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SPECIAL ISSUE

GIS-based subsurface databases and 3-D geological modeling as a tool for the set up of hydrogeological framework: Nabeul–Hammamet coastal aquifer case study (Northeast Tunisia)

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Abstract The subsurface data are a basic requirement for the set up of hydrogeological framework. Geographic information systems (GIS) tools have proved their usefulness in hydrogeology over the years which allow for management, synthesis, and analysis of a great variety of subsurface data. However, standard multi-layered systems are quite limited for modeling, visualizing, and editing subsurface data and geologic objects and their attributes. This paper presents a methodology to support the implementation of hydrogeological framework of the multi-layered aquifer system in Nabeul–Hammamet (NH) coastal region (NE, Tunisia). The methodology consists of (1) the development of a complete and generally accepted hydrogeological classification system for NH aquifer system (2) the development of relational databases and subsequent GIS-based on geological, geophysical and hydrogeological data, and (3) the development of meaningful three-dimensional geological and aquifer models, using GIS subsurface software, RockWorks 2002. The generated 3-D geological models define the lithostratigraphy and the geometry of each depositional formation of the region and delineate major aquifers and aquitards. Where results of the lithologic model revealed that there is a wide range of hydraulic conductivities in the modeled area, which vary spatially and control the groundwater flow regime. As well, 17 texturally distinct stratigraphic units were identified and visualized in the stratigraphic model, while the developed aquifer model indicates that the NH aquifer system is composed of multi-reservoir aquifers subdivided in aquifers units and separated by sandy clay aquitards. Finally, this study provides information on the storing, management and modeling of subsurface spatial database. GIS has become a useful tool for hydrogeological conceptualization and groundwater management purposes and will provide necessary input databases within different groundwater numerical models.

Keywords GIS · RockWorks · 3-D geological models · Multi-layered aquifer system · Nabeul–Hammamet · Tunisia

Introduction

Hydrogeological problems require representation of the subsurface depth dimension in addition to the areal extent of topographical and geological features and linkages to various hydrological and geological data manipulation procedures (Kolm 1996; Turner 1991). Surface and subsurface hydrological and geological features play an important role in groundwater replenishment. The access to surface data such as landforms, drainage density, and water bodies is easier than the subsurface data. Subsurface data characterization such as lithology, geological structure, weathered/fractured thickness, and stratigraphy, relying on

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geologic framework, is difficult due to the variability of geologic environments and the sparseness of geologic data. In addition, a variety of data types must be combined or synthesized.

Through conventional methods alone it is not an easy task to study all the surface and subsurface parameters of a large area and to identify a satisfactory hydrogeological framework. Since many controlling parameters must be independently derived and integrated, this involves additional cost, time, and manpower. Consequently, a centralized database capable of manipulation and analysis of a great variety of data is required such as geographic information systems (GIS) techniques. These technologies have many advantages over older conventional methods, due to their facility of integration and analysis of large volumes of data and have proved to be useful for studying geological, structural, and geomorphologic, hydrodynamic conditions together with conventional surveys. Each of these steps can be accomplished utilizing a GIS for (1) data management, analysis, and visualization (2) integration of diverse data sources, and (3) rapid development, visualization, and testing of alternative hypotheses.

The integration of GIS has proven to be an efficient tool in groundwater studies (Krishnamurthy et al. 1996; Saraf and Choudhury 1998). GIS allows the hydrogeologist to interact with the database in ways that retain the spatial relationships in order to visualize the subsurface in two or three dimensions (Kolm 1996; Turner 1989). The development of 3-D spatial models is the result of surface and subsurface characterization and field conceptualization. Surface and subsurface characterization is accomplished using careful data gathering and preparation techniques.

GIS tools have proved their usefulness in hydrogeology over the years but standard multi-layered systems are quite limited for modeling, visualizing and editing subsurface data, and geologic objects and their attributes.

Hence, the main purposes of this paper are to present and define

- the hydrogeological framework and 3-D geological modeling of a multi-layered aquifer system based on GIS approach; and
- the procedure whereby subsurface GIS software RockWorks 2002 is used to facilitate geological and hydrogeological conceptualization and characterization, which will be used thereafter in the development of groundwater flow models.

With the aim to achieve these objectives, it was decided to opt for a study area that has a multi-layered aquifer system, actually problems with groundwater availability, and requiring a suitable plan of action for groundwater development.

The Nabeul–Hammamet (NH) area is chosen for the study (Fig. 1) and is located in Northeastern Tunisia, in the Eastern part of the Cap Bon peninsula. The local coordinates are between 4020,000–4050,000 N and 627,000–663,000 E in Universal Transverse Mercator (UTM) and lie in Zone 32 North, 6° East. It encompasses an area of around 330 km^2, 27 km in length and from approximately 6–18 km in width, and bordered by the Mediterranean Sea in the South. The geology of this area is complex, and well data range from sparse to very concentrated, which makes it difficult to establish a general view of the main geological features and consequently the hydrogeology framework of the aquifer system.

In addition, the NH region is heavily populated and is considered an interesting area for its tourist attractions as well as its significant urban, agricultural, and industrial activities.

The unconfined aquifer represents the only way to overcome the water scarcity during dry years. Fast population growth and expanding touristic, agricultural, and industrial areas have resulted in a rapid increase in water demand from the shallow aquifer. The long-term withdrawals have engendered several deleterious problems such as water-level decline, salinization by seawater intrusion, and pollution of groundwater resources (Trabelsi et al. 2006, 2011).

Groundwater management planning is not already set up for this area, and the decisions are pending by various local and state agencies. In response to a new management policy of water resources, it is necessary to exploit the underground water reserves to fulfill this need. The estimation of the new potential groundwater exploitation requires a good knowledge of the reservoir geometry and the relation between the different units' aquifers of this multi-layered aquifer system. Hence, the development of GIS-based subsurface databases and geological models is necessary in this area.

The specific objectives include

- the development of a complete and generally accepted hydrogeological classification system for NH aquifer system,
- the development of geological and hydrogeologic relational database management system (RDBMS) and subsequent GIS of the NH aquifer system, and
- the production of hydrogeological cross sections and 3-D meaningful geological models (stratigraphic and lithologic models) to identify, visualize and analyze geological subsurface units and their geometric form, and the spatial extension of each hydrogeological classified unit of aquifer system.

This work will be proven for predicting the response of the groundwater aquifer system under the proposed future

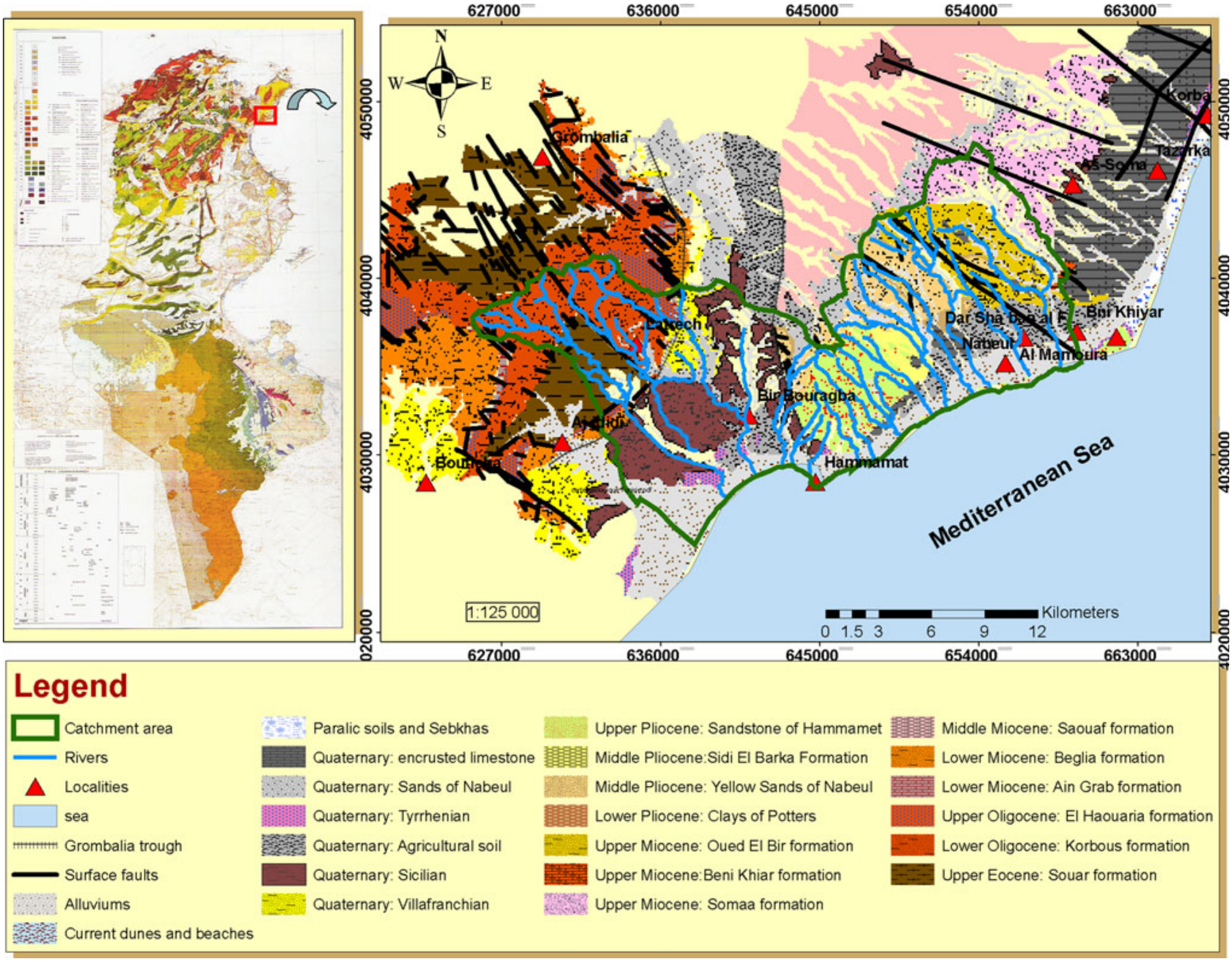


Fig. 1 Location map showing regional geology of the study area

management scenarios and helping formulate a good management strategy.

