Groundwater Management for Sustainable Development Plans for the Western Nile Delta

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Abstract Egypt is considered an arid country and the primary water resource is the River Nile. The limited availability of renewable freshwater for agriculture and urban development is a major constraint. The role of groundwater is steadily increasing and will cover 20% of the total water supply in the coming decades especially in the reclaimed areas of the Western Nile Delta. Serious environmental problems are emerging in the groundwater aquifer in Western Nile Delta such as waterlogging, soil salinity, and the risk of saline water intrusion to the north aquifer. An efficient integrated and sustainable management plan for groundwater resources is needed to avoid the deterioration of the groundwater aquifer in Western Nile Delta. In this chapter, a brief description of the groundwater aquifer in Western Nile Delta and a review of previous studies on groundwater hydrology were presented. GIS and MODFLOW models were integrated to simulate the groundwater flow in the studied Quaternary aquifer. The developed model was calibrated for steady-state and transient conditions for groundwater heads till 2002. The groundwater potentiality was evaluated, and different management scenarios were analyzed for groundwater prediction. The results of the current situation of groundwater showed that groundwater aquifer in Western Nile Delta is susceptible to significant water table reduction especially in the unconfined parts for the case of overstress discharge. The net aquifer recharge was increased for the case of reducing the surface water inflow while increasing the annual abstraction and improving the irrigation system. The annual aquifer potentiality was increased by the construction of a new canal to feed the aquifer towards the northwest direction. Therefore, efficient integrated and sustainable management of

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groundwater resources relies on a comprehensive database that represents the characteristics of the aquifer and modeling software to achieve the impacts of decision alternatives.

Keywords Groundwater management, MODFLOW, Sustainable development, Western Nile Delta

Contents

1 Introduction

With the increase in the demand for freshwater, the attention of nonconventional water resources is drawn. Nile water alone is no longer adequate for the increasing water requirements for the different development activities in Egypt. Groundwater is playing an essential role in water supply because of its importance for the domestic, agricultural, and industrial use. However, many cautions and worries are increasingly being voiced about the dangers that surround the groundwater resources. These concerns are related to the groundwater depletion as a result of overabstraction [1] and also, quality deterioration brought by many modes of contamination. Intensive expansion in land reclamation, increased population, and construction of new industrial projects cause changes in water demand and the groundwater regime. Ministry of Water Resources and Irrigation [2] introduced the West Delta water conservation and irrigation rehabilitation project aiming to the implementation of a pipe network to transfer surface water to irrigate about 107,000 ha (264,403 feddan) located in the South of the West Delta. This will be reflected in rising of groundwater levels accompanied by the formation of local groundwater mound sand logging problems.

The Nile Delta aquifer is considered an essential source of groundwater abstraction as it represents 87% of the total groundwater abstraction in Egypt [3]. The

primary source of the Nile aquifer recharge is the seepage from the surface water irrigation/drainage systems and infiltration from the cultivated land. The conjunctive use of surface water and groundwater plays an active role during the period of peak irrigation demand. The amount of water abstraction from the Nile aquifer (Delta and Valley) was estimated in 2010 at 6.2 BCM, which is within the safe yield (8.4 BCM) that was evaluated by MWRI [4].

In the Western Nile Delta region, groundwater is the primary source for domestic, industrial, and agriculture use. With the expansion of developing activities in this area, it is essential to develop a groundwater management strategy to avoid any environmental impacts on the aquifer system due to the extensive future abstraction of groundwater. For better management of groundwater resources, it is crucial to have enough data about the physical and hydrogeological settings for the study area. Physical parameters include land use, meteorological data, topography, soil classification, and drainage as well as irrigation systems. Hydrogeological setting comprises the aquifer system, boundary conditions, hydraulic parameters for all aquifer layers, and monitored groundwater levels.

Data used in groundwater modeling consists of the aquifer system stress factor, the aquifer system geometry, and the hydrogeological parameters [5]. Stress factors for groundwater flow include effective recharge, pumping volumes, water surface flow exchanges, etc. Appropriate aquifer system geometry can be determined using geological information (maps and cross sections), topographic maps, as well as contour maps of the upper and lower limits for the aquifer strata and aquitards. Links can be organized between MODFLOW, groundwater model, and the GIS. The GIS software is used to preprocess and postprocess the spatial data. Recently, the use of GIS has grown rapidly in groundwater assessment and management researches such as Arshad and Zulfiqar [6], Kharad et al. [7], Sarma and Saraf [8], and Singh and Prakash [9].

2   Study Area West Nile Delta

Western Nile Delta region occupies the area between Cairo and Alexandria. The southern boundary is near Cairo, the eastern boundary is the Rosetta Branch, and the north is bounded by the coast of the Mediterranean Sea. It extends westward to the desert area from the west of Wadi El-Natrun up to the eastern edge of the Qattara Depression. The modeled area covers about 15,170.6 km^2 (Fig. 1).

