Um Ghanam, Hafafit, and Fawakhir) and in the alluvium aquifers in the proximity of the River Nile (e.g., Wady Tarfa, Wady El Ashrafia). We have shown (Sultan et al., 2000) that the groundwater of the Wady Tarfa area are mostly evaporated flash flood waters, with relatively short underground residence times indicated by the presence of live tritium (i.e., <45 years). The most enriched sample, from Wady Sheikh El Fadl, was shown by Sultan et al. (2000) to be evaporated Nile River water. The second group (Group II) of analyzed samples have depleted (δD = -32 to -59) isotopic compositions compared to Group I samples. Their isotopic compositions could be accounted for by mixtures of modern precipitation (i.e., flash flood waters) and Nubian aquifer water of depleted compositions. The isotopic composition of the Nubian aquifer water is best explained by progressive condensation of water vapor from paleowesterly wet oceanic air masses that traveled across North Africa and operated in the wet climatic periods at least as far back as 450,000 yr before the present (Sonntag et al., 1978; Sultan et al., 1997). Available data for tritium activities for these samples revealed no measurable tritium, indicating residence times in excess of 50 years for these waters.

The group II samples of the Eastern Desert waters are apparently intermediate between the Western Desert paleowaters and the Gulf of Suez area paleowaters, possibly reflecting a geographic trend in the isotopic composition of paleoprecipitation stored in the Nubian Aquifer. Alternatively, the apparent progressive enrichment in the isotopic composition from west (Western Desert) to east (Sinai) could reflect variable degrees of mixing between fossil water that precipitated during wet climatic periods and meteoric precipitation that is deposited during the interleaving dry climatic periods (e.g., nowadays). This hypothesis is supported by the patterns of modern precipitation. Currently, rainfall over the Nubian sandstone outcrops (recharge areas) in southern Sinai is considerable (~100 mm/yr) compared to their counterparts in the Western Desert that hardly receive any precipitation (0-5 mm/yr) (EMA, 1996; Nicholson, 1997; Legates and Wilmott, 1997). Precipitation in the Eastern Desert is intermediate between that reported for the Western Desert and for Sinai. Regardless of which hypothesis is adopted, shallow groundwater samples in alluvial aquifers that have depleted isotopic compositions must have been largely derived from the fossil water of the Nubian Aquifer. Locating these aquifers is an important step towards the identification and the assessment of discharge. We use the isotopic signatures of the investigated groundwater to identify shallow alluvial aquifers that host Nubian Aquifer groundwater and search for features that are being shared by these aquifers and which could be used in the identification of similar reservoirs elsewhere.

6. LOCATING NUBIAN AQUIFER GROUNDWATER RESIDING IN ALLUVIAL AQUIFERS

We classified as Group I and as Group II, the following groups of samples on the basis of their isotopic compositions (O, H): (1) samples that we collected from the shallow alluvial aquifers in this study, (2) samples from similar aquifers in Wady Tarfa and surroundings (Sultan et al., 2000), and (3) thermal waters from springs and shallow artesian wells that are being discharged along the coastal plane of the Gulf of Suez and the alluvial sediments that make up these plains. The majority of Group II samples are thermal waters that discharge in the alluvial deposits proximal to the River Nile and the Gulf of Suez (Figure 4); their discharge temperatures exceed ambient temperatures reaching up to 70°C in some cases Hammam Faroun (Sturchio et al., 1996). The distribution of alluvial aquifers could be inferred from the distribution of relatively bright sediments that floor the valleys (Fig. 4). Drilling and geophysical investigations have shown that in general, the thickness of these aquifers sediments increases progressively towards the River Nile and towards the Gulf and so does the depth to the Nubian sandstone reaching depths of up to 3 km in the Gulf area and up to 2 km in the vicinity of the Nile Valley (Fig. 2). It has been suggested that many of the these deep seated sub-vertical faults are NW-trending Neoproterozoic faults that have been reactivated in the Neogene during the rifting events associated with the opening of the Red Sea. These NW-trending faults and shear zones are the most prominent structural elements in the Neoproterozoic Red Sea hills terranes. They are part of the Najd Shear System, the largest pre-Mesozoic transcurrent fault system on Earth (Stern, 1985), extending in a NW-SE direction over 1200 km in outcrop, with a width of approximately 300 km; the system terminates at the eastern margin of the Red Sea and extends into the Eastern Desert of Egypt (Moore, 1979; Abu Zeid; 1984; Stern, 1985; Sultan et al., 1993).

All of these features suggest that the Nubian aquifer water access deep seated sub-vertical faults in the proximity of the River Nile and Gulf of Suez graben and discharge into the thick alluvial aquifers that are delimited by these faults (Fig. 2). Consequently, we have identified three main criteria to locate alluvial aquifers that host Nubian Aquifer groundwater: (1) investigated groundwater have isotopic compositions similar to those of paleo-water in the Eastern Desert and undetectable tritium, (2) thick alluvial deposits that are found proximal to the Nile Graben and Gulf of Suez, and (3) NW-trending fault systems intersecting or bounding the alluvial sediments in question. Using these criteria, we have identified a coverage (areas in yellow) that shows the distribution of the areas encompassing alluvial aquifers that are likely to be recharged by ascending Nubian aquifer groundwater (Fig. 5). Next we use one of the better studied discharge areas (Wady Asuity) to validate the reliability of the criteria we selected for locating alluvial aquifers hosting Nubian Aquifer groundwater.

A major agricultural development project is underway in Wady Asuity, where over 70 production wells were drilled over the past two decades, each well pumping 50-100 m3/hour. All of the analyzed samples that were collected from Wady Asuity (8 samples) show depleted isotopic compositions (δD: -34.68- -51.96). These depleted compositions, undetectable tritium (<1 TU), and discharge temperatures (27-32°C) indicate that these waters are paleowater, largely derived from the underlying Nubian sandstone. In this area, the Nubian sandstone is found at depths exceeding 1 km and thus, the groundwater must have ascended via deep-seated faults. Three major sub vertical, NW-trending faults were identified along cross section A-A' (inset Fig. 5) using geophysical data and utilizing information extracted from drilling (RIGW, 1993). The thickness of the alluvium aquifer increases significantly (to more than 300 m) from the northeast to the southwest. The location of these sub vertical faults plots along NW-trending structural discontinuities that could be readily identified on landsat TM images and on digital topography. Figure 5 is an overlay of Landsat TM data over digital elevation, an image that integrates and displays information contained in the two images. Inspection of the image shows that topographic expressions (valleys and grabens) mark the projected extensions of the traces of three NW-trending faults into the adjacent mountains. Because of the high cost involved in the acquisition of geophysical or drilling data, we heavily rely on the analysis of remote sensing data and published subsurface data (composition, thickness, structure) where available, to infer the presence of reactivated

NW-trending faults. As described early, locating these systems is one of the criteria we use for identifying alluvial aquifers that host Nubian aquifer groundwater.

