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Full Length Research Paper

Groundwater vulnerability and risk mapping of the Quaternary aquifer system in the Northeastern part of the Nile Delta, Egypt

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As the most valuable natural resources, protection and management of groundwater is vital for human evolution, socio-economic development and ecological diversity. This paper presents the groundwater vulnerability mapping of the Quaternary aquifer system in the northeastern part of Nile Delta using Weighted Multi-Criteria Decision Support System model (WMCDSS). This model has been implemented using Geographic Information System to delineate groundwater zones and to suggest a protection and improvement plan for major groundwater wells in the area. Six thematic layers were digitally integrated after assigning different weights (W_f) and rates (R_f) to them. These GIS layers have been created to adopt the most indicative criteria for investigating the groundwater degradation trends from sea level rise and seawater intrusion. The chosen layers are: total dissolved solids (TDS), $rCl/rHCO_3$ ratio, sodium adsorption ratio (SAR), groundwater type, hydraulic conductivity (K) and well discharge (Q). Weights have been assigned to all these layers according to their relative importance for groundwater vulnerability, whereas their corresponding normalized weights were obtained from their effectiveness factors. The groundwater vulnerability map indicates four classes ranging from very low to high. According to this map, the promising localities for groundwater usage are located in areas where very low to low vulnerability has been observed. These localities are distributed over 4080 Km^2 area, covering 53.68% of the total study area. The areas having moderate to high groundwater vulnerability are more than 3520 Km^2, indicating a deterioration of groundwater quality in 46.32% of the study area, which need special treatment and cropping pattern before use.

Keywords: Nile Delta, Egypt, groundwater, vulnerability, Quaternary aquifer, sea level rise.

INTRODUCTION

The study area, which is located in the northeastern part of Nile Delta, extend between latitudes 30° 00′ – 31° 30′ N and longitudes 31° 00′ – 32° 20′ E (Figure 1). This area is bounded to the north by Mediterranean Sea and Manzala Lake, to the south by Ismailia Canal, to the east by Suez Canal and to the west by Damietta Branch Canal. The northern part of Nile Delta is currently undergoing rapid environmental degradation and ecological transformation. Most serious among these problems are the combined effects of land subsidence, sea level rise due global climate changes, damming/irrigation/ and other anthropogenic activities. As a result of the first two processes, the deltaic area is experiencing seawater intrusion and coastal erosion (Stanly and Wame, 1993). On the other hand, salinization has increased substantially since the construction of the Aswan High Dam in 1964, which resulted in to reduced agriculture productivity (Biswas, 1993) and a significant change in water chemistry of the delta's lagoon lake (Kerambrun, 1986).