Geological setting

The NH area has a very complex geological structure caused by polydirectional fractures and a highly varied lithological cover. The oldest outcrops are allotted to the lower Eocene; the most recent are allotted to the old and recent Quaternary (Ben Salem 1992). The study area shows four main landscapes separated by an expressed scarp (Fig. 1):

- The Quaternary marine platforms are located in the south. The coastal consolidated dunes are formed within the old cover from Tyrrhenian deposits (Ozer et al. 1980). The encrusted limestone extends over long distances. The Holocene deposits are formed by recent alluvia of rivers, current dunes, and beaches.
- Toward the northeast, elevated mountains make up a monocline structure (Ben Salem 1992) and consist of Mio-Pliocene sequences showing essentially three formations from upper to middle Miocene (sands of Somaâ, limestones of Béni Khiar, and sands and clays of Oued el Bir) and four Pliocene formations (Potter clays, sand of Nabeul, Sidi Barka clays, and sandstone of Hammamet) (Colleuil 1976).
- Throughout the middle part is a NW–SE structure that corresponds to the Grombalia trough covered by Quaternary continental sediments (Castany 1948), giving the area a synclinal shape bordered by major faults towards the northeast (Ben Ayed 1993; Chihi 1995; Turki 1985). The Hammamet fault observed over a 5-km length in the subsurface which forms a major deep poly phased strike-slip fault represented by a flower structure (Ben Ayed 1993; Ben Salem 1992; Chihi 1995; Colleuil 1976; Hadj Sassi 2006).
- In the western part there exist two main structures: the anticline of Sidi Jedidi and the syncline of Borj

Slouguia where outcropping the Villafranchian Quaternary, Lower Miocene (Ain Grab and Mahmoud formations), Oligocene (Fortuna formation: Oued El Hmmam, El Hawaria and Korbous members), and Eocene (Souar and Bou Dabbous formations) deposits.

Hydrogeological setting

Hydrogeological study of the NH region shows five aquifers available for exploitation: the Quaternary, the Pliocene, the Miocene, the Oligocene, and the Eocene. These aquifers form a semi-confined multilayer system, showing several lithologies: sand, sandstone, limestone, and sandy clay interconnecting by leaky-confining aquitards.

In 1980, the annual abstraction was 7.5 million cubic meters (1,243 pumping wells) and increased to 20 million cubic meters (2,920 pumping wells) in 2005. These aquifers have mostly been threatened by use of groundwater. In some cases, the pumping rate can reach 175% (Kallali et al. 2007).

Several measures were taken to face this threat such as prohibiting the construction of new wells (the region has been declared a protected area since 1941), developing alternative sources of freshwater, building dams and water by-passes from the north of the country, distributing efficient irrigation systems, and reusing treated waste water for artificial recharge of the aquifer (e.g., Oued Souhil plant).

Groundwater is being recharged in the Nabeul–Hammamet area through five sources: rainfall water infiltrates at about 11.18 Mm^3/year (DWR 2005); surface water from major watersheds seeps in at approximately 1.17 Mm^3/year (DWR 2005); excess surface irrigation water infiltrates the region and leaks downward from the northern water adduction through the Medjerda open channel; treated waste water is reused to increase groundwater level; groundwater from inter-aquifer flow.

Groundwater is discharged through four processes: outflow into the drainage system, direct abstraction, evapotranspiration, and inter-aquifer flow of groundwater. The main discharge components of the aquifer are from groundwater returning flow to the rivers and drains and extraction by wells.

Methodology

The main purpose of this study was to develop a geological and hydrogeological relational database management system (RDBMS) and GIS of NH coastal aquifer system useful for geologic and aquifer modeling.

To carry out the goals of this work, RockWorks 2002, version of RockWare's integrated software package, was used on a PC with a Windows XP (Microsoft) platform. This tool works with spatial data from the surface and subsurface, offers easy-to-use tools for modeling and is mainly developed for applications in the petroleum industry, although it is being increasingly used in the geosciences.

In this paper, RockWorks software was used for geological and hydrogeological data management, analysis, and visualization, including drill hole logs, lithostratigraphic profiles, and cross-sections. It provides several methods of gridding and interpolation of well log data to build 3-D spatial models.

The 3-D models generated will be exported for further use in the groundwater modeling system and will propose at which site investigation should be done to test a pre-existing spatial model based on actual data rather than a conceptual model.

Before building the RDBMS and GIS, it is required to develop an accepted hydrogeological classification for NH aquifer system. This is the base of the development of hydrogeological cross sections and 3-D geological models of the area.

Traditionally, chronostratigraphical classification is used to delineate geological formations, but for hydrogeological purposes the Local Groundwater Management Authority of the governorate of Nabeul (CRDA Nabeul) and the General Direction of Water Resources (DGRE) in Tunisia developed their own classification system. However, this hydrogeological classification is incomplete as it was developed only for specific objectives.

Due to the lack of a complete and widely accepted hydrogeological classification for NH aquifer system, a new hydrogeological classification is projected in this study. To achieve this purpose, the interpretation of various boreholes, geophysical, and geological data are required prior to being entered in RockWorks databases.

Data acquisition

The important data are collected from a variety of sources including the Local Groundwater Management Authority (CRDA Nabeul), the Tunisian National Oil Company (ETAP), and data of field surveys such as data from geophysical campaigns carried out in the study area.

Borehole data

Spreadsheets of digital borehole data from more than 180 water monitoring wells and boreholes, and 26 oil wells were used. Borehole locations were determined either from borehole records or construction reports. In several instances, borehole coordinates were verified on a georeferenced digital topographic map of the NH area (seven maps at scale 1:25,000 georeferenced with UTM projection, Zone 32 North, 6° toward the East, datum: Carthage Tunisia) or were manually checked in the field with GPS (Global Positioning System) receptors, and were also plotted on a georectified air photo of the study area. Borehole databases contain coded information regarding depth, water strike level and yield, groundwater levels measured on a network of monitoring wells, and sediment texture and elevation of changes in textural characteristics recorded by the well drill.

Cartographic data

Digital information from altimetry or aerial ortho-photographs was used not only to characterize the relief and land use of the area but also to identify the main geological and morphological structures and streamlines. Also, four georeferenced geological maps at scale 1/50,000 (with UTM projection, Zone 32 North, 6° toward the east, datum: Carthage Tunisia) were used (Johan and Krivy 1969; Bujalka et al. 1971; Ben Salem 1991; Colleuil and Ben Salem 1991). These digital maps supply regional information concerning the geology of the study area. However, to validate this information or obtain more detailed geological mapping it may also be necessary to use data of site observation.

Geophysical data

The geology of this area is complex, and well geological data range from sparse to very concentrated. The geophysical data proved to be helpful to establish a general view of the main geological features of the NH aquifer system.

Boreholes wire line logging (Resistivity, GR, SP) of water boreholes and oil wells are routinely recorded during drilling and provided useful geological information. Using the DIGIDATA extension, logging curves were digitalized in the appropriate scale and then reconstructed using the LOGPLOT extension for lithostratigraphic interpretation.

In addition, other geophysical data were used to support the borehole log interpretation. These data correspond to apparent resistivity values obtained from time domain electromagnetic (TDEM) survey carried out in the study area (Trabelsi et al. 2006).

The penetration depth of these geophysical surveys is up to 150 m, which is significantly deeper than most boreholes. Where boreholes are not sufficiently deep, geophysical data are applied. Geophysical data inform on the position of saturated areas of reservoir layer and determine the depth of bedrock and groundwater level.

For instance, TDEM soundings were conducted at existing drilled boreholes wherever possible, or at a maximum distance of 1 km from the wells, making it possible to correlate apparent resistivity logs with borehole wireline logging (SP, GR, and Resistivity). This comparison defined the position of saturated areas within individual aquifers (Trabelsi et al. 2006).

Note that special care should be taken in interpreting geophysical data in which contrast in resistivity is not very distinct. In fact, intervals overlap and the signals may be distorted by electrical installations in the field. In the series of interbedded layers, it is difficult to identify precisely the transition between sediment types and water content of the soil. Consequently, geophysical data alone are often not adequate to establish a hydrstratigraphic classification and furthermore the geological models. However, techniques have been developed so that geophysical surveys cover large areas and geophysical data may be an important source of information in areas with scarce borehole data. Borehole data are treated as the primary source of information and geophysical data serve as 'background' information.

Geological data

To support geophysical interpretation, geological records from engineering, oil and hydrogeological reports were also examined and data describing sediment texture and their depth were used and will be entered into the database.

Hydrogeological classification

One of the initial steps in the set up of hydrogeological classification is identifying appropriate lithologic units and consequently stratigraphic units.

However, a major focus of this study was on the identification and delineation of coarse- and fine-grained lithologic units as textural characteristics provide considerable information regarding depositional conditions and are a primary control on fluid transmissivity and aquifer potential.