Following the identification of the targeted alluvial aquifers, we develop a hydrologic model to assess the discharge and to constrain sustainable extraction in Asuity area and to demonstrate a replicable model for similar reservoirs along the Nile and the Gulf. The rising Nubian groundwater ascend to the near surface, discharge into the alluvial aquifers and ultimately into the River Nile or the Gulf of Suez. If we were to intercept these waters before they make it to the River Nile and at a rate that does not disrupt the existing steady state groundwater flow regime, we would probably attain sustainable exploitation of this ground water resource.

7. ASSESSMENT OF NUBIAN AQUIFER GROUNDWATER RESIDING IN ALLUVIAL AQUIFERS: WADY ASUITY

The Assiuty hydrologic system comprises two flow components: (1) the surface water system of the Assiuty watershed, and (2) the Assiuty groundwater flow system. The Assiuty watershed is one of the main drainage systems that ultimately flows into the Nile River Valley in the Eastern Desert (Figure). The watershed collects rainfall over an area of 5589 km^2 in the Red Sea Hills and adjacent mountains and is channeled towards the Nile River. The Quaternary alluvium aquifer floors the main channels within the Assiuty watershed; the surrounding outcrops are mainly Tertiary Lime stones (inset: Fig. 5). Gheith and Sultan (2002) estimated that the infiltration to the limestone is limited and transmission loss to the alluvium aquifer along the stream channels is significant at an average annual rate of 2 $x10^7$ m^3. The flow to the outlet of the watershed is also minimal, amounting to only 7% of the total rainfall. In this section we discuss our conceptual model, the construction of the groundwater flow model, and finally we present simulations using the calibrated model for the sustainable development of the Asuity.

7.1 Conceptual Model

We constructed a ground water flow model for steady-state and transient simulation under the representative flow conditions and calibrated the model against well data and pumping test data reported by RIGW (2003).The mathematical model was based on the following conceptual model: The Groundwater flow system in the area includes two possible sources: (1) groundwater upward discharge from the Nubian aquifer through deep-seated faults, and (2) surface water infiltration from the runoff (transmission loss along the ephemeral streams). Support for this conceptual model comes from: (1) presence of extensive drainage networks that channels rain precipitating over large segments of the Eocene limestone platforms through Wady Asuity (Fig. 5), (2) reported recent flash flooding events in Wady Asuity (Naim, 1994), and (3) analysis of the isotopic affinities of the Eastern desert groundwater. Analyzed groundwater from the Assiuty area are composed of two end-member water sources that can be identified from stable isotope compositions: (1) isotopically enriched water, most likely recharged recently by flash-floods, and (2) isotopically depleted water, most likely Pleistocene water from the Nubian sandstone aquifer. Mass balance calculations indicate mixtures of approximately 80% Nubian aquifer depleted water with 20% flash flood enriched water. In the next sections we show that the inferred proportions of the two water sources are consistent with our findings from the results of the hydrologic model.

7.2 Model Construction

The well data cover an area extending from the central part of the Wady Aswuti all the way to the Nile River (Fig. 6a). Records for ground water levels prior to pumping are not available posing difficulties to conducting simulations for ground water levels under steady state conditions. Seventy seven production well data and 9 observation well data were examined and grouped into groups, each encompassing a cluster of wells that lie in the same approximate location. For each group, we selected the wells with the highest water-level measurements. We assumed that these wells approximate the water levels at steady state conditions and are least affected by the subsequent pumping associated with the agricultural development of Wady Asuity. Out of the investigated eighty seven wells, nineteen were selected for calibration purposes (Fig. 6a).

The geographic limits of the model were chosen to coincide with natural boundaries of the alluvium aquifer on the north, east, and south. The Nile River is considered as the western boundary for the model. The model grid is constant with spacing of 200 m by 200 m. The model was simplified to accommodate a single alluvium layer; the bottom of the layer is defined by the depth of the underlying clay or limestone layer. The top of the alluvial layer was extracted from the digital elevation data for the area and the bottom of the layer was delineated from depth information extracted from well log data and from geologic cross sections (NWRC, unpublished report).

Three types of boundaries were adopted: river, general head, and no flow boundaries (Figure 6b). The Nile River was considered as a river boundary with river stages ranging from 41 m AMSL (up gradient) to 35 m AMSL (lower gradient). General head boundaries in the study area are lumped into two groups: firstly, boundaries that are perpendicular to the general flow direction and are here presumed to intercept the bulk of the flow from fractured limestone and from the channels (3 orange segments on Fig. 5). Secondly, deep-seated faults that represent discharge zones for Nubian Aquifer groundwater. Four major faults were located using information portrayed in cross section A-A’ (Figure 5), well data, and inferred from remote sensing data as discussed in the previous section. Boundaries of the alluvial sediments that are sub-parallel to the general flow direction (i.e., perpendicular to River Nile) receive minimal groundwater flow from adjacent units and intercepting channels and were considered as no-flow boundaries.

The direct surface water recharge is mainly through transmission loss along the streams length to the underlying alluvial aquifer. The recharge area, the area covered by the ephemeral streams, was identified using morphological and spectral characteristics of these streams that are portrayed in satellite imagery. The outlines of the ephemeral streams appear as spectrally bright areas compared to their surroundings (Figure 5). The longer the travel distance for sediments in a watershed, the finer the grains that are being transported and deposited in the underlying stretch of the channel, and the brighter the spectral reflectance of the deposited sediment on satellite imagery (Sultan et al., 1987). Our field investigations and inspection of Fig. 5 show that to be the case with the deposits outlining the extent of the ephemeral streams in Wady Asuity; they are fine-grained sediments that are spectrally bright. We assumed that recharge of the alluvial aquifers in Wady Asuity could be approximated by the transmission losses arising from infiltration throughout the stream reaches and adopted as recharge rates. The average transmission loss per unit length is approximately 4 x 104 m3/year per kilometer based on the estimated total transmission loss of 2 x 107 m3/year over reaches with a total length of 500 km (Gheith and Sultan 2002) for the Wady Asuity.