3   Physical Setting

3.1   Climate Condition

Table 1 shows some data from meteorological stations situated in the Western Nile Delta region. These data include air temperature, relative humidity, evaporation, and
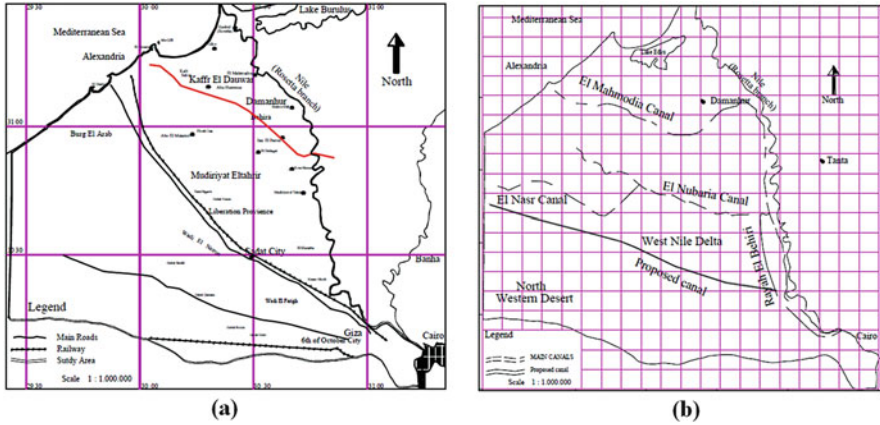
Fig. 1 (**a**) Location map of Western Nile Delta area; (**b**) surface water system of Western Nile Delta [10]

rainfall. The annual mean of the evaporation intensity decreases from South to North and from summer to winter. Rainfall increases in the northward direction. Given the available rainfall records, a 100 mm amount of rainfall may take place intermittently and at intervals hardly exceed a couple of hours.

3.2 Geology and Geomorphology

West Nile Delta consists of a sedimentary succession which ranges in age from the Late Cretaceous to Quaternary. The eastern area of the studied region is covered with Holocene clay while the western part is covered with Quaternary sediments [11]. West Nile Delta area can be classified into four forms: young alluvial plains, old alluvial plains, fanglomerates, and dunes [12]. The young alluvial plains dominate the cultivated lands bordering Rosetta branch. Irrigation canals and drains dissect these plains, sloping from South to North. The ground elevation ranges between 18 m (+MSL) in the South, to about 4 m (+MSL) in the North by an average slope value of 1 m/10 km [13]. The old alluvial plains expand over the western fringe of the Nile Delta and are occupied by most of the newly reclaimed areas. Fanglomerates are considered to represent the Wadi downwash brought by the drainage lines depositing their loads before reaching the Nile. They are covered by relatively thick conglomerates and loose sand deposits. They are mainly composed of fine-grained sand.

Table 1 Summary of meteorological data for Western Nile Delta region

Station	Temperature (°C)			Relative humidity	Evaporation	Rainfall	
	Annual average	Max.	Min.	Annual average (%)	Annual average (mm/day)	Annual (mm/year)	Max. (mm/day)
El-Tahrir	20	34.5	5.80	64.0	6.6	34.4	8.50
Cairo	21.2	34.0	7.50	56.0	8.7	17.62	4.60
Alexandria	20.1	26.4	13.5	68.7	5.0	190.9	53.5
Damanhur	19.6	25.8	12.3	67.7	4.4	90.2	24.2
Wadi el-Natrun	20.9	27.4	13.2	55.3	9.6	38.5	11.2

3.3 Land Use

The traditionally cultivated lands are predominating in the eastern part of the Western Nile Delta region. Reclaimed areas are present in the western part of the region that depends on surface water or groundwater for agriculture. Drainage water from open drains is partly reused for irrigation to cover the shortages of the irrigation water [14].

3.4 Surface Water and Drainage System

The main surface water channels are Rosetta branch, Rayah El Beheiry, Rayah El Nasseri, and El Nubariya canals (Fig. 1b). These water channels are mainly cutting through sands. Therefore, a direct connection between the surface water and groundwater exists [3]. Table 2 lists the average monthly surface water levels and inflow through the surface water system. The Rosetta branch (239 km in length) acts as a drain for the groundwater [15]. Rayah El Beheiry starts from Delta barrage and extends for a distance of 65 km. Rayah El Nasseri begins from Delta barrage and extends for a total length about 68 km running northward in the beginning and then northwestward until it joins with El Nubariya canal. Rayah El Beheiry, Rayah El Nasseri, and El Nubariya canals in their first reaches act as influent streams and are considered the main source for groundwater recharge in the study area [11]. El Nubariya canal, in the end reaches, acts as a discharging effluent stream for groundwater. The open drains are intensively distributed in the old lands of the eastern part of the study area. These drains discharge large quantities of drainage water, but their effects are local. In most of the reclaimed areas in the western desert fringes, there is no tile drainage system. More open drains must be planned and constructed to solve many problems of water logging in these areas.

Table 2 Monthly average surface water inflow to the Western Nile Delta aquifer (in million m^3/day) (after [14])

Month	Rosetta branch		Rayah El Beheiry		Rayah El Nasseri		El Nubariya canal	
	Water level (m)	Discharge	Water level (m)	Discharge	Water level (m)	Discharge	Water level (m)	Discharge
August	12.76	20.56	16.12	26.76	16.03	9.50	9.55	13.85
September	13.06	13.14	18.53	24.57	15.54	7.19	9.42	14.46
October	13.05	11.82	15.36	20.76	14.78	4.17	9.06	19.95
November	12.98	8.16	15.11	18.85	14.78	5.54	8.90	21.04
December	12.94	5.84	14.43	17.83	14.65	3.87	8.41	19.44
January	12.68	9.06	14.44	11.88	14.66	4.09	8.12	21.70
February	12.99	8.94	14.79	16.20	14.90	4.99	8.69	20.18
March	13.03	11.07	15.13	18.69	15.24	5.64	8.82	16.54
April	13.09	12.52	15.31	20.18	15.24	5.59	9.00	16.41
May	13.11	16.09	15.72	23.18	15.16	5.42	9.31	12.30
June	13.20	22.52	16.06	25.53	15.73	7.40	9.51	9.66
July	13.18	21.07	16.12	26.50	15.95	9.02	9.54	11.76
Average	13.01	13.40	15.37	20.91	15.22	6.03	9.03	16.44