Stratigraphic units consist of one or more lithologic units that are closely associated in vertical succession, have similar textural characteristics, and were probably deposited under similar environmental conditions. Analysis of the vertical stacking of sediment types is important for hydrostratigraphic work.

However, sedimentary successions of the NH area were taken by interpreting and combining several data with classical geophysical and geological rules.

Thus, the interpretation of borehole wireline logging (Resistivity, GR, and SP) and apparent resistivity logs of

TDEM survey, calibrated for detailed geological information and, complementing data collected from geological maps and field observation gives new lithostratigraphic descriptions and provides information of the depth to bedrock and the groundwater level for each unit aquifer. An example of this interpretation was given in the Fig. 2.

The interpretation suggests the presence of two Pliocene reservoir aquifers (R1-P) and (R2-P), separated by clayey substratum (S):

- The interval of depth between 11 and 32 m: is formed by sedimentary series of clay, sand, and shale.
- The first reservoir layer (32–107 m of depth) is formed by sandy and sandstones series interbedded by clay which is corresponding to 'sand and sandstones of Hammamet formation' (Upper Pliocene). The decline in TDEM curve is recorded at 32 m of depth subsequent to water level (WL). Thus, these coarse- and fine-grained lithologic units form the confined deep aquifer.
- The interval of depth between 107 and 124 m is formed by clay layers of the stratigraphic formation 'Clays of Sidi El Barka' (Middle Pliocene). Hence, these series constitute the substratum of the first Pliocene aquifer.
- The second reservoir layer (124–140 m) is formed by alternation of sand layers with argillaceous intercalation and allocated to 'Yellow sands of Nabeul formation' (Lower Pliocene). These layers form the second Pliocene confined aquifer.

Generally, in this classification different chronostratigraphical strata with same era and quasi-similar hydrogeological properties are joined into one hydrogeological reservoir. Each reservoir of this classification is subdivided on aquifer units and separated by aquitards. For instance, alternating clayey and sandy depositions of the same era with quasi-similar conductivities and water storage capacities are classified as one hydrogeological reservoir and subdivided into several hydrogeological units.

On the other hand, sand layers deposited in consecutive time periods with different conductivities and water storage capacities and separated by clay layers are classified as different hydrogeological reservoirs.

Although this classification is stratigraphically based, the reservoirs are ordered chronologically, e.g., RQ is assigned to quaternary hydrogeological reservoir, which groups several local, more or less unconnected depositions of quaternary age, and other units are spatially continuous.

Finally, a new hydrogeological classification or hydrostratigraphical chart of NH aquifer system is set up (Fig. 3) in the framework of the development of the geological models and is intended to be used for the delineation and management of groundwater bodies.

These new lithostratigraphic descriptions are classified into an Excel spreadsheet and then reformatted for entry into RockWorks software package for models developing. The steps adopted in this work are detailed in the chart in Fig. 4.

Modeling tool

Hydrogeologic cross sections

Prior to the construction of the model surfaces, one of the most challenging aspects of the modeling task was to adequately correlate borehole attributes to a given stratigraphic units.

It was necessary to examine many cross sections of the study area to ensure that correct and consistent hydrostratigraphic classification was applied to the data to identify the spatial extension of aquifer units and to determine the elevation of the top and base of the substratum.

In NH basin, sedimentary units are frequently thin and discontinuous and similar facies can be found in different unconnected units. Therefore, assigning a lithology to a specific unit automatically by querying a database will provide results of limited use or validity.

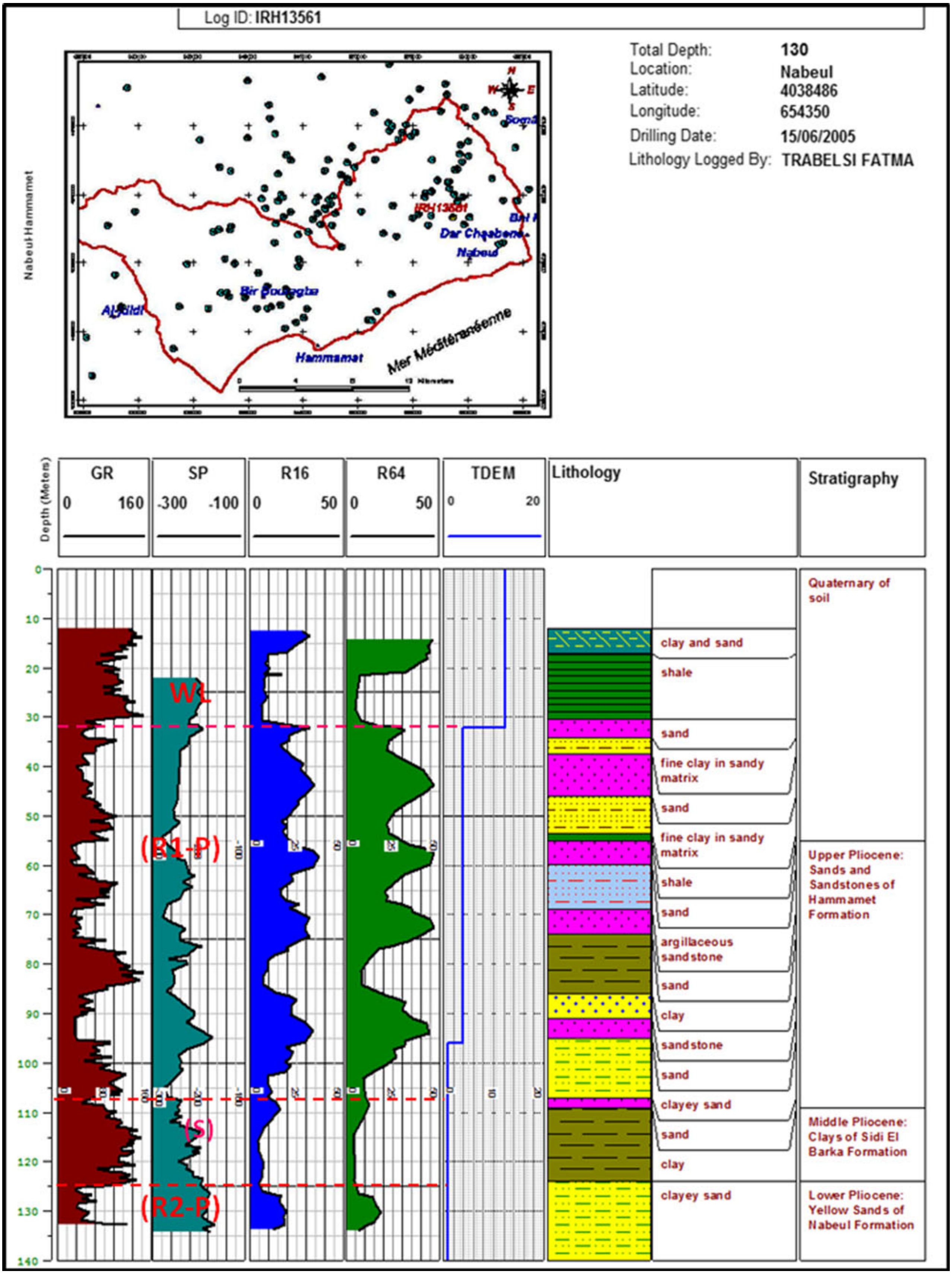
As the known composite stratigraphic sequence is usually incomplete at most sites, correlations must be made carefully. However, it was decided to build 2-D geologic cross sections in the georeferenced environment.

The RockWorks Borehole Manager tool was used to interpolate grid models for the upper and lower surfaces of each stratigraphic unit and to display these units on multiple 2-D cross section panels. The sections are drawn along any path through the study area. Correlations were made between reliable data through expert knowledge (e.g., facies models and relationships, geologic rules).

More than 40 hydrostratigraphic cross sections were established by the correlation between resulted lithostratigraphic columns of boreholes where the depth of bedrock and level of groundwater for each unit aquifer are marked (Fig. 5). These cross sections were built this way to show the structure and the geometry of each depositional formation and consequently of aquifers and aquitards and to form the basis of the 3-D geological framework.

Three-dimensional geological modeling

As mentioned earlier, an important objective of this work was to provide a common framework capable of accommodating several specific needs. In regional hydrogeology, these needs vary from detailed visualization and analysis of geologic objects, stratigraphic cross sections, and a suite of



Log ID: IRH13561

Total Depth: 130
Location: Nabeul
Latitude: 4038486
Longitude: 654350
Drilling Date: 15/06/2005
Lithology Logged By: TRABELSI FATMA

Fig. 2 Correlation between borehole wire line logging and TDEM resistivity log showing the lithostratigraphic interpretation

Fig. 3 Hydrostratigraphical chart of Nabeul–Hammamet aquifer system

AGE	Aquifers & Substratums	Transmissivity (m^2/s)
Quaternary	Quaternary: Agriculture soil	10^{-3} to 10^{-5}
	Tyrrhenian Quaternary	
	Sicilian Quaternary	
	Villafranchian Quaternary	
Upper Pliocene	Sand and sandstone of Hammamet Formation	
Middle Pliocene	Sidi El Barka Clay Formation	
Lower Pliocene	Yellow Sand of Nabeul F°	10^{-3} to 10^{-4}
	Potter Clays Formation	
Upper Miocene	Oued El Bir Formation	10^{-3} to 10^{-6}
	Beni Khiar Formation	10^{-4} to 10^{-6}
	Somaa Formation	10^{-3} to 10^{-5}
Middle Miocene	Saouaf Formation	10^{-4} to 10^{-5}
	Beglia Formation	10^{-4} to 10^{-5}
Lower Miocene	Mahmoud Formation	
	Ain Grab Formation	
Upper Oligocene	El Haouaria Formation	10^{-2} to 10^{-3}
Lower Oligocene	Korbous Formation	10^{-4} to 10^{-6}
Upper Eocene	Souar Formation	
Lower Eocene	Bou Dabbous Formation	10^{-2}
Upper Paleocene	El Haria Formation	

thematic maps ranging from hydrogeologic settings characterization to parameter estimation (e.g., distribution of recharge rates, transmissivity, etc.). During the assessment of aquifer vulnerability to contamination, complex answers to simple questions such as "What is the lithology at the water table?"; "What are the geometry and the thickness of the reservoir layer?" may be obtained quickly and efficiently with geological models. Similarly, water budget assessments require volume estimations of groundwater stored in different aquifer units of reservoir layers and this can be generated through geological models.