Hydraulic conductivity of the alluvium aquifer is heterogeneous over the area. Spatial variations in the hydraulic conductivity of the alluvium aquifer was determined (Fig. 6d) by contouring (Kriging method; contour interval 2m/d) estimates of hydraulic conductivities for 77 production wells (RIGW, 2003).

7.3 Model Calibration

The calibration was accomplished via a four-step process to adjust specific model parameters at each step. In order to estimate sustainable production rate, the calibration was performed for both steady state and transient state. Water levels measured from 19 wells were used for steady-state calibration and two sets of pumping test data were used for transient calibration. The initial two calibrations were under the steady state and third is under transient. The final calibration is a fine tune for steady state again to incorporate changes in parameters due to transient calibration. Most of the calibrations were performed through an automated process to estimate specific model parameters that produce the best possible match to measured water levels. The inverse model, MODFLOW 2000 PES (Hill et al 2000), was used in this automated process. The detailed descriptions for the four step calibration are as follows:

(1) Calibration for conductance of three inflow boundaries and four faults under a steady state. Inflow from three boundaries and four faults were calibrated first as they account for the majority of water flux in the system. All of the seven boundaries were considered as general head boundaries in the model. The head of the inflow were estimated using ground surfaces as upper limits. The initial conductance was estimated based on hydraulic conductivities of the limestone and faults, the geometry of the boundaries, and the approximated depths of Nubian aquifer, The calibration was conducted using inverse modeling through automatic adjustment of (MODFLOW 2000 PES process).

(2) Calibration for recharge rate under a steady state. The recharge rate is the secondary inflow compared to the seven inflows described above. The initial recharge rate was estimated based on 4 x 10^4 m^3/year per kilometer reach applied

to the area where reaches are well developed as identified by remote sensing data. The rate was adjusted by the inverse model through the process. However, the upper and lower limits were set at one order of magnitude from the initial value to keep the rate within the possible range of surface water supply due to transmission loss.

(3) Calibration for aquifer properties under the transient state. Two 24-hr pumping test data were used to calibrate the flow system under transient conditions. The parameters of hydraulic conductivity and storativity were adjusted to fit the drawdown in water level in response to the pumping. The computed drawdown matches well with the observed drawdown from the pumping tests through this curve-fitting process. The results are shown in Figure 7a.

(4) Final tune for calibration of seven inflows at boundaries and faults to adjust any changes in flow system due to adjustment of aquifer properties in step 3.

Figure 7b compares the simulated water levels from the calibrated model through the four processes to the observed water levels and shows a good agreement between them. The major deviations occurred at 1-2 locations where a locally water-level low is inconsistent with the general flow pattern, which indicates that observed water levels at these locations were impacted by effect of pumping at that time. Two quantitative measures of calibration can be used to examine the deviations: the root mean square error (RMS) and mean error. The RMS is low (3.12) and the mean error is close to zero (-0.012). Thus, the deviations are insignificant to model calibration.

7.4 Simulation Results

The groundwater flow system in Wady Asuity simulated by the calibrated flow model is illustrated in Figure 8. The results provide a quantitative estimate for each of the flow components entering the Asuity shallow groundwater system (Table 1). The results indicate that the majority of groundwater sources is coming from the Nubian aquifer through four faults. The Nubian groundwater approximately constitutes 75% of the volume of the Asuity groundwater, whereas the groundwater inflow through three boundaries from the channel alluvium and surrounding fractured limestone is estimated at a maximum of 22%. The groundwater inflow is largely formed from initial loss and transmission loss through drainage network up gradient of the Asuity valley. Direct surface water recharge (transmission loss within the Asuity valley) is limited (about 3%). Thus recharge from surface water estimated by the calibrated model amounts about 25%.

8. POTENTIAL SUSTAINABLE GROUNDWATER PRODUCTION

The potential sustainable groundwater production is an important concept for maintaining a long-term water supply to the area. It highly depends on the capacity of the aquifer and water supply to the flow system. The calibrated model for Asuity alluvium aquifer provides an quantitative tool to estimate the maximum water production without damaging the aquifer capacity.

To determine the potential sustainable production, the model was used to identify (1) the maximum sustainable rate and (2) the minimum well spacing at this rate. An simulation experiment was conducted using the calibrated model. Five pumping wells (P1-P5) were placed to test different locations representing variation of aquifer property (Figure 9). All test wells are located between faults to estimate a minimum sustainable rate. The daily pumping schedule was determined based on the common practice for water production in the area. Based on the water level records (RIGW 2003), the daily pumping usually occurs from morning to early afternoon for less than eight hours. The rates were selected at each location through multiple trials in order to keep water level in aquifer fully recoverable. Figure 10 shows the result at P1 as an example, indicating that sustainable rate for 8 hours daily is 40 m^3/hr and the radius of significant influence at this rate is about 500m, which provides an estimate for well spacing. The production at the other pumping location has lower rates and greater radius of influence. In general, in the area of P! and P2, the daily production is 320 m^3 (40 m^3/hr times 8 hours) and well spacing is less than 1000 m, while in the area surrounding P3, P4, and P5, the daily production is about 160 m^3 and well spacing is greater than 1000 m.

Based on the simulated results, only a few production wells can be placed in the up gradient area around P3, P4, and P5. The annual sustainable production is only about 5000 m3/km2. The down gradient area surrounding P1 and P2 is the major production area for Asuyti. The estimated sustainable annual production is approximately 3.7 x 104 m3/km2. The well spacing is mostly less than 1000 m. The minimum total sustainable annual production is 7 x 106 m3 for the entire Asuyti alluvium aquifer.

Table 1: Estimation of Annual Flow Rates Entering the Asuity Shallow Groundwater System

Flow Component	Annual Flux (m^3/year)	Percentage
Recharge from channel alluvium and surrounding fractured limestone (General Head Boundaries)	9.36×10^6	22%
Recharge from surface water runoff	1.47×10^6	3%
Recharge from Nubian Aquifer via faults	3.19×10^7	75%

9. References

Gheith, H., and Sultan, M., 2002, Construction of a hydrology model for estimating Wady runoff and groundwater recharge in the Eastern Desert, Egypt, *Journal of Hydrology*, v. 263, pp. 36-55.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000. MODFLOW-2000, the USGS Modular Ground-water Model—User Guide to the Observation, Sensitivity, and Parameter-estimation processes and three post-processing programs, USGS Open-File Report 00-184 , Denver, Colorado.