4 Hydrogeological Conditions

4.1 Groundwater Quaternary Aquifer

Quaternary aquifer, the Pliocene aquifer, and the Miocene aquifer are groundwater aquifers reusable for exploitation in the Western Nile Delta region (Fig. 2). The Quaternary aquifer is the main water-bearing formation in the study area. The most important one is the Quaternary aquifer that consists of Pleistocene sand and gravel, and clayey facies in the North. This aquifer is overlaid by a clay cap which is considered as a semi-confining layer with a thickness varying from 10 m in the South to 30 m in the North. The thickness of the Quaternary aquifer ranges between 50 m along the desert fringes in the West and 800 m in the North. Tables 3 and 4 show the hydraulic conductivity of the Quaternary aquifer and clay cap layer. The groundwater salinity is about 800 ppm in the South, and it reaches about 359,000 ppm in the North due to the effect of seawater intrusion [25]. The piezometric lines show radial flow towards the depression of Wadi El-Natrun and the groundwater is discharged through seepage zones into small lakes, ponds, and sabkhas, where the water evaporates in amounts up to $70 \times 10^6 \, \text{m}^3$/year.

4.2 Groundwater Levels

The depth from the ground surface to the groundwater is less than 3 m in the eastern part of the Western Nile Delta region. It decreases northward and to the northeast. It ranges from 3 to 8 m in northeastern part and increases in the southwest direction ranging from 20 m to more than 50 m near western desert fringes (high topography area) (Fig. 3). The piezometric head levels are decreasing within the Western Nile Delta region from more than 15 m (+MSL) in Cairo to 1 m (+MSL) near the coast. The piezometric contour lines in the hydrogeological maps of the Western Nile Delta show a local increase in heads due to the effects of old reclamation projects based on surface water using the traditional flood irrigation method where the infiltration rate is very high. Also, local depression appeared due to extensive groundwater abstraction where many recent private reclamation projects have been developed.

4.3 Recharge and Discharge of Groundwater

The groundwater in Quaternary aquifer in Western Nile Delta exists mainly under free water table conditions (unconfined). Semi-confined conditions are locally present where clay cap is found (northeast of the study area). The aquifer in the floodplain (southern and central portions) is continuously recharged by the leakage of excess surface irrigation water; thus, the aquifer acts as a storage reservoir. It is also recharged by the
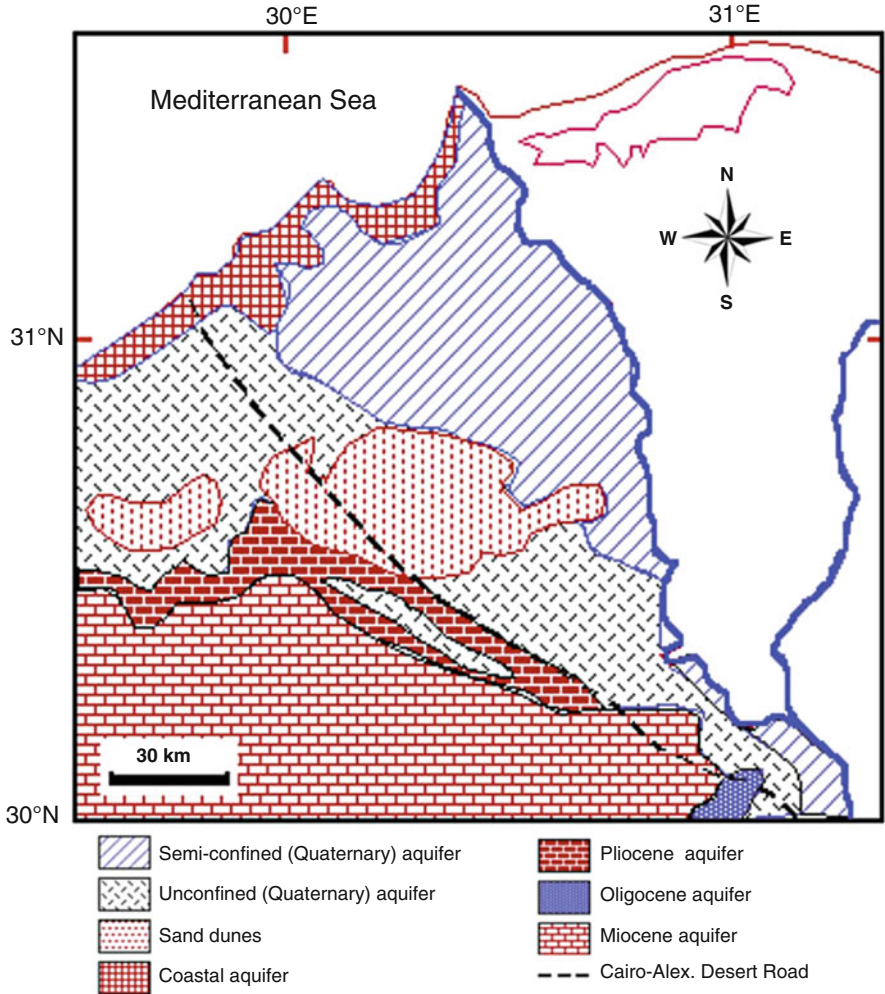
Fig. 2 The groundwater aquifers in Western Nile Delta (after [16])

seepage from canals, and infiltration of rainfall that takes place only during the winter months. In the southern and central parts of the floodplain, the downward leakage towards the aquifer ranges between 0.25 and 0.8 mm/day, depending on irrigation, and drainage practices, and the soil type. In the desert areas, relatively high leakage rates are observed for basin, furrow, and sprinkler irrigation (1.0–1.5 mm/day) with much lower rates for drip and central pivot irrigation (0.1–0.5 mm/day). Discharge of groundwater takes place naturally through the outflow into the Rosetta branch and drainage system, evapotranspiration, and inter-aquifer flow of groundwater, and artificially through direct abstraction. Groundwater return flow to Rosetta branch and drains and extraction by production wells are the main discharge components.