The 3-D geological models can serve as a basis for developing a conceptual model of the hydrogeological system, essential for understanding movement of water and pollution, where the starting point of any hydrogeological conceptual model is a description of the geology.

Parameterizing the 3-D geological models enables the user to view and analyze not only vertical and lateral variations in rock properties but also the variation in their lithostratigraphy and hydrogeological properties (such as permeability, porosity, etc.). For example, a user wanting to identify high-permeability units at depth and assess aquifer storage and recovery potential can easily identify these units, their depth, thickness, and lateral extent. This provides the hydrogeologist the necessary tools to incorporate more detailed geological information into the groundwater model.

In this paper, such 3-D lithologic and stratigraphic models referred to as geological models were created which can be viewed from any angle or direction.

First, the lithologic model is generated to show the spatial variability, the heterogeneity of the NH basin lithology and to aid in the identification of distinct stratigraphic units.

Second, a solid model of the whole stratigraphy is required to provide a detailed definition of the stratigraphic architecture, to more accurately define the lithostratigraphy and the geometry of each depositional formation of the region, and to delineate main aquifers and aquitards.

The present method used the lithologic and startigraphic modeling techniques based on the "solid modeling" concept provided in the RockWorks software package, in which a Closest Point gridding method was used. Using Closest Point, each grid node is assigned a value equal to the value at the closest control point.

Furthermore, the "box" models were created of regularly spaced nodes from irregularly spaced data by interpolating measured values of lithology or stratigraphy types. The resolution of each model was 1,000 m (X) × 1,000 m

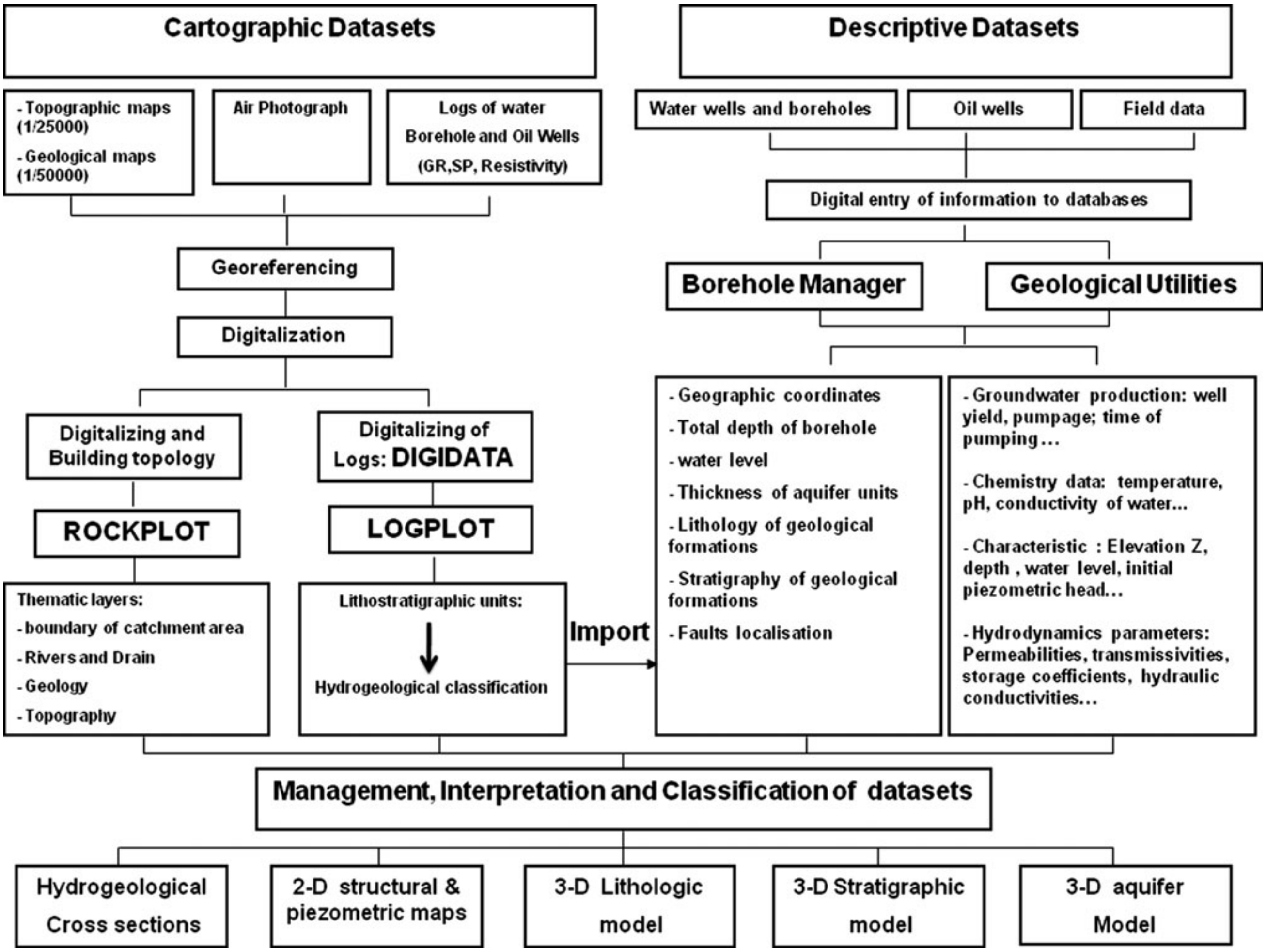


Fig. 4 Analysis flow chart for RockWorks databases

(Y) × 5 m (Z). The resulting discretization consisted of 42 X nodes × 31 Y nodes × 51 Z nodes, thus having 66,402 solid model nodes, each model with a voxel volume of 5,000,000 m^3.

RockWorks Borehole Manager Tool was used to interpolate grid model for the lithology types or for upper and lower surfaces of each stratigraphic unit and to create 3-D diagrams that illustrate these lithologic units or stratigraphic layers, with side panels. The completed diagrams are displayed in a RockPlot3-D window, with volume and mass of each lithologic unit or stratigraphic formation noted.

Three-dimensional aquifer modeling

The aquifer model is intended to illustrate the complexity of the hydrostratigraphic framework of the study area and to show the spatial trends and variability of thickness and heterogeneity of the aquifer system.

To develop a 3-D model of the main aquifers, a solid model was used. However, 3-D aquifer model is generated for the three basic characteristics of the solids: extent, base level, and thickness. The methodology used to develop aquifer model is to interpolate a grid model for the upper and lower surfaces of a single aquifer listed for a particular date or date range in the water levels table and create a 3-D diagram that illustrates these surfaces, with side panels. The completed diagram is displayed in a RockPlot3-D window, with aquifer volume noted. The aquifer block can be combined with other 3-D diagrams, such as the stratigraphic surfaces (top and/or base of the relatively stratigraphic unit). However, groundwater level data can be difficult to use, because of both its limited availability in digital format and the dynamic nature of groundwater levels. Thus, one of the starting points was to examine the available groundwater information and decide on the most appropriate data to use. Relationships between groundwater level (potentiometric) surface, geological horizons, and land surface can thus be easily visualized (Fig. 8). The aquifer block gives the outer boundary or extent of the hydrogeological classified unit, either at the surface or in the underground. Instead of topography, the top of aquifers is modeled.