IN-WARDAM, 1990, Water assessment for Arab League countries, No 10: Amman, Jordan, Islamic Network on water resources development and management.

RIGW, 1993, Hydro geological map of Egypt, Asuit map, scale 1: 100,000

RIGW, 2003. Review of the Groundwater Studies in the Eastern Desert, Technical Report, Task 12b. Research Institute for Groundwater, Ministry of Water Resources and Irrigation, Cairo, Egypt.

Said, R., 1993, The River Nile, geology, hydrology, and utilization, Pergamon Press, New York, USA

Soliman, M., LaMoreaux, P., Assaad, F., Memon, B., and LaMoreaux, J., 1998, The Nubian sandstone aquifer, *in* Soliman, M., LaMoreaux, P., Assaad, F., Memon, B., and LaMoreaux, J., eds., Environmental hydrogeology: New York, Lewis Publishers.

Sultan, M., Arvidson, R.E., Sturchio, N.C., and Guinness, E., 1987, Lithologic mapping in arid regions with Landsat Thematic Mapper data: Meatiq Dome, Egypt, *Geologic Society of America Bulletin*, v. 99, pp. 748-762.

Thorweihe, U., 1990, Nubian Aquifer System, *in* Said, R., ed., Geology of Egypt: Rotterdam, Balkema.

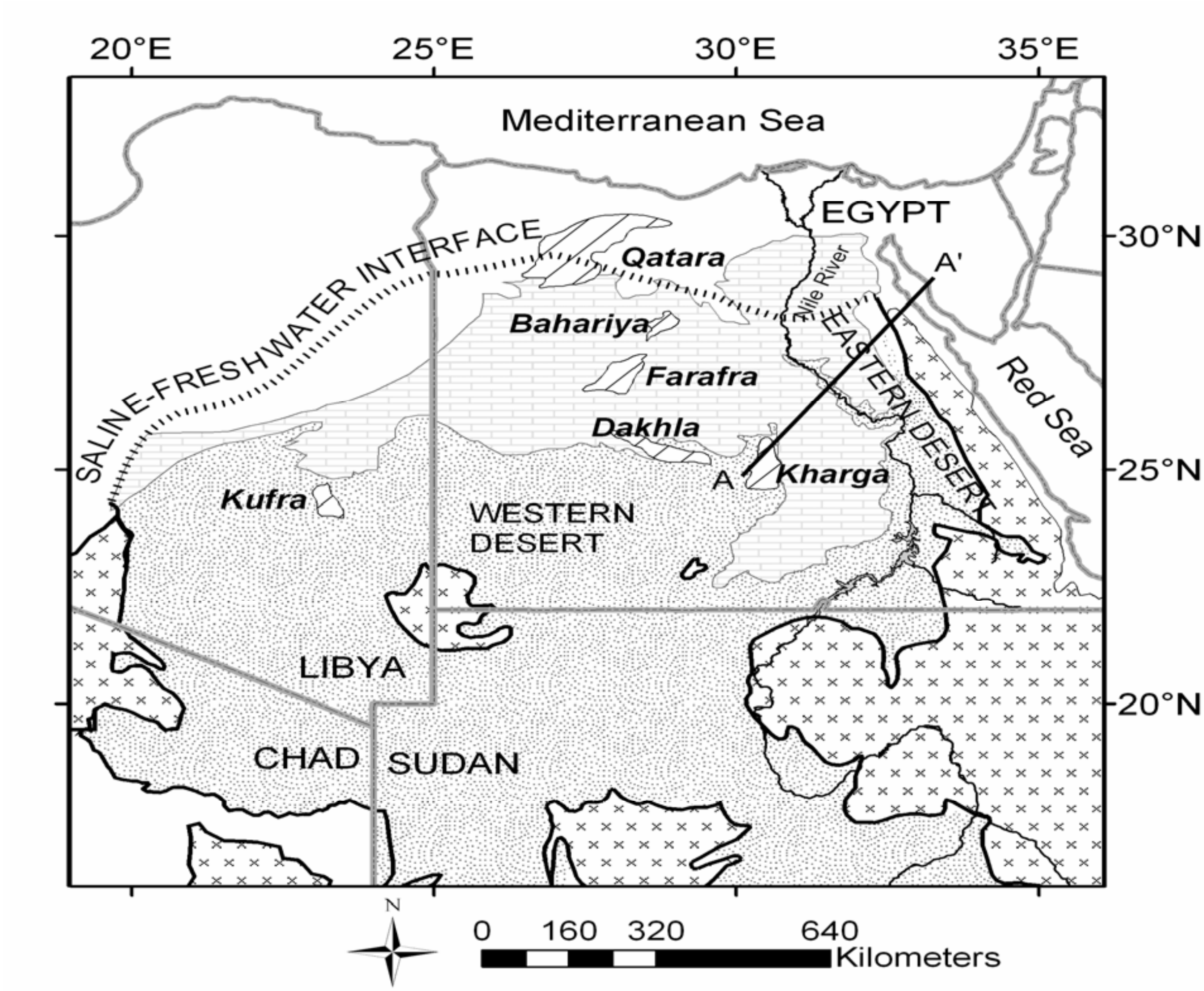


Fig. 1: Location of the Nubian Aquifer and distribution of Eocene limestone (grey), Nubian sandstone (yellow), and crystalline bedrock outcrops (x symbol)