Table 3 Hydraulic parameters of the Quaternary aquifer in Western Nile Delta

Study	K (m/day)	T (m^2/day)	S	S_y	Porosity (%)	Effective porosity (%)
Zaghloul [17]	119.00		10^{-4}–10^{-3}	0.15	30	
Shahin [18]	50.00	2,500–25,900	10^{-5}–10^{-4}	0.20	25	23.25
Laeven [19]	150.00	10,350–59,800			25–30	
RIGW [20]	75.00	15,000–75,000	10^{-4}–10^{-3}		25–40	
Bahr [21]	75.00		1.1×10^{-3}		25	18

K hydraulic conductivity (m/day), T transmissivity (m^2/day), S storage coefficient, Sy specific yield

Table 4 Hydraulic conductivity of the semi-confining clay cap layer

Study	K_h (m/day)	K_v (m/day)
Farid [22]	0.2160	0.0025
RIGW/IWACO [23]	0.2505	0.0484
Warner et al. [24]	0.2160	0.0073

5 Groundwater Flow Modeling

In the present study, TRIWACO a steady-state, three-dimensional, finite-difference groundwater flow model has been employed to simulate flow and get the budget of groundwater in the study area. TRIWACO is a numerical program package for three-dimensional simulation of groundwater flow under the steady-state and transient conditions by finite element technique. MODFLOW has been used through the comprehensive packages of the program. It has been used in the present study as tools for every phase of the groundwater simulation including area characterization, model development, postprocessing, calibration, and visualization [27].

5.1 Conceptual Model Development

To develop a conceptual model, the locations of rivers, canals, drains, wells, layer parameters such as hydraulic conductivity, and model boundaries for the simulation have been defined at the conceptual model level. Once these data are completed, the conceptual model is converted to the grid model, and the program performs all of the cell-by-cell assignments automatically. The model consists of the multilayer aquifer system. The first layer represents the semi-confining layer (upper clay layer) that is modeled as an aquifer in which horizontal and vertical flow is simulated. All surface water features such as Rayah El Beheiry, Rayah El Nasseri, and El Nubariya canals and main open drains are included as "rivers" in the model. Groundwater abstraction occurs from Quaternary and Miocene aquifers, while storage changes (confined or
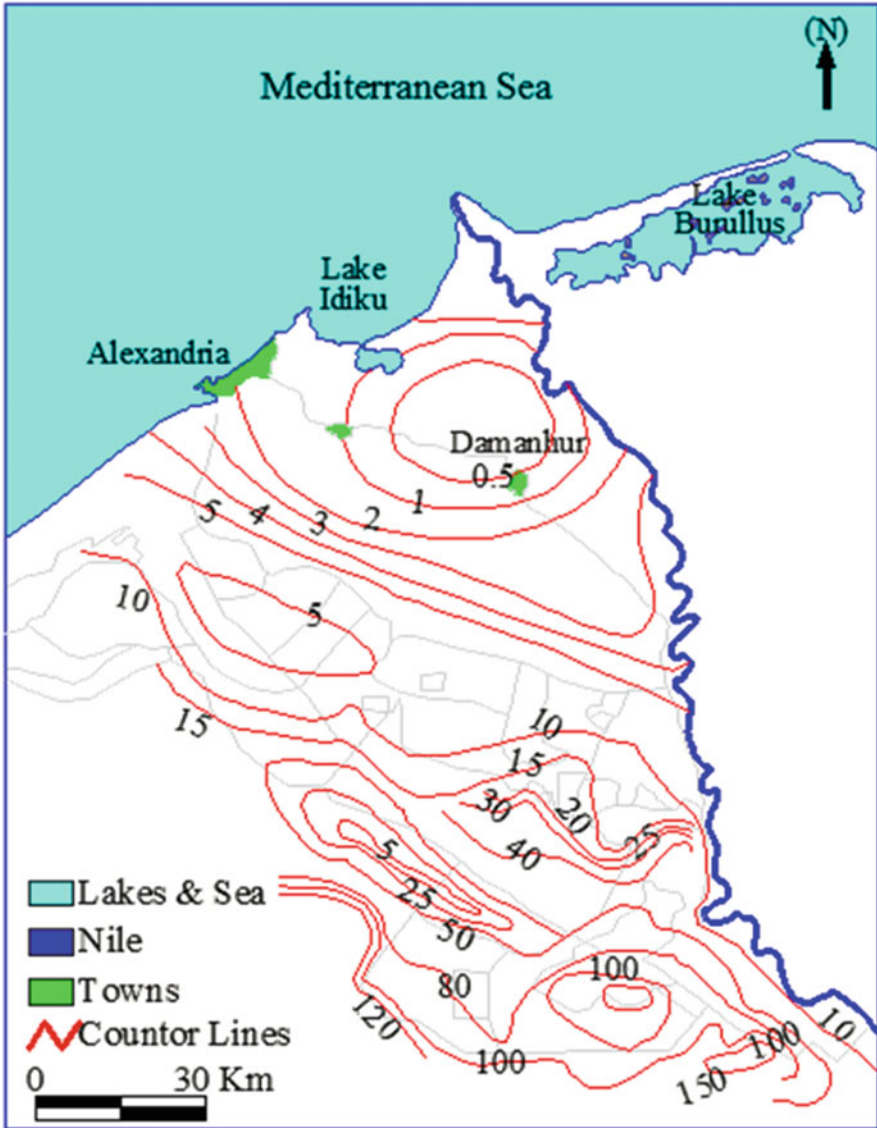
Fig. 3 Average depth to groundwater in the Quaternary aquifer in Western Nile Delta in 2008 [26]