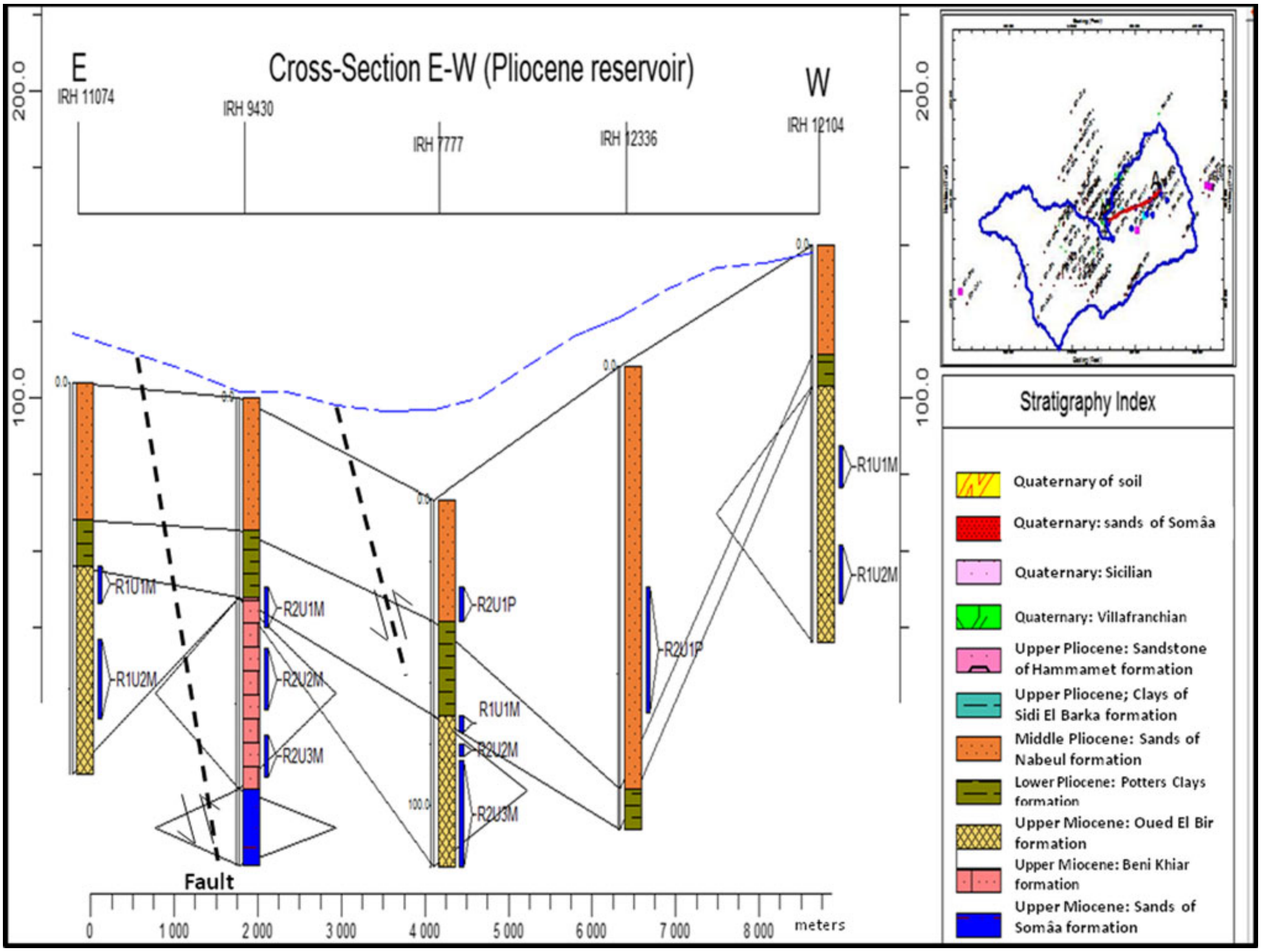


Fig. 5 Hydrogeological cross section (E–W) showing the geometry of Pliocene aquifer (Sand of Nabeul formation) interconnected with Miocene aquifer (Oued el Bir or Beni Khiar formations), and the variation of reservoirs thickness caused by major faults

Results and discussions

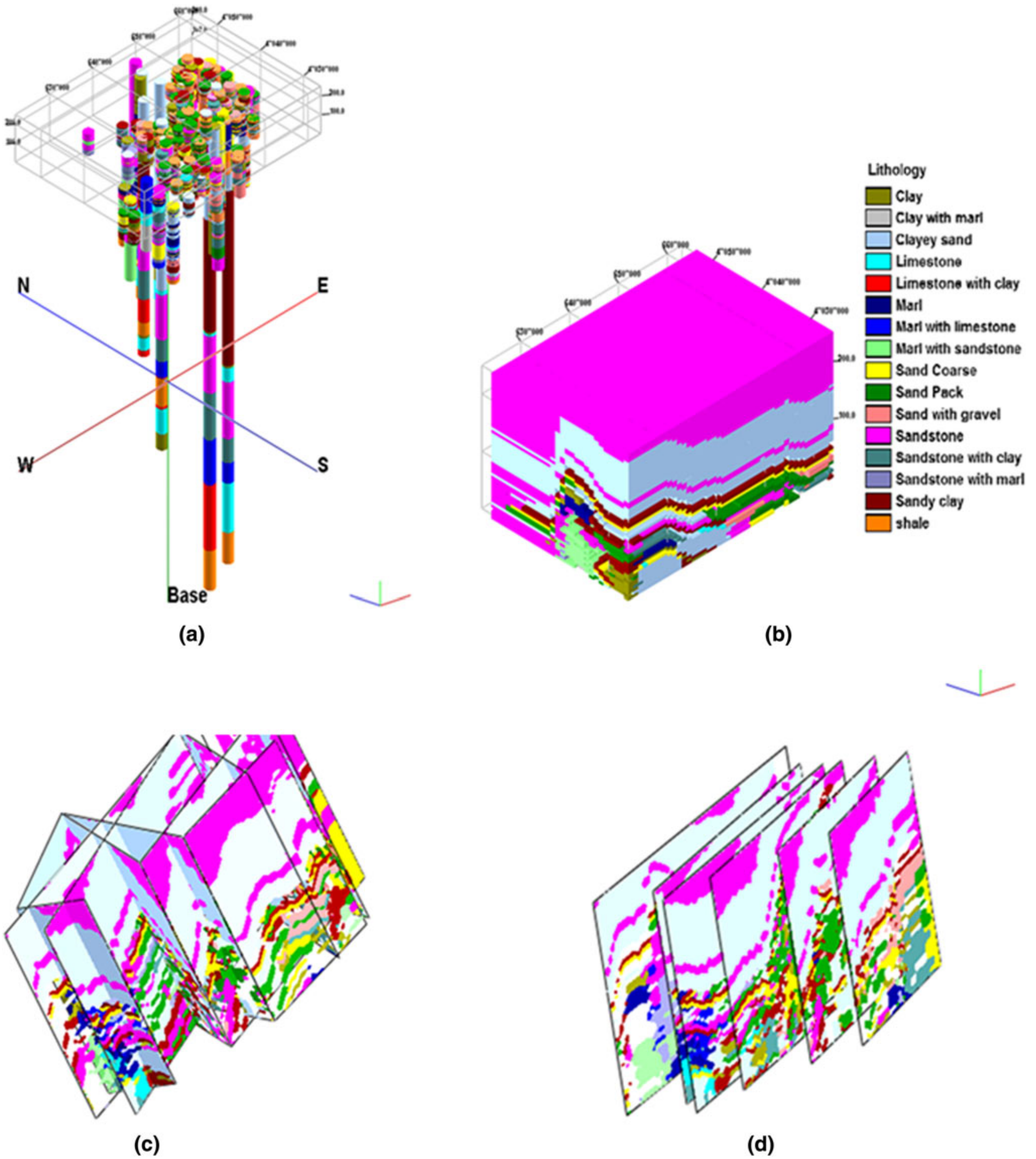
The lithological, stratigraphical, geophysical, and hydrodynamical data of NH aquifer system were interpreted, organized, stored, and managed in GIS database platform. This database offers capabilities for geological and aquifer modeling, and hydrogeological conceptualization as well as other hydrogeological studies.

Lithologic model

The 16 main lithologic categories of the NH basin (clay, clay with marl, clayey sand, limestone, limestone with clay, marl, marl with limestone, marl with sandstone, sand coarse, sand pack, sand with gravel, sandstone, sandstone with clay, sandy clay, and shale) are represented as spatially repeated sequences that have significant spatial changes in terms of their occurrence, thickness of individual categories, and elevation of top and bottom of each layer.

Interfingering and presence of lenses is a main characteristic of the sedimentary basin represented in the study area. Due to these characteristics, heterogeneity of the aquifer system is represented by a spatial variation in hydraulic conductivity ranging between that of clay and gravel, where the hydraulic properties (hydraulic conductivity, specific storage, specific yield) were assigned for the different lithologic materials in the databases.

Results of the lithologic model (Fig. 6a, b) and the generated 3-D fence diagrams (Fig. 6b, c) revealed that there is a wide range of lithologic categories and therefore of hydraulic conductivities in the modeled area, which vary spatially and control the groundwater flow regime and will have a great importance if this model is to be used in



(a) (b)

(c) (d)

Fig. 6 **a** Three-dimensional representation of boreholes and lithology; **b** lithologic model showing the three-dimensional representation of the sedimentary system. The resolution of the model was 1,000 m (X) × 1,000 m (Y) × 5 m (Z); **c** and **d** lithologic fence diagrams showing lithologic heterogeneity in the study area

groundwater modeling and contaminant transport studies. Heterogeneity of the aquifer system is spatially represented in the study area where different hydraulic conductivity fields are found in the different directions.

Due to the presence of a wide range of hydraulic conductivities and their spatial variation in the study area, sandy materials tend to be connected to form a certain continuation which likely controls flow and contaminant transport. Hydraulic continuity is represented by interfingering and connection of sandy materials within the aquifer system as illustrated in the fence diagrams.

Consequently, a lithologic model provides a 3-D representation of the subsurface. Especially, this model represents directly the heterogeneity in three dimensions. This enables illustration of the spatial relations of the lithofacies between the boreholes and indicates the presence of lenses.

Also, the individual lithologic, units identified on the lithologic model were vertically separated to emphasize the geometry of individual horizons and to aid in the identification of distinct stratigraphic units.

This model must honor the borehole data and must reveal the complexity of the sedimentary system that controls groundwater flow and contaminant transport. Because this model depends on interpolation schemes to fill the gap between the boreholes, it is worth mentioning that the lithologic representation between boreholes may not reflect the reality. For prediction purposes, it is recommended that more boreholes be used to achieve a finer resolution and more accurate results.

Thus, the proposed model has been useful in conceptualizing the aquifer system of the study area, while this will be used in future studies of modeling groundwater flow and contaminant transport where lithologic units will be used as necessary input data to build the groundwater flow model.

Stratigraphic model

The integrity of 3-D attributed stratigraphic model depends on having an array of accurately logged boreholes, good down-hole geophysics and access to other site investigation data at a sufficient density to allow geological units (including groups, formations, members or beds depending on the level of detail required) to be modeled, and their physical properties to be characterized with confidence.