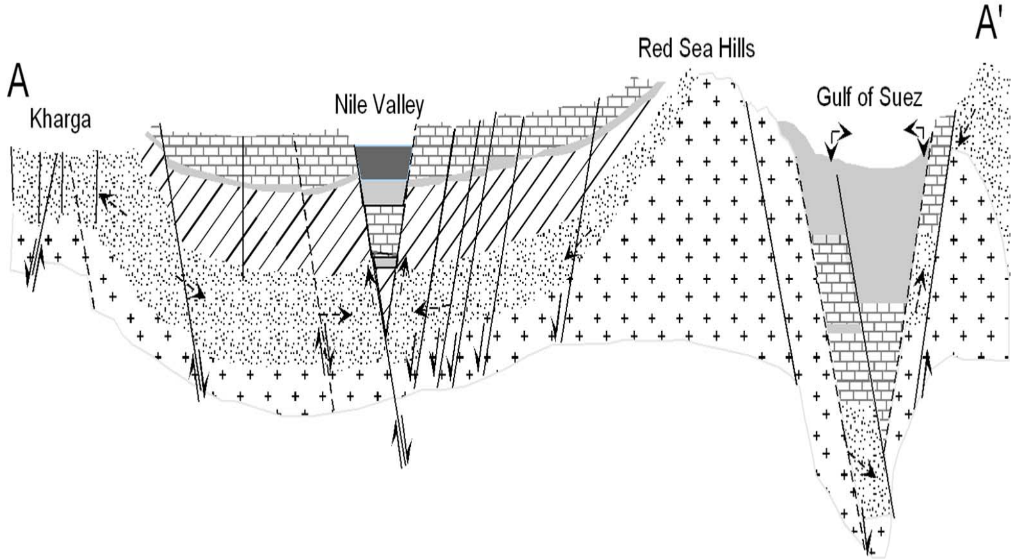


Fig. 2: **E-W-Trending Cross Section Showing the Nile and Gulf of Suez Grabens. The Grabens are Defined by High Angle Deep-Seated Fault Systems. The Basement is Overlain (Pink) by Nubian Sandstone (yellow), followed by Eocene limestone (Green) and shale (brown) (RIGW, 1994).**

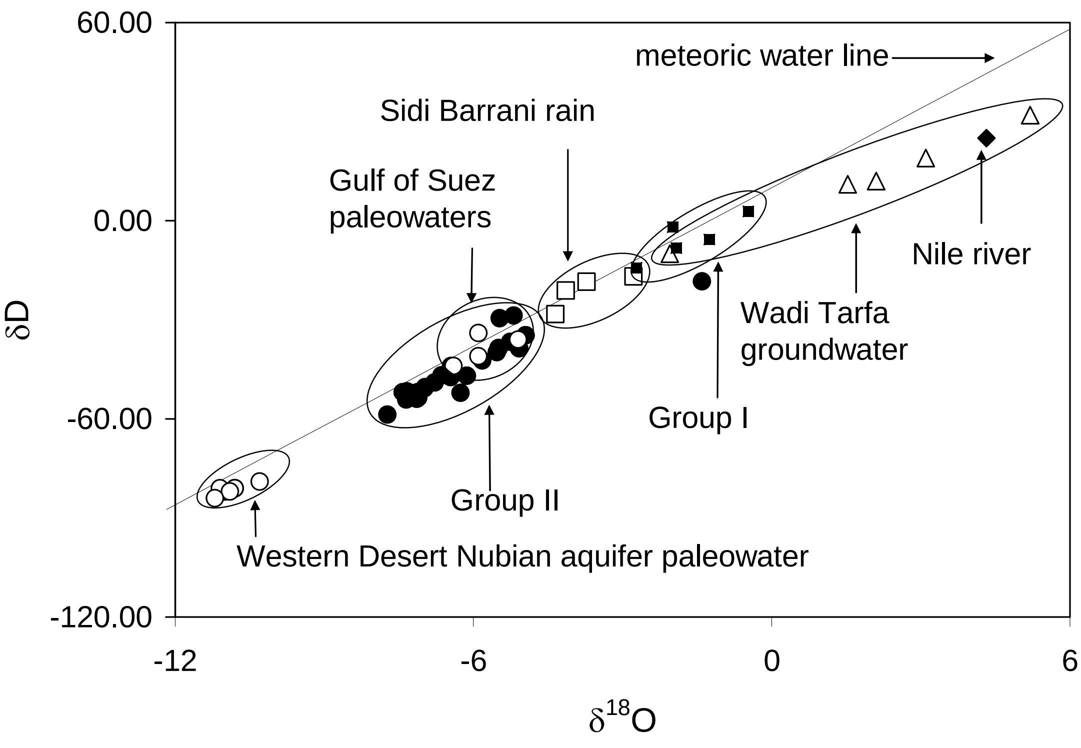


Fig. 3: **Comparison Between Stable Isotope Ratios [Hydrogen (δD) vs. Oxygen ($\delta^{18}O$)] for Groundwater Samples**