unconfined, depending on the groundwater level relative to the top of the layer) are simulated when the model is running in the transient state (Fig. 4).
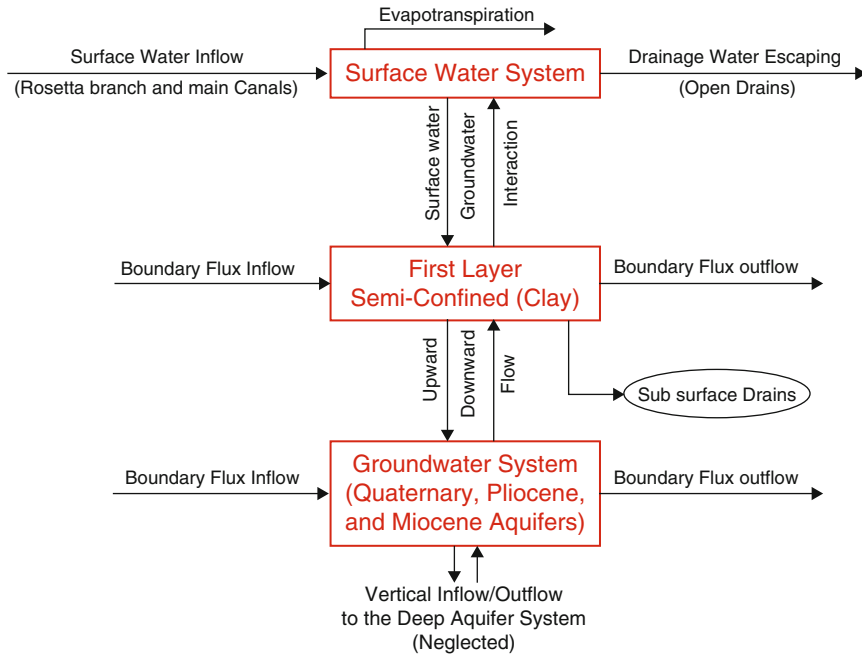
Fig. 4 Multilayer conceptual model for the study area

5.2   Numerical Simulation

After initializing the numerical model data, interpolation is used to define the top and bottom elevations of the layer and the starting (observed or initial) head levels of groundwater. The conceptual model is then converted from a high-level feature object-based to a grid-based MODFLOW numerical model. GIS was used to manage the spatially distributed input parameters and outputs of the model [28]. Primarily, the hydrogeological properties of the aquifer (geological layers, hydraulic conductivity, and porosity), and also maps of land use, the location of pumping wells, and surface water bodies were imported to the database of the ArcGIS. Ground elevation and topography map was generated by the interpolation of the points' data from boreholes over the area. Two aquifer layers covering an area of about 15,170.6 km^2 have been simulated in the computational 3D grid that consists of 32,800 nodes and 64,870 equilateral elements incorporating the triangular elements size that ranges from 500 m in the main area of interest to 1,000 m in the remainder of the area and the desert fringes outside the area.

5.3   Boundary Conditions

For the southwestern border where faults exist, and no flow from the western desert enters the aquifer system, no flow boundary was specified (Neumann conditions). In this case, the derivatives of the head (flux) across the boundary are set to zero. Water levels in Rosetta branch were almost constant. Therefore, the piezometric heads are constant (Fig. 5) and do not change with simulation time. This eastern border is specified across the model as a fixed head boundary (Dirichlet conditions). Rayah El Beheiry to the east and El Nubariya canal to the north are defined as stream flow-routing (River) package that simulates the interaction between surficial streams and the groundwater. Water can move from the stream to the aquifer or from the aquifer to the stream depending on the relative differences in the stream stage and the water table elevations. The recharge zones depend on the land use and hydrogeological conditions for each zone. The influx to the system is assumed primarily through recharge due to infiltration from canals, excess irrigation water, and limited rainfalls.

5.4   Model Calibration

The model was calibrated against the available average annual groundwater heads of about 60 observed wells during the period from 1990 to 2002. The calibration is by steady-state and transient nonlinear conditions using trial and error method which requires several trials by adjusting the hydraulic conductivity, specific storage, and recharge. Model is repeatedly run within an acceptable level of accuracy (± 0.5 m) until the computed solution is matched with the observed values. Figure 6 presents a map of the calibrated piezometric surface for the Western Nile Delta area.