Once a subset of borehole lithostratigraphic data and geophysical data is selected, the stratigraphic model is established. Interpreting the model requires an ability to conceptualize which must correspond to its purpose.

The stratigraphic model of NH area is made of interlocked surfaces representing the top of bedrock and each of the main stratigraphy units recognized in the study area. Some units are only partly represented and lag deposits less than 1 m thick are generally not included. This model shows the regional distribution and the geometry of subsurface units. Altogether, 17 distinct stratigraphic units can be identified and examined in this study, each one with different depositional conditions (Fig. 7).

Unit 1 The bedrock of the aquifer system lies at a depth of between 228 and 2568 m and consists of thick shale interbedded with limestone of 'the El Haria formation' of the upper Maastrichtian–Paleocene (Burollet 1956; Saadi 1997).

Unit 2 Ypresian–Lower Eocene deposits of 'the Bou Dabbous formation' immediately overlying bedrock consisting of limestone and thin bedded marl (Bishop 1988; Saadi 1997; Ben Ferjani et al. 1990). The fractured limestone layers of this formation, together with the fractured bedrock surface, form a discontinuous confined aquifer in the region.

Unit 3 The Upper Eocene deposits of the 'Souar formation' were outcropped in the western part of the study area, containing marl interceded with thin bedded limestone (Burollet 1956; Ben Ferjani et al. 1990). These deposits form an extensive lower aquitard.

Unit 4 The siliciclastic sand and detrital clay deposits, that overlie the 'Souar formation', corresponds to the Aquitanian–Oligocene sediments of the 'Fortuna group' (Burollet 1956). This group is subdivided into two formations (1) the upper one corresponds to 'El Haouaria formation' (upper Oligocene–Lower Miocene) made up of sandstone and clay (Ben Ayed et al. 1979). This is unconformably overlain by the lime deposits of the Upper Langhian, which are organized in a transgressive sequence, starting at its base with sporadic clayey-sandy deposits (Horizon A) and clay (Oued Hammam Formation; Hooyberghs 1977). (2) The lower one, the 'Korbous formation' (lower Oligocene), contains interlaminated brown gray claystone, silty claystone and siltstone, mainly carbonaceous with intercalations of pyritic and glauconitic, white to gray sandstone, and quartz sand. These deposits form a continuous thick aquifer.

Nevertheless, the unconformities mark the top and bottom of Fortuna group (Ben Ayed et al. 1979; Bismuth and Hooyberghs 1994; Ben Ismaïl-Lattrache 1981; Hooyberghs 1977, 1991, 1995). However, this Oligocene aquifer is considered as single confined aquifer. It is interbedded between two thin impermeable deposits from the Souar formation (Unit 3) on the bottom and the Cap Bon group (Mahmoud and Ain Grab formations) on the top (Unit 5).

Unit 5 'The Cap Bon group' (Lower Miocene) is made up of the 'Ain Grab formation' (Burollet 1956) and the 'Mahmoud formation' (Biely et al. 1972). The shelly limestone of 'the Ain Grab formation' indicates that it dates from the Langhian age (Hooyberghs 1977; Ben Ismaïl-Lattrache 1981; Blondel 1991; Ben Salem 1992; Yaïch 1997). The 'Mahmoud formation' rests above the Aïn Grab limestone beds (Tayech 1984; Méon and Tayech 1986; Bismuth and Hooyberghs 1994; Bédir 1995; Bédir et al. 1996) and consists of glauconitic greenish gray shale, with some siltstone and traces of pyrite (Hooyberghs 1977; Ben Ismaïl-Lattrache 1981; Hooyberghs and Ghali 1990). These sedimentary series form together an extensive thick aquitard.

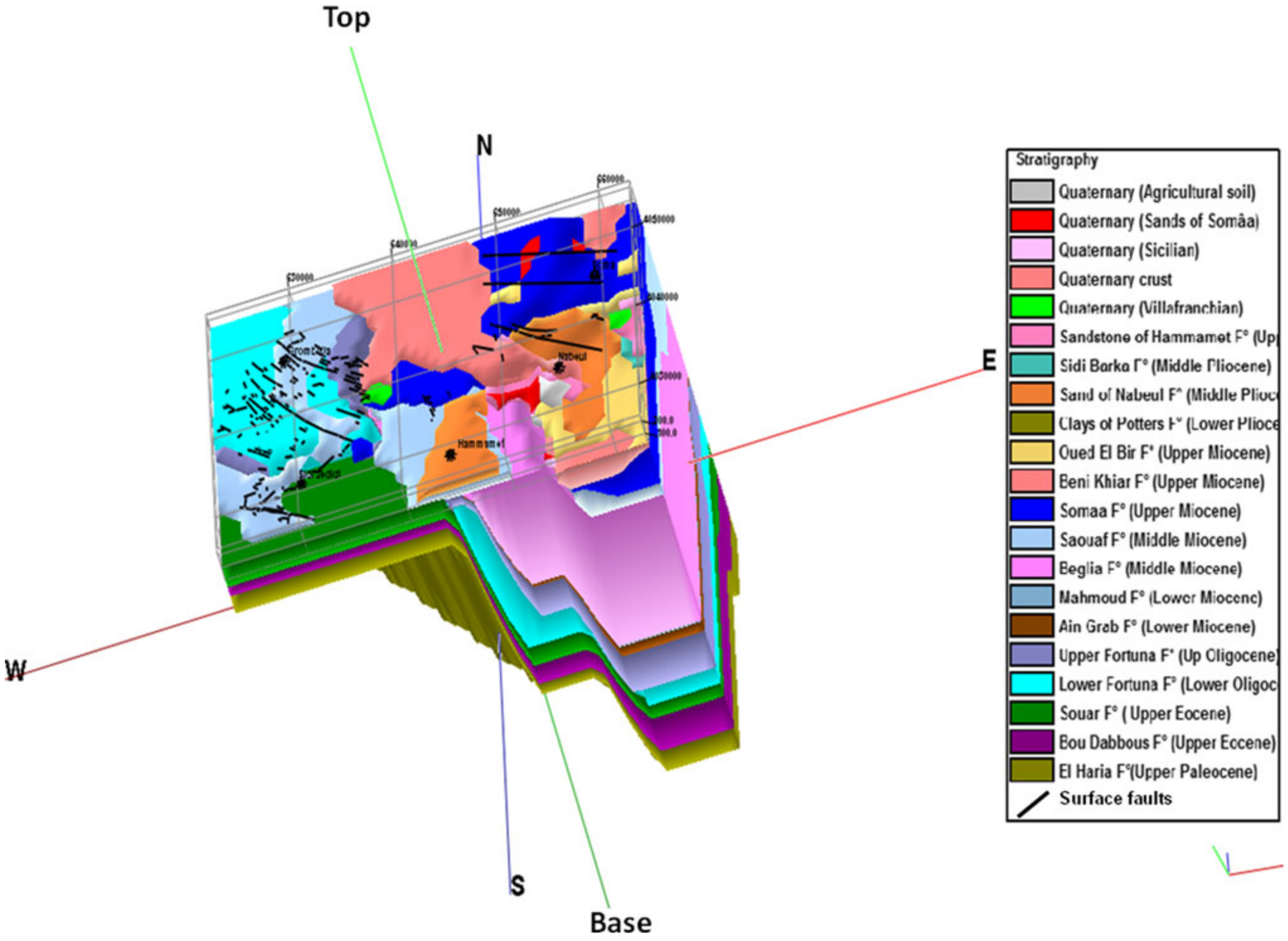


Fig. 7 Three-dimensional stratigraphic model of the Nabeul–Hammamet area. The resolution of the model was 1,000 m (X) × 1,000 m (Y) × 5 m (Z)

Unit 6 The 'Oum Dhouil group' from the Serravallian-Tortonian–Middle Miocene is formed by two formations. The 'Beglia formation' is overcome by thick deposits from the 'Saouaf formation' (Biely et al. 1972).

The 'Beglia formation' has stratified fine-grained sandy sandstone packages (Burollet 1956) subdivided into two large subunits. The upper subunit is formed by partly calcareous light-to-medium-gray claystone and occasionally gray siltstone and sandy claystone with traces of pyrite and lignite. The lower subunit contains light-to-medium gray claystone and siltstone alternating from fine- to coarse-grained sand and fine-grained white to gray sandstone with traces of glauconite, mica, dolomite, and blue green claystone (Robinson and Wiman 1976; Mannaï-Tayech et al. 1996).

The 'Saouaf formation' encompasses sand, sandstone, and clay alternating with lignitiferous beds and shelly lime beds (Biely et al. 1972; Ben Salem 1992; Bédir et al. 1996). This sedimentary series is subdivided into two subunits. The upper subunit is characterized by alternating buff calcareous clay and fine- to coarse-grained quartz sand and, occasionally, argillaceous or anhydritic fine- to medium-grained sandstone with traces of anhydrite and lignite. The lower subunit contains buff calcareous clay, local sand to gray clay and siltstone with some intercalations of fine to coarse sand with traces of pyrite, lignite, and glauconite (Wiman 1976).

Consequently, the 'Oum Dhouil sedimentary group' forms the largest and thickest aquifer in the region. This is a semi-confined aquifer interconnected by more or less thick sandy clay aquitards which are well individualized in the lithostratigraphic interpretation of borehole logging.