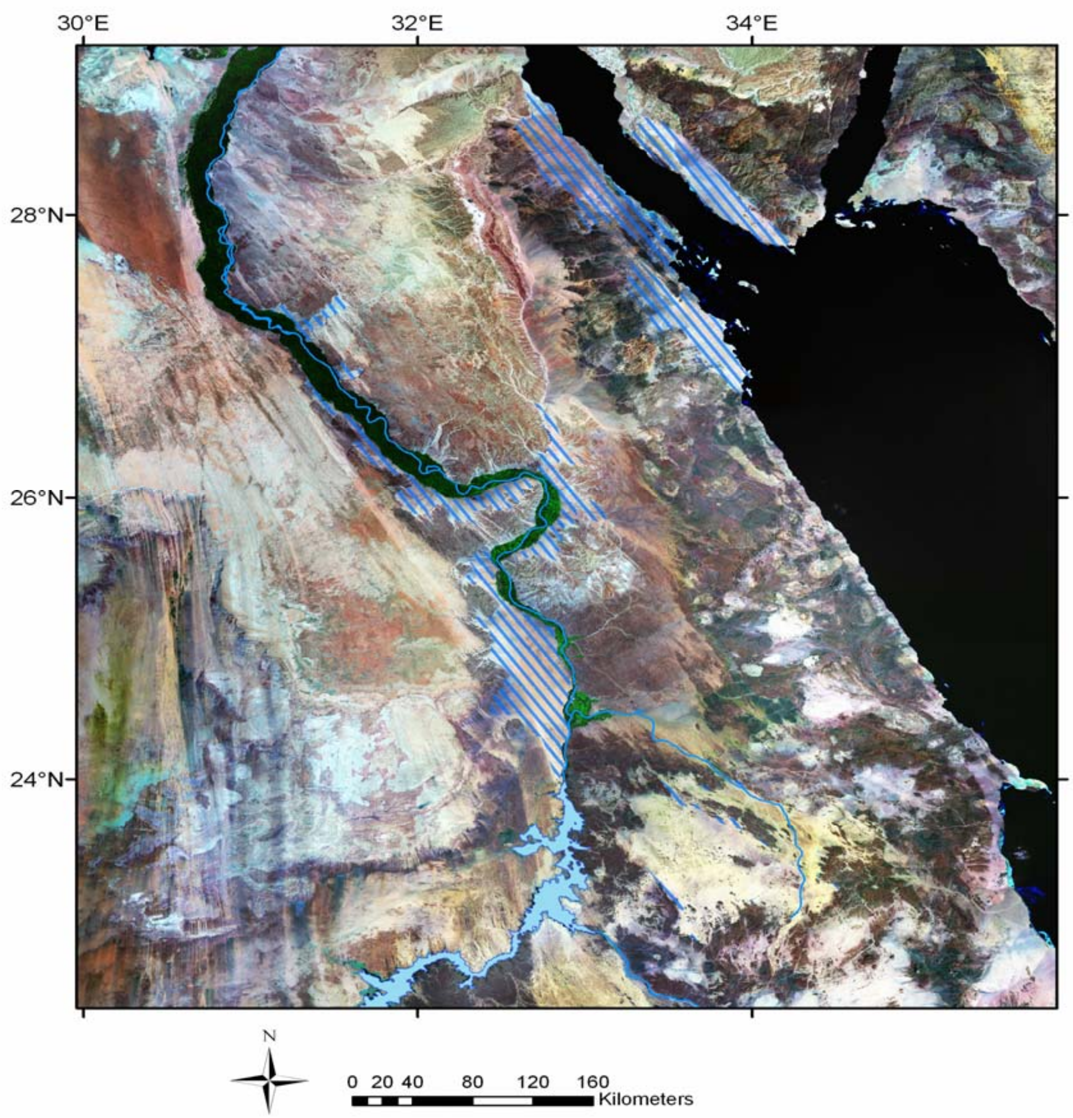


Fig. 4: **Landsat TM Image Showing the Red Sea Hills (Outlined by Dashed Line) Inferred Distribution of Alluvial Aquifers (Outlined by Solid Line) that are Likely to be Recharged by Ascending Nubian Aquifer Groundwater.**

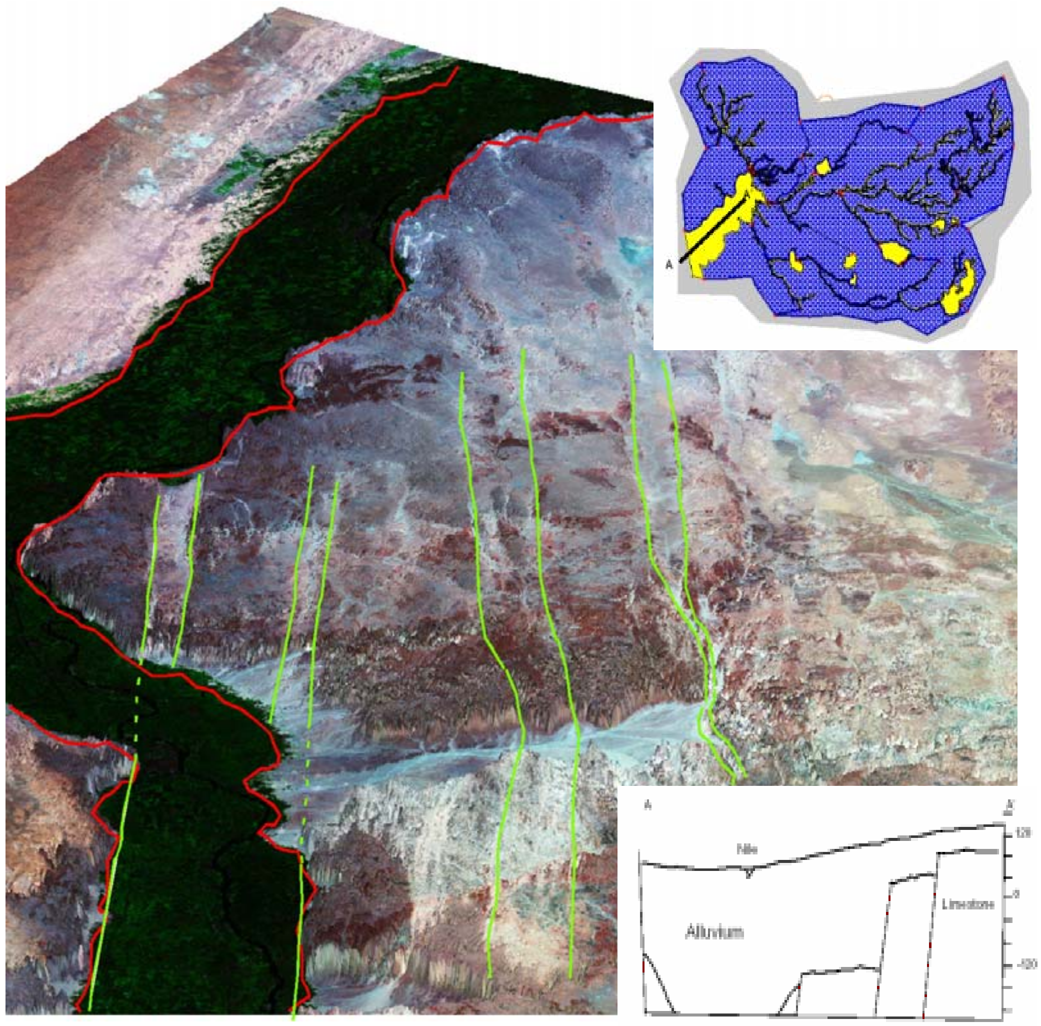


Fig. 5: **Landsat TM Image Band 4 for the Wady Asuity Area and Surroundings Drapped on Digital Topography. Upper Right Inset: Asuity Watershed with Network of Channels Flowing from Red Sea Hill Towards the Nile River Valley; Main Rock Units are Quaternary Alluvial Deposits (yellow) and Tertiary Limestone. Lower Right Inset: Cross Section Along Traverse A-A' (simplified from RIGW, (1993).**