5.5   Groundwater Assessment

To assess the groundwater resources within the study area, the calibrated model has been used to calculate the water balance and the groundwater aquifer potentiality. The surface water inflow to the study area is about 9,375 million m^3, and the drainage water is approximately 4,545 million m^3, out of this volume about 875 million m^3 is reused for irrigation. The calculated water balance indicated that the annual net recharge to the aquifer system is estimated at 1,950 million m^3 and the annual total aquifer potentiality at about 468 million m^3. Figure 7 shows the schematic diagram for the calibrated water balance for the Western Nile Delta.
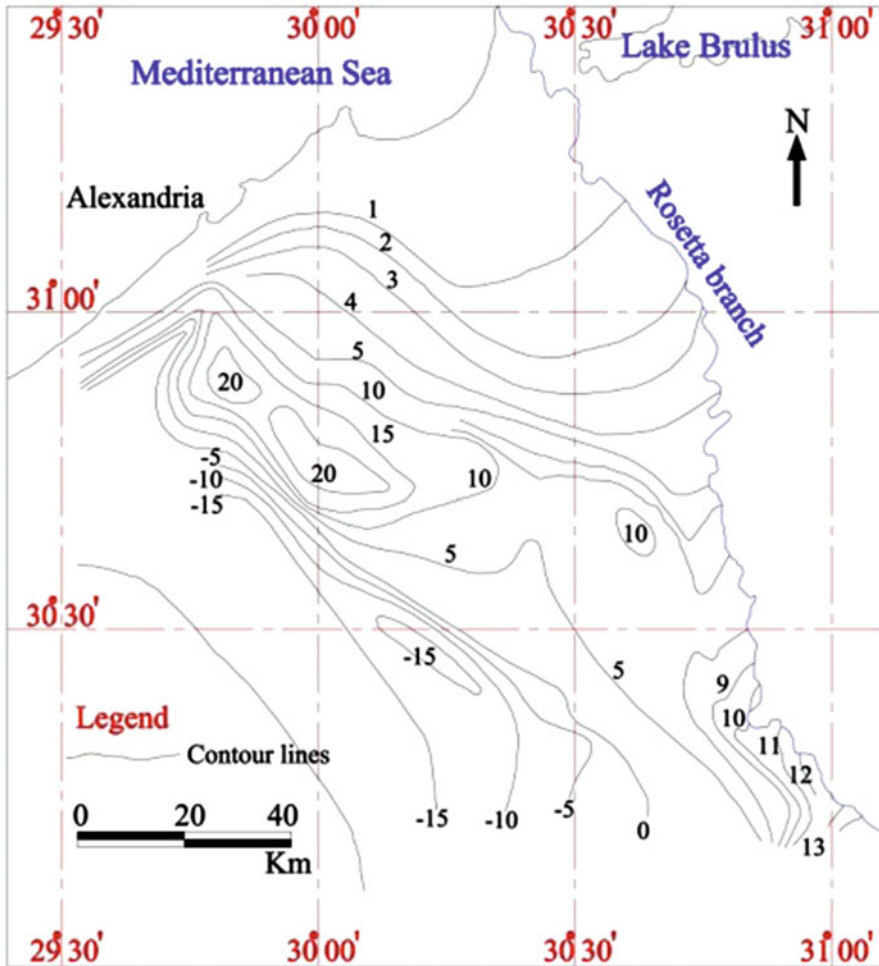
Fig. 5 Constant heads for Western Nile Delta [26]

6   Groundwater Management Plans

To achieve the sustainability plan of water resources developments of the Ministry of Water Resources and Irrigation [4] at Western Nile Delta, it is clear that the management plans are required to provide the water requirements for the newly proposed reclaimed areas. Therefore, water budgets analysis till the reference year should be adequately calculated for accurate prediction of the groundwater heads and tested with different alternative scenarios. Previous researchers studied the groundwater management for sustainable developments of Western Nile Delta (e.g., [10, 29, 30]).

El Molla et al. [10] studied different management scenarios for the Western Nile Delta aquifer to satisfy the need for 465,000 feddan of new lands reclamation. Water
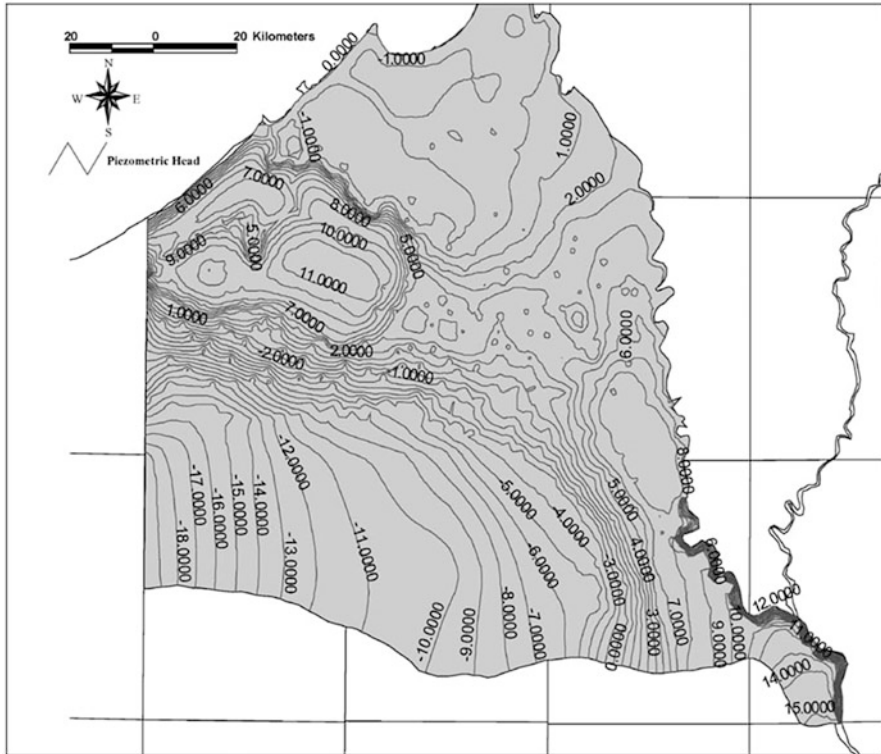
Fig. 6 Calibrated groundwater piezometric heads for Western Nile Delta [29]