The Egyptian part of Mediterranean shoreline is most

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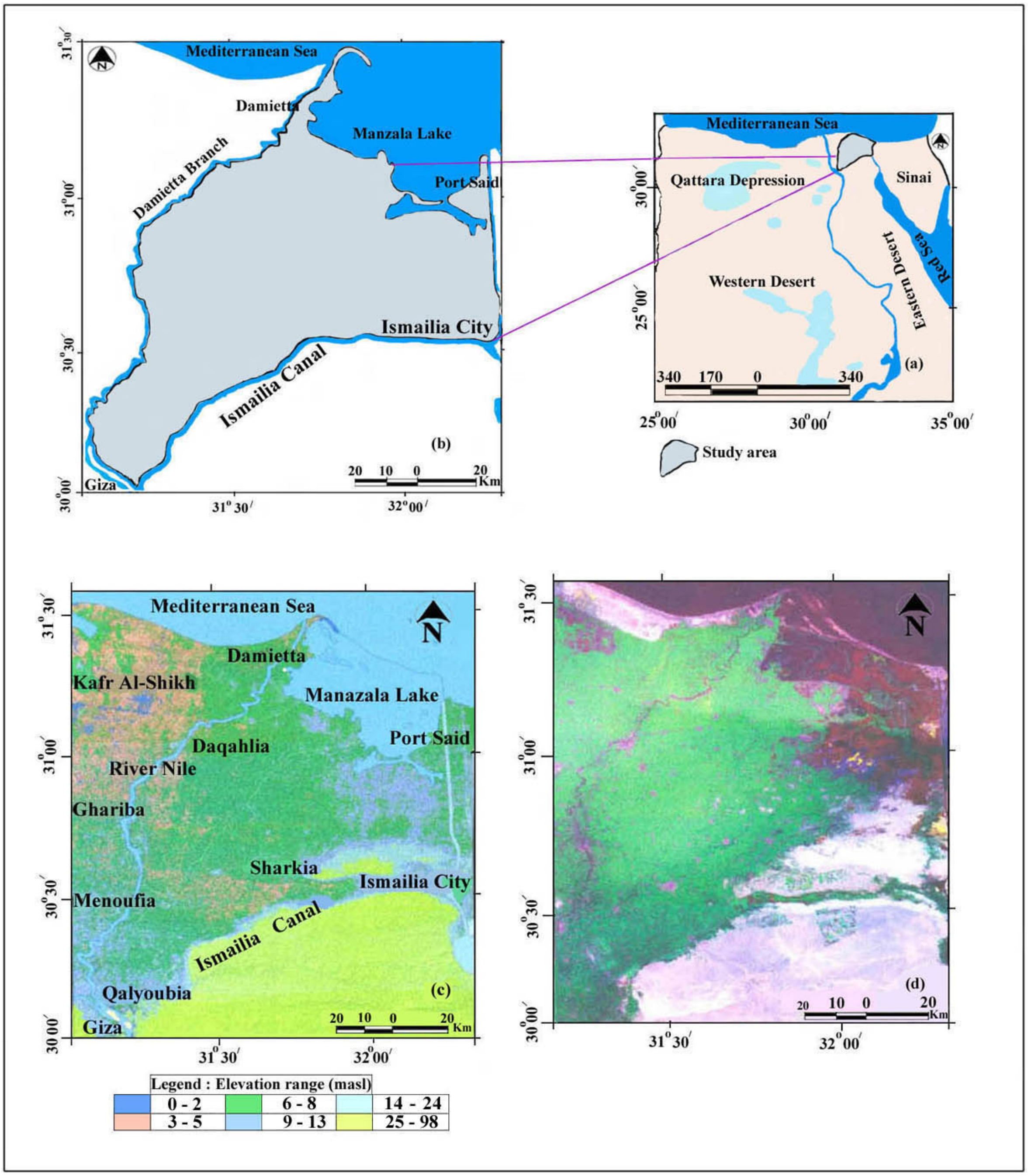

Figure 1. (a,b) Location map of the study area; © Digital Elevation Model; (d) False color composite image of the TM sensor acquired in 1984.

Vulnerable to sea level rise due to its relatively low elevation. The coastal zones in Egypt are of paramount importance in terms of economical, industrial, social and cultural activities. In addition to enhanced tourism activities, a move towards building new industrial complexes is progressing rapidly. However, an increasing level of vulnerability is going to affect the agricultural productivity, human settlements and tourists activities in these areas (El-Raey, 2009). Prior to the construction of Aswan Dam, the Nile delta shore remained in fluctuating equilibrium between the sediments supplied by river and the transport along the coast (Douglas, 2005). However, after the construction of this dam, sediments input in the delta registered a significant reduction, which resulted in severe shoreline erosion and salt-water intrusion (Jelgersma, 2005; Ericson *et* al., 2006). Currently, the Nile delta is experiencing erosional waves driven by currents in the east Mediterranean gyre that sweep across the shallow shelf with a speed up to 1 m/s. Moreover, construction of man-made waterways for irrigation and intense shipping activities has trapped the already depleted sediments supply to the Nile delta. This phenomenon is a key contributor to coastal erosion and land loss occurring in the delta as well in its two branches; the Rosetta and Damietta (Inman *et* al., 1992; Fanos, 1995; Stanley J., 1996; Stanley *et* al., 1998; El-Raey, 1999).