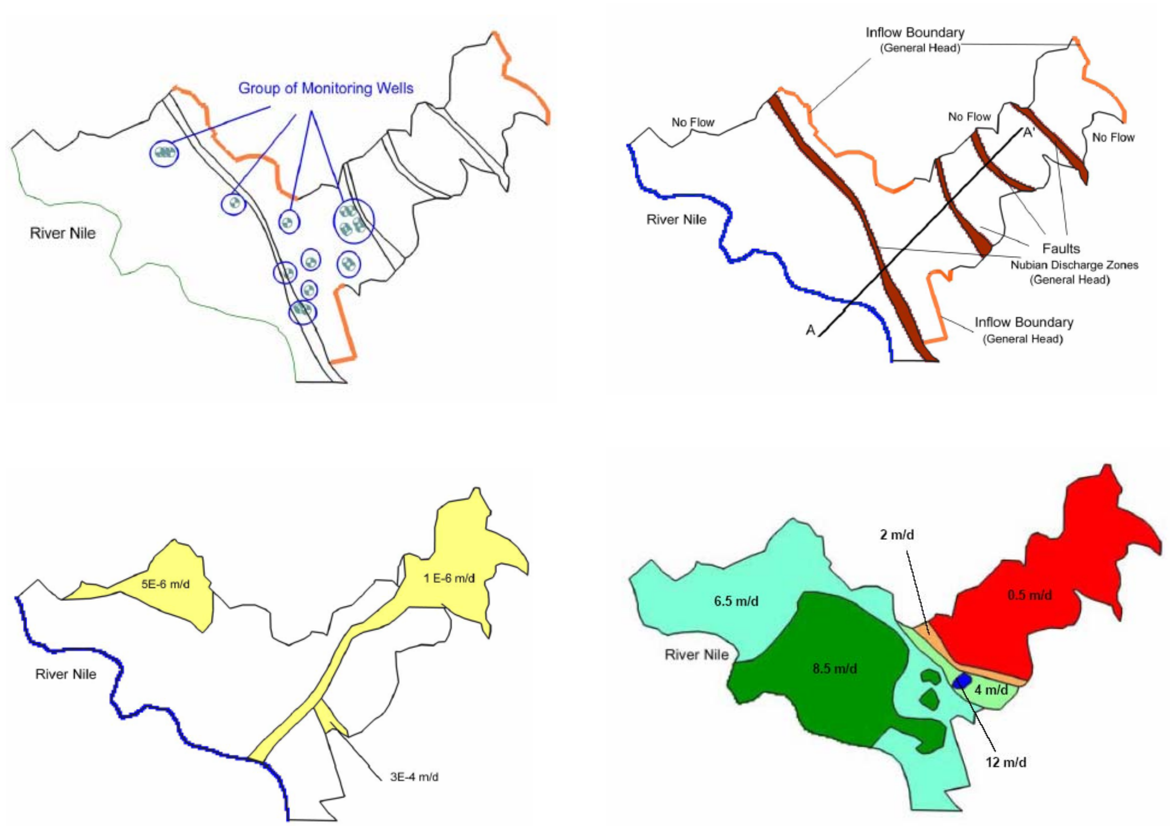


Fig. 6: **Sketch Map Showing Elements of the Constructed Groundwater Flow Model: (a) Upper Left: Distribution of All Groups of Wells That Are Used in Wady Asuity for Steady-State Calibration, (b) Upper Right: Model Boundaries and External Stress Through Faults, (c) Lower Left: Postulated Recharge Areas, and (d) Lower Right: Spatial Variations in Hydraulic Conductivities.**

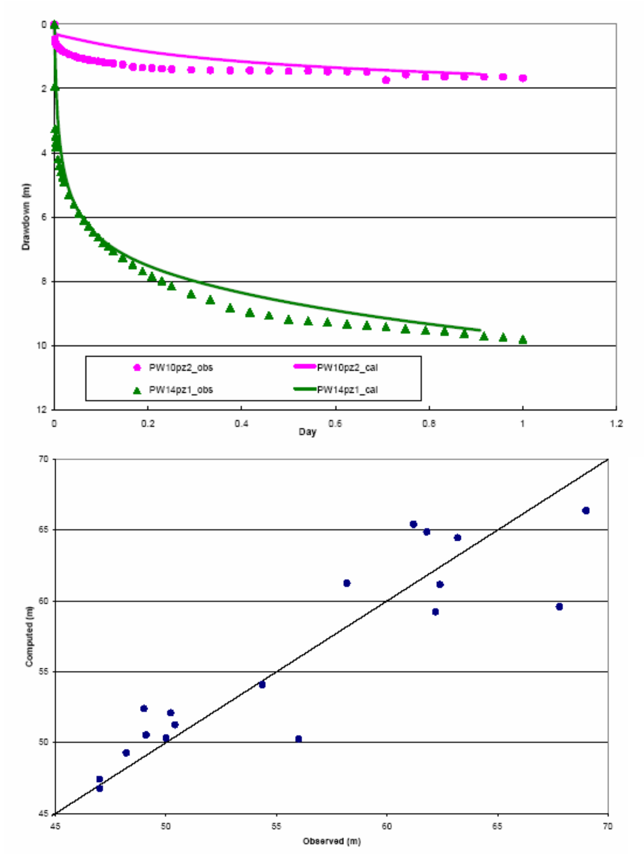


Fig. 7: **(a) Top: Results of Transient Calibration, (b) Bottom: Results of Steady-State Calibration**