demand of 7,000 m³/year/feddan as an average for Western Nile Delta is assumed [3]. Therefore, the excess inflow required for irrigation water supply is nearly 3.25 bm³. Recharge seepage down to the aquifer after full reclamation is 1.2 mm/day per feddan. Safe abstraction from the groundwater aquifer in the year 2017 was calculated after reclaiming all areas for cultivation in Western Nile Delta. Three different scenarios were studied with alternative conjunctive uses for available water resources in Western Nile Delta (surface water, groundwater, and drainage water reuse) to prevent aquifer depletion.

The first scenario is the construction of a new canal with 2.1 BCM of surface water taken from Rayah El Beheiry as proposed by MWRI [3]. The increase of safe groundwater abstraction to avoid aquifer exploitation, as calculated by the model, is about 1.0 BCM/year. Groundwater piezometric heads for the first scenario are shown in Fig. 8a. It is clear that observed excess recharge has affected the piezometric head in the southern part of the study area, that is raised from −15 to 3 m. These changes caused moving back of the contour lines in the northern area especially in the part near to the Rosetta branch. Contour lines in the southern section near Rosetta branch were decreased by about 1 m. It is observed that the amount of abstraction by wells was approximately equal to the net recharge of the aquifer. Therefore, finally no changes
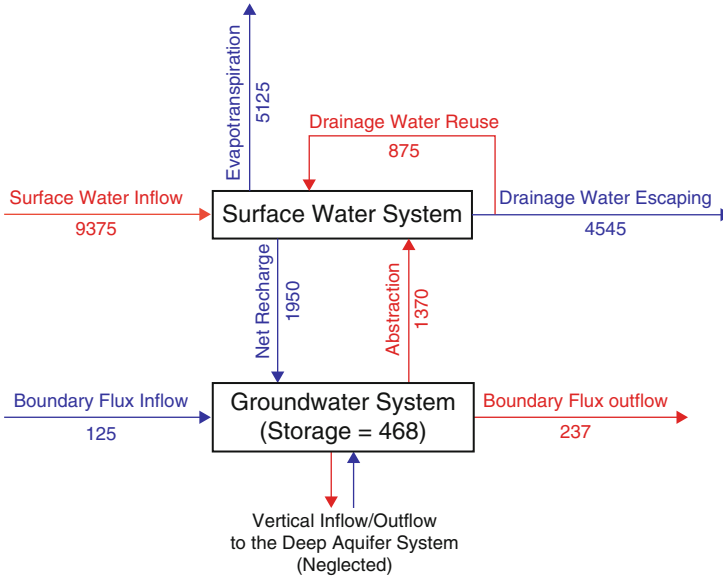
Fig. 7 Schematic diagram for the water balance of Western Nile Delta [29]

in piezometric levels except for local conditions are attributed to the vicinity of the modeled abstraction wells. Water budget analysis shows an increase in recharge with 1.0 BCM according to the increase in the cultivated area. Constant head outflow increased by 0.05 BCM, and the influx changed only with 0.001 BCM.

The second scenario is the drainage water reuse of the drainage water that flows into the sea. The drainage water reuse accounts 4.50 BCM, 5.50 BCM, 13.50 BCM, and 15.50 BCM in year 2005, 2007, 2015, and 2017, respectively [2, 10, 31, 32]. This scenario was processed by using the same input data as in the first scenario, but without the proposed canal therefore extra 2.25 BCM was gained from the use of drainage water. Quantitatively, this situation is similar to the first one except for the additional amount of freshwater needed for mixing with drainage water and also salt concentrations are increased.

The third scenario is the reduction of Rosetta branch discharge to account for Toshka project. Water requirements for Toshka project is 5.5 BCM per year. In 2017, the Ministry of Water Resources and Irrigation was organizing a plan to decrease 4 BCM from delta region by changing the crop patterns and 1.5 BCM from current discharges of Upper Egypt [3]. This reduction of 4 BCM will be divided between western, middle, and eastern delta with a ratio according to the current recharge. The current water distribution for Western Nile Delta is 10.98 BCM (32.3% of the delta). This scenario has an effect on the total water resources availability Western Nile Delta. Rosetta branch flow will decrease to 9.69 BCM, which is not enough for the existing cultivation area.
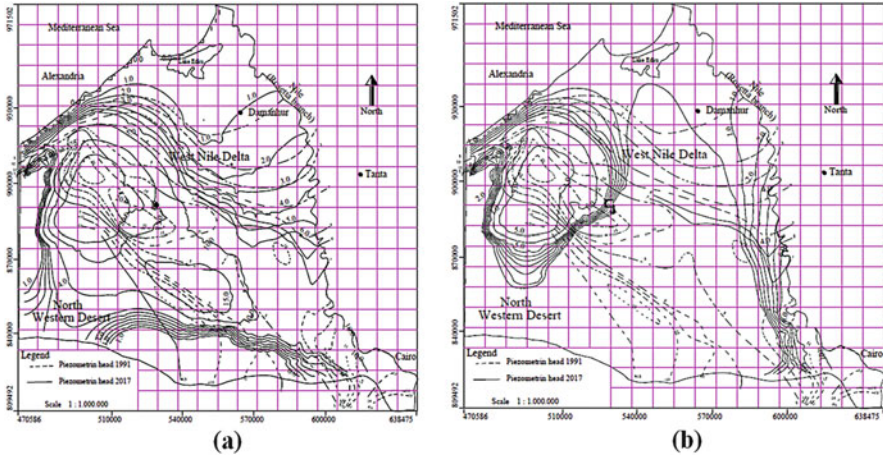
Fig. 8 Groundwater heads, (**a**) for the first scenario; (**b**) for the third scenario [10]