Unit 7 This sequence is unconformably deposited on the 'Oum Dhouil group' (Ben Salem 1992), and is attributed to the Tortonian–Upper Miocene of 'the Somaa formation'. This formation consists of a silty to sandy succession with either thinning- and fining-upward or graded bedded sequences (Colleuil 1976; Mannaï-Tayech and Otéro 2005; Mannaï-Tayech 2006). Also, this permeable stratigraphic unit forms a regional aquifer.

Unit 8 The 'Béni Khiar formation' (Colleuil 1976; Fournié 1978; Bismuth 1984; Bédir et al. 1996) is thought to be of the lower Messinian age (Ben Salem 1995; Hooyberghs and Ben Salem 1999), crops out in the Northeast of the area, on at least 1 km of the Béni Khiar village, and consists of oolitic and bioclastic limestone alternating with sandy and marly levels (Moissette et al. 2010). Between these deposits flows a perched and low productive aquifer.

Unit 9 The Oued el Bir formation (Colleuil 1976; Fournié 1978; Bismuth 1984; Bédir et al. 1996), from the lower Messinian (Hooyberghs and Ben Salem 1999) with a crop-out in the northeast part, between Oued el Kébir and Oued Souhil rivers,is announced by a Messinian transgressive series which consists of sand, sandstone, and clay with gypsum (Colleuil 1976; Bédir et al. 1996; Moissette et al. 2010). As well this formation contains a laterally continuous aquifer.

The trangressional marine Pliocene sediments were unconformably deposited on Serravallian-Tortonian formations (Derbel Damak and Zaghbib Turki 2002). These deposits are mainly composed of sandstone-sand-marl alternations topped by sandstone and sand (Damak et al. 1991). This facies changes laterally to argillaceous sand or to more or less argillaceous consolidate sandstone.

Unit 10 The 'Potter clay formation' forms the bedrock of the Pliocene and Quaternary aquifers, composed of gray shale and indicating a Tabanian-Plaisancian–Lower Pliocene age (Colleuil 1976; Hooyberghs 1977, 1991, 1995).

Unit 11 The extensive unit of coarse- to fine-grained sands of 'yellow sand of Nabeul formation' outcrops in the extreme northern part and attributing to the Lower Tabianian–Lower Pliocene age (Colleuil 1976).This permeable unit contains a continuous reservoir aquifer.

Unit 12 'Clays of the Sidi El Barka formation' presents characteristics similar to the 'Potters clay formation' dating from the Lower Plaisancian-middle Pliocene age (Colleuil 1976; Derbel Damak and Zaghbib Turki 2002). These argillaceous series form the substratum of the first Pliocene aquifer (yellow sand of Nabeul).

Unit 13 The 'Sand and Sandstone of Hammamet formation' indicates an upper Plaisancia–upper Pliocene age (Colleuil 1976; Derbel Damak and Zaghbib Turki 2002). This permeable stratigraphic formation forms a laterally continuous aquifer.

Unit 14 The Villafranchian Quaternary deposits outcrop on the west side of Grombalia graben. These deposits are mainly composed of sandstone–clay alternations within facies laterally changing to argillaceous sands or to more or less argillaceous consolidate sandstones (Johan and Krivy 1969). As well these permeable series form a continuous aquifer where the clayey series of this formation form the substratum.

Along the coastline of the NH area, the Pleistocene-Quaternary outcrops by two marine formations: the Sicilian and the Tyrrhenian Quaternary (Colleuil 1976).

Unit 15 The Sicilian Quaternary deposits, made up of high beach deposits, overlain in unconformity over the Pliocene and Miocene outcropping formed by detrital deposits of grey sands. These sandy sedimentary series form a continuous shallow aquifer which is limited by sandy clay aquitards.

Unit 16 The Tyrrhenian Quaternary sediments mostly compose the Réjiche formation (Paskoff and Sanlaville 1983) subdivided into two subunits. The lower unit of marine facies is sandy limestone with mollusks indicating the maximum flooding surface of the Tyrrhenian transgression. The upper unit is mainly composed of a continental facies (Ozer et al. 1980) with the occurrence of oolitic limestone and coprolites or pelloïds. Nowadays, these deposits form coastal consolidated dunes built by wind following marine regression (Ozer et al. 1980; Chakroun et al. 2005). The old consolidated dunes cover the Tyrrhenian deposits (Ozer et al. 1980). The encrusted limestone extends over significant distances. They are very rich in calcite and silica, sometimes in gypsum and alumina, and frequently colored by iron salts.

The Tyrrhenian deposits are a good reservoir and a key point for coastal aquifer recharge because groundwater flow occurs within the Tyrrhenian limestone before reaching the sea. Meteoric water recharge of the shallow aquifer is thought to occur through the coastal consolidated barriers which characterize the Tyrrhenian beach (Ennabli 1980).

Unit 17 Thick sequences of superficial deposits making up river terrace gravels and alluvium are underlain by Palaeogene deposits of the quaternary of soil formation. This unit, attributed to the Holocene deposits is formed by recent alluvia of river deposits, current dunes, and beaches. Although unit 17 is a relatively permeable stratigraphic unit, it lies predominantly within the unsaturated zone above the regional water table, and is considered as an unconfined aquifer.

Aquifer models

The developing of a solid model of the whole stratigraphy provides the delineation of the main aquifers and aquitards of the study area. Consequently, it is possible to develop a GIS model of the main aquifers.

The aquifer model corresponds to the 3-D visualization of the extension and the thickness of each hydrogeological unit. Hereby, the top of the underlying unit is completely equal to the base of the unit itself. Thus, the volume and extent of a solid are unambiguously defined.

The 3-D GIS maps are generated for the three basic characteristics of the solids: extent, base level, and thickness. Extent maps give the outer boundary or extent of the hydrogeological classified unit, either at the surface or in the underground.

Instead of topography, the top of aquifers or aquitards is modeled. Thickness maps represent the spatially distributed thickness of a hydrogeological unit. For each hydrogeological unit of the NH aquifer system, the extent, top level, and thickness 3-D maps are presented. An example of 3-D aquifer model was given in Fig. 8a. This model shows the extension and thickness of 'Quaternary of soil' hydrogeological unit combined with 3-D stratigraphic surfaces (top of the relatively stratigraphic unit).

The aquifer block (Fig. 8b) shows the representation of all modeled hydrogeological units. This indicates that there are different aquifer reservoirs subdivided into aquifers units and separated by aquitards units. These reservoirs form the semi-confined aquifer system: the Quaternary reservoir, the Pliocene reservoir, the Miocene reservoir, the Oligocene reservoir, and the Eocene reservoir.

The majority of these reservoirs are interconnected by sandy clay aquitards. This suggests that considerable recharge between underlying and overlying aquifers can occur by vertical movement through time.

The most important regional shallow reservoir in NH is the Quaternary reservoir. Pleistocene graded sand and gravel, changing to fine and clayey facies, are found along the entire NH plain, especially throughout the coastal zone and the Grombalia trough.

The quaternary depositional units: Alluviums, Quaternary of soil, Sicilian quaternary, Tyrrhenian quaternary, and Villafranchian quaternary together form a discontinuous semi-unconfined multilayer aquifer interconnected by sandy clay aquitards, while the Potters clay or the Sidi Barka formations (Lower Pliocene) make up the substratum. The saturated thickness of the quaternary aquifer ranges from 5 to 10 m along the coast while reaching about 30 m upstream in higher topographical zones. The estimated overall volume of this reservoir in aquifer model is 24.10^9 m^3.

The Pliocene reservoir is presented by two hydrogeological formations: 'Sands of Nabeul' and 'Sandstone of Hammamet'. The first Pliocene aquifer is extended from the north of Hammamet area to the southwestern riverside of Oued Souhil and ranged in thickness from 60 to 140 m. The second Pliocene aquifer lies predominantly within the saturated zone of quaternary reservoir aquifer. It is considered as a productive regional aquifer with thickness ranges between 20 and 200 m and reaches its maximum extension in the coastline.

The 'Potters clays' and 'Clays of Sidi El Barka' formations constitute the substratums of the 'Sand of Nabeul' and the 'Sandstone of Hammamet' aquifers, respectively.

The estimated overall volume of the Pliocene reservoir in aquifer model is 16.10^9 m^3.

The Miocene aquifer is considered as a large semi-confined aquifer, consisted of an alternation of sand, sandstone and clayey layers and interconnected by sandy clay aquitards. This thick reservoir is located in the Oued el Bir, Beni Khiar, Somaa, Saouaf, and Beglia formations.

The Oued el Bir aquifer is located in the northeast, from the area of Oued el Kebir to Oued Souhil, with a thickness ranging from 20 to 150 m. The Beni Khiar aquifer is considered as a local, perched and low productive aquifer. The Somaa aquifer is shallow in the northeastern part (Somâa region) and extends deeper towards the coast with a thickness ranging from 50 to 250 m. The Saouaf aquifer is identified in the extremely northeastern part of the study area where the aquifer is shallow and becomes deeper towards the south. The Beglia aquifer underlies the Saouaf aquifer. This aquifer is shallow to the northwestern part and extends deeper towards the sea and Grombalia graben.

Therefore, the main lithology of the Miocene sediments is clayey sand, explaining why it formed very large semi-confined aquifers interconnected by semi-permeable aquitards. The clays of the 'Mahmoud formation' and the limestone and marl of the 'Ain Grab formation' make up the substratum of this multi-layered aquifer.

The estimated overall volume of the Miocene reservoir in aquifer model is 35.10^9 m^3.

The Oligocene aquifer is located in the western part, sealed between thick sediments of the 'Korbous formation' (Lower Oligocene) of 'Fortuna group'. This aquifer is shallow beneath the western part of the study area (Sidi Jedidi and Latrech region) and deeper towards the sea. This is collapsed towards the Grombalia graben (the eastern part). The estimated overall volume of Oligocene reservoir in the aquifer model is 11.10^9 m^3.