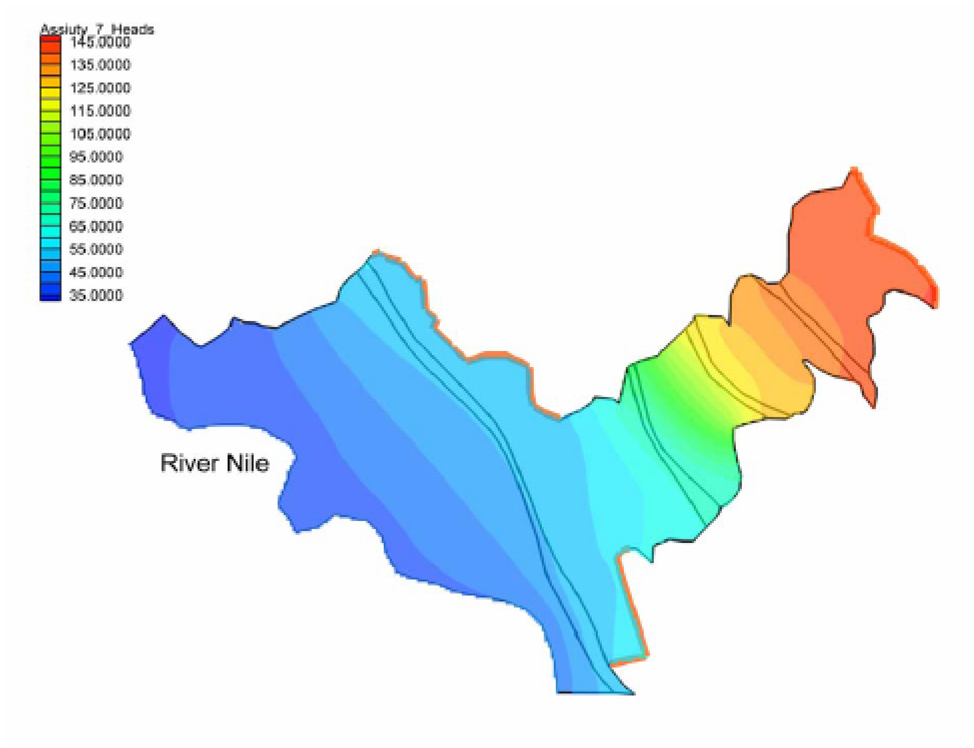


Fig. 8: **Simulated Water Level in Asuity Alluvium Aquifer Based on the Calibrated Model**

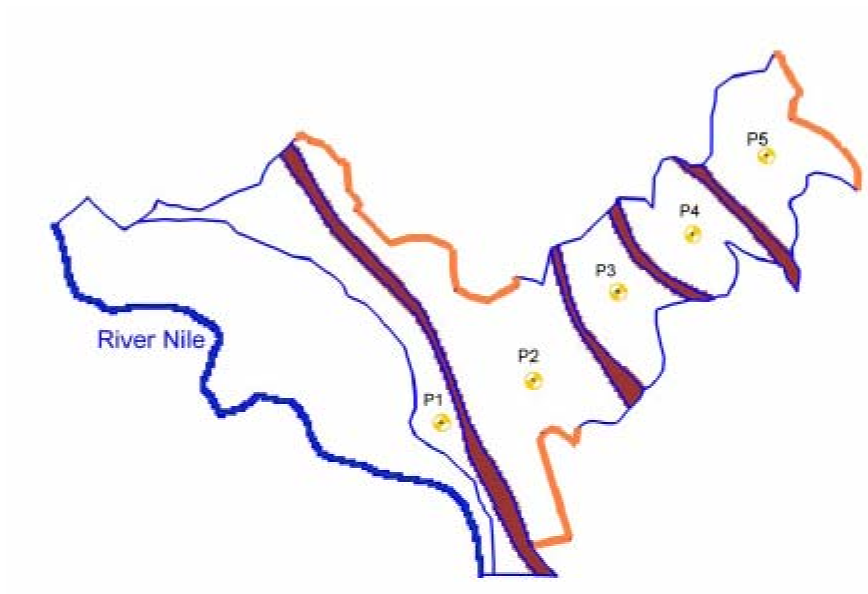


Fig. 9: **Locations of Production Wells for Pumping Experiment**.

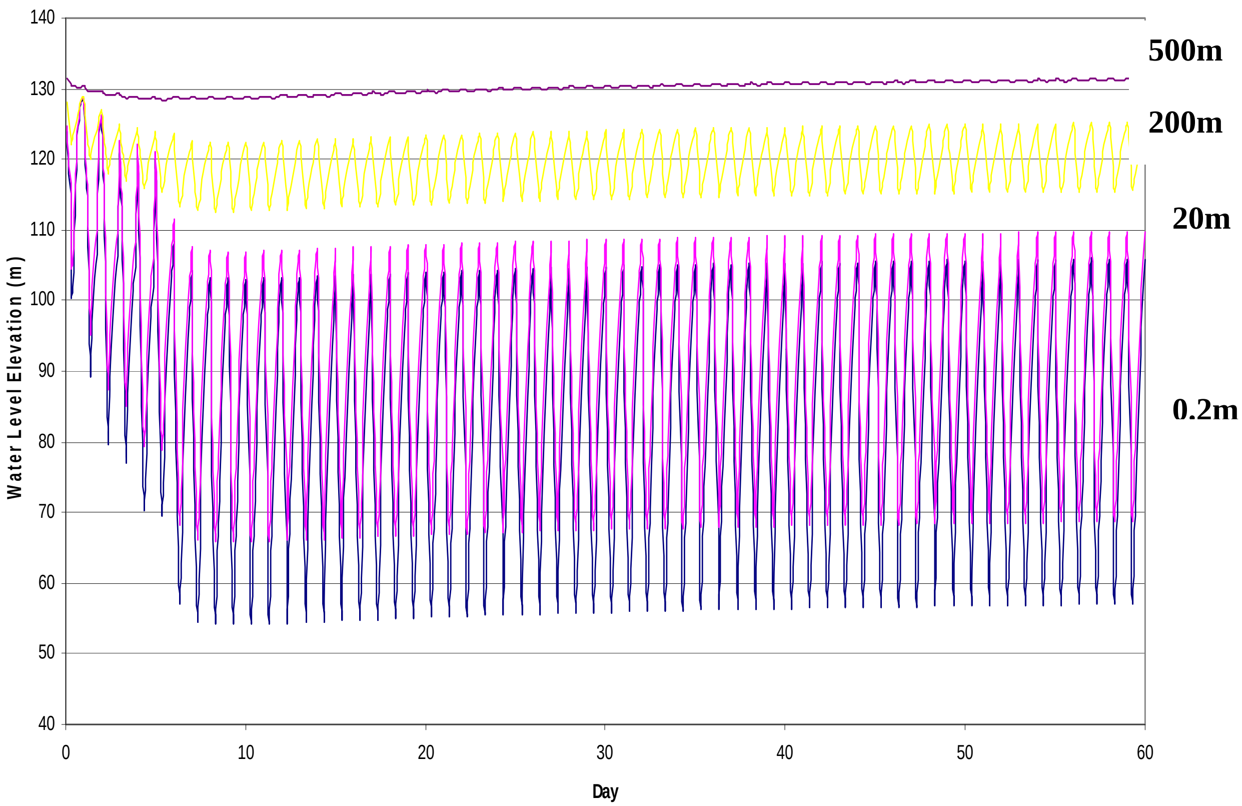


Fig. 10: **Drawdown at Various Observation Points, 0.2m, 20m, 200m, and 500 m from the Pumping Well in Response to Pumping at 40 m^3/hr for 8 Hours per Day.**