Groundwater levels are declined, and the highest groundwater level is about 6 m. This lowering in the piezometric head would increase the saltwater intrusion from the Mediterranean Sea. Water budget for the groundwater aquifer indicated an apparent shortage in the recharge values in comparison to the abstraction. The water budget analysis for the study area in 2017 is listed as follows [10]:

Available water quantities:

- Rosetta branch, 9.69 BCM
- Abstraction from groundwater aquifer, 2.08 BCM

Required water quantities:

- Old cultivated areas, 10.9 BCM
- Newly cultivated lands, 3.25 BCM

Shortage of about 2.38 BCM/year will occur if this scenario is applied. It is therefore recommended to either decrease cultivated area (do not reclaim all the planned regions) or change the crop pattern to decrease irrigation water application or increase the canals' network discharge by the 2.38 BCM.

Dawoud et al. [29] developed a GIS-based model for the Western Nile Delta aquifer to evaluate groundwater potentiality. Two scenarios were simulated and tested using the calibrated groundwater model in 2002. The first scenario considers a reduction of the surface water inflow to Western Delta region. The problem of shortage in irrigation water could, in this case, be partly solved by increasing the annual abstraction from the groundwater by about 450 million m^3 and also by improving the tradition flooding irrigation system. The surface water is hydraulically connected with the Quaternary aquifer in Western Nile Delta. So, any change in the surface water inflow would have a direct impact on the groundwater heads. Also,

irrigation system improvement could reduce the rate of water application and then minimize the amount of recharge to the aquifer system.

The new water levels in the surface water bodies after the reduction of surface water inflow have been calculated along with the new rate of recharge after the irrigation system improvement. After running the model, it was found that although recharge input to the model has been reduced by 10%, the net recharge calculated from the model is increased by about 5.7%. This is due to the effect of river/aquifer interaction. The increase in net recharge is coming from the seepage from the surface water bodies. But, it was also found that the aquifer potentiality has been reduced by about 91%.

The second scenario has evaluated the effect of constructing a new canal that diverts the water from Rayah El Beheiry to the western part of the study area. It could help to feed the newly reclaimed lands and to minimize the overpumping of groundwater in the stressed areas. Although the path of this new canal is not yet defined along with the water levels, a preliminary test has been evaluated and shows that the annual aquifer potential could be increased by about 23%.

Morsy [30] studied the impact of groundwater development plan from the year 1992 to 2008 for the Western Nile Delta aquifer on the water table and highlighted the waterlogging problems. A drawdown of groundwater levels in the southern part of the western fringes of the Nile Delta (between 5 and 15 m) due to extensive exploitation of groundwater and lack of recharge was recorded.

7 Conclusion and Recommendations

This chapter summarizes the physical and hydrogeological settings of the Quaternary aquifer in Western Nile Delta including land use, meteorological data, topography, soil classification, drainage as well as irrigation systems, boundary conditions, and hydraulic parameters. The groundwater aquifer is mainly recharged by Rayah El Beheiry, Rayah El Nasseri, and El Nubariya canals in their first reaches. Discharge from the aquifer takes place through the outflow into the Rosetta branch and drainage system, evapotranspiration, inter-aquifer flow of groundwater, and direct abstraction by production wells. Groundwater aquifer in Western Nile Delta is in direct connection with Rosetta branch and main canals. A GIS-based model has been developed with the conjunction of MODFLOW groundwater model to simulate the water resources in the Western Nile Delta. The model has provided a useful tool to evaluate the groundwater resources status and to test the different proposed management alternatives in the region of West Nile Delta. The model was calibrated against the average annual groundwater heads of about 60 observation wells during the period from 1990 to 2002.

Results showed that, in case of planned reclamation completion for 460,000 feddan, the regional water balance indicated that the extra abstraction must not increase more than 1.0 BCM/year to avoid aquifer exploitation. Water budget in Western Nile Delta shows the need to increase the surface water quantity by 2.1

BCM through the newly proposed canal to fulfill the required irrigation demands for the new reclamation area. Results also clearly indicate that reducing the surface water inflow and increasing the dependency on groundwater abstraction and irrigation system improvement would decrease the annual aquifer potentiality by about 91%. These results illustrate the need for a more detailed analysis concerning the effect of irrigation improvement and thus could be considered as preliminary regional evaluation for testing the alternative water management scenarios in Western Nile Delta area.

It is strongly recommended to study the effect of saltwater intrusion on the groundwater quality for a better understanding of the water management scenarios especially if drainage water reuse is implemented. To avoid groundwater deterioration at Western Nile Delta, it is recommended to apply well-controlled license system of wells abstraction to update the wells inventory database. Some baseline data is available, but it is full of inconsistency due to several reasons among them the unregistered or unofficial abstraction from wells. Updating this information would be a first step and additional research will be needed for the optimum operation and maintenance of the whole groundwater aquifer system in Western Nile Delta.

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