The Eocene aquifer flows between the fractured limestone layers of the 'Bou Dabbous formation'. This aquifer is shallow in the southwestern part (Sidi Jedidi region) and becomes deeper towards the sea and eastern part. This is a very low productive aquifer, of which the shale series of the upper Paleocene El Haria formation made up the substratum. This reservoir is not presented in the aquifer model because it is not modeled due to the lack of boreholes data capting this reservoir in order that it not presented in the aquifer model.

Summary and conclusions

In this paper, a methodology is elaborated in support of the implementation of the hydrogeology framework of Nabeul–Hammamet (NH) area, which is the delineation of groundwater bodies, as the basic units for management and reporting. The methodology consists of (1) the development of a complete and generally accepted hydrogeological

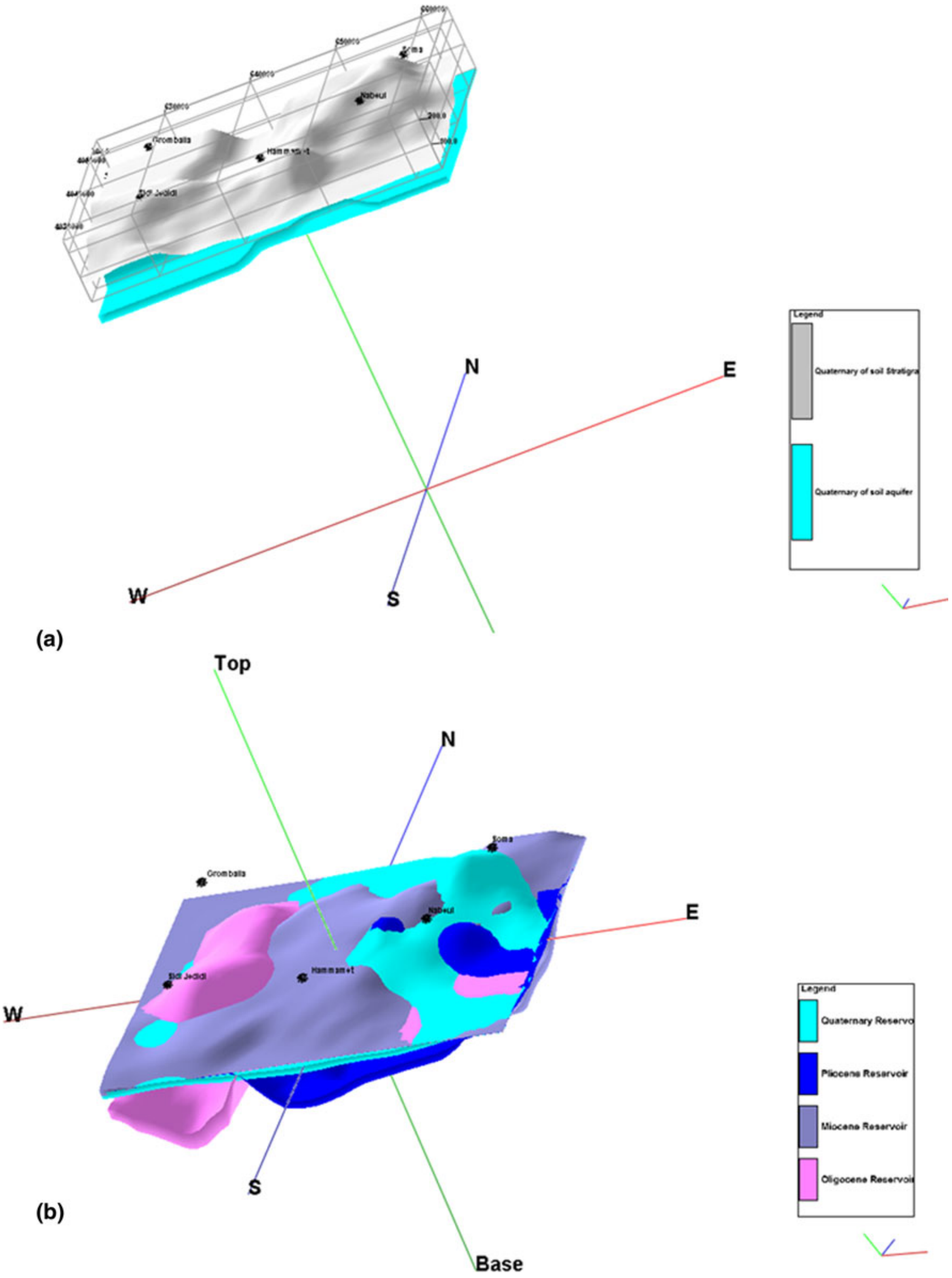


Fig. 8 **a** Three-dimensional aquifer model showing the thickness of Quaternary of soil hydrogeological unit combined with three-dimensional stratigraphic model of the top of relatively stratigraphic unit; **b** Three-dimensional aquifer model showing the extension and the geometry of the Nabeul–Hammamet aquifer system

classification system for NH aquifer system (2) the development of a GIS-managed geological, geophysical, and hydrogeological database (3) the development of hydrostratigraphic cross sections, and (4) the development of 3-D geological and aquifer models by means of a solid modeling approach.

Summarizing, the geological and hydrogeological GIS database described in this paper offers capabilities for geomodeling and hydrogeological conceptualization as well as other hydrogeological studies, as described below:

Data verification and validation are essential. Using an advanced database supported by GIS, this operation could be done in a simple way. For example, anomalies in hydraulic-head data could be observed directly on the generated hydraulic-head maps.

Automatic data treatment is required before input to the numerical model. Because of the huge amount of work that is required to prepare the data used in the process-based models, the GIS database is essential.

A global view of the geological and hydrogeological data can be obtained using the generated 2-D maps and 3-D spatial models. Geological, lithological maps and models; hydraulic head maps; maps of pumping-rate allocations; and maps of statistical data show very clearly the data distribution and allow a view of geometry, lithology and conditions of the aquifer system behavior and stress factors.

Aquifer vulnerability studies can be performed using the existing spatial database and 3-D geological models. New procedures for quantification of physically significant parameters can be developed using this hydrogeologic database. From this point of view, coupling GIS to process-based numerical models with applications to groundwater phenomena as well as to the unsaturated zone would represent one of the most interesting steps in future hydrogeological researches.

However, the authors consider that the presented database schema fully satisfies the requirements of their hydrogeologic studies. Changes, updates, or further developments of the schema could be incorporated in a simple way. At the same time, the database was designed so that its flexibility makes the data retrieval process easy. Also, the spatial database was conceived as being modular. Users who are using only an RDBMS in the absence of a GIS tool can handle the attribute data.

Furthermore, this study illustrates the importance of 3-D subsurface modeling in a complex geology area underlain by variable thick successions of deposits. For a better understanding of the sedimentary infill and the potential groundwater resources of NH area, it is required to more accurately understand the geology, identify and delineate major aquifers and aquitards, and contaminant migration pathways.

Results of the lithologic model revealed that there is a wide range of lithologic categories and therefore of hydraulic conductivities in the modeled area, which vary spatially and control the groundwater flow regime, whereas the stratigraphic model showed the regional subsurface sediment distribution and the geometry of 17 stratigraphic units and identified the main aquifers and aquitards in NH area.

Hence, the development of 3-D aquifer models identify the extension and the geometry of each aquifer unit and indicates that the NH aquifer system is composed of multi-reservoirs aquifers subdivided in aquifers units separated by sandy clay aquitards. These reservoirs form the semi-confined aquifer system composed the Quaternary aquifer, the Pliocene aquifer, the Miocene aquifer, the Oligocene aquifer and the Eocene aquifer.

It is the view of the authors that a 3-D modeling approach is the most adequate way to capture the subsurface complexity of most geologic settings, which can lead, in the context of an integrated approach, to improved hydrogeologic appraisals.

However, reconstructing the stratigraphic architecture in 3-D is not a trivial task and close interactions with some hydrogeologic applications such as groundwater flow modeling remains a significant challenge.

Furthermore, the results of the geomodeling effort presented in this paper have thus highlighted a series of advantages and limitations regarding the proposed approach. On the one hand, the advantages can be summarized as follows:(1) The geologic model is made of interlocked discrete surfaces which represent current knowledge of the stratigraphic architecture of the modeled domain in a common and consistent framework which does not require large computer power; (2) it truly helps to understand the geologic and hydrogeologic settings and can provide complex and consistent end-products as well as simplified framework depending on the needs of the application (hydrogeologic settings characterization, aquifer vulnerability mapping, groundwater flow simulation, etc.); (3) it is thus a step toward more integrated approaches where data and knowledge are grouped in a common system/model to reduce redundancy. It allows for multiple usages and improves the consistency/uniformity between end-products. It also contributes to streamline updating procedures.

On the other, the limitations of this approach are the following (1) model reliability is limited by data quantity and quality and, since it is a knowledge-based model, by the experience of experts and the efficiency of their interaction; (2) more reliable regional geologic models could be produced if training, regulations and a standardized procedure were developed to improve the quality of water well databases; (3) improvement in the inter-operability with database systems and end-process technologies need to be achieved in order to further increase the usefulness of these models and to streamline the process of data exchange.

Finally, the proposed models have been useful in conceptualizing the NH aquifer system in the study area, and they will be used in future studies of modeling groundwater flow and contaminant transport where geological and hydrogeological databases stored, lithologic and stratigraphic models will be used as necessary input data to build the groundwater flow model.

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