The Aswan dam now controls flood cycle throughout the year, which previously flushed the Nile Delta plain and prevented substantial accumulation of salts in this evaporitic setting. Another factor of concern is the tapping of sediments in the Nasser Lake behind the dam, reducing nutrients formerly carried downstream by flowing water via Nile Delta to offshore. At the same time, the rapidly increasing population has necessitated intensified agricultural development by diverting the Nile water through dense and complex irrigation system. In addition, an unprecedented municipal expansions and land reclamation of the vital deltaic water bodies (such as lagoons and marshes) have also affected the natural flow in the river. As a matter of fact, the northeastern Nile Delta is one of the most important agro-economical regions in Egypt, which accommodates about 60% of the total arable lands inhabited by 45% of the total population (Coleman et al., 1981; Hereher, 2009). Additionally, the northern part of the study area comprises about 25% of the total Mediterranean wetland (Sestini, 1992).

The Nile Delta aquifer system serves as a major source of fresh water supply, which is considered as a unique renewable aquifer system in the country. Since, the Nile Delta received heavy urbanization during the past few decades, a demand for freshwater become multifold. Groundwater in the northeastern part of Nile Delta is fragile in terms of their vulnerability to sea level changes and an eventual salinization by seawater intrusion. Human activities represented by heavy consumption rates make the problem more severe. Inappropriate management of the coastal aquifer may lead to its destruction as a freshwater source much earlier than those not connected to the sea. Seawater intrusion is one of the widespread and important processes, which degrade water quality by rising salinity to a level that exceed a standard permissible limit for drinking and irrigation purposes and, thus, endangers the future exploitation of coastal aquifers (Bear *et al.*, 1999). In the Nile Delta, the inland saltwater encroachment is the most commonly observed reason for increasing salinity in the Quaternary aquifer system (Shehata, 2004). Compared to the Early Pleistocene aquifer system, the superficial Holocene aquifer in the area is more likely to become contaminated as a result of activities at or near the land surface (NARSS, 2007).

The objective of this study is to construct groundwater vulnerability map for Quaternary aquifer system in the northeastern part of Nile Delta (Egypt) using hydrogeological and hydrochemical criteria. This is a new approach to delineate potential groundwater zones and to suggest a protection plan for improving groundwater quality using Weighted Multi-Criteria Decision Support System model (WMCDSS). Accordingly, Geographic Information System (GIS) is used to construct a weightage- based spatial modeling technique for judging the Quaternary aquifer system vulnerability to seawater intrusion. This type of vulnerability map, which become an essential tool for groundwater protection and environmental management, will predict and highlight the areas where chances of contamination are higher than the others.

The Impacts of Sea Level Rise (SLR) on Groundwater Resources in Egypt

Egypt is one of the African countries that have been listed vulnerable to acute water problem, where both the water supply and demand are expected to be affected by climate changes and the SLR. A combination of saltwater intrusion by SLR and increasing soil salinity by enhanced evaporation are expected to reduce the quality of shallow groundwater in the coastal areas. Rainfall frequency along the coastal areas is getting unpredictable in terms of its increasing or decreasing trend. A demand for water in Egypt is dominated by three major users: agriculture, domestic and industries. The agricultural sector consumes about 85% of the total water used annually. It is, therefore, most likely that any effects of climate change on water supply and demand will be increased by much larger increase in demand due to population growth (El-Raey, 1999).

One of the most significant impacts of SLR on the water resources is an increase in the occurrences of saline intrusion that can contaminate groundwater resources in the coastal area. The eastern part of Manzala Lake appears to be subsiding at a rate of 4.5 mm /y (Stanley, *et* al., 1993), which is much faster than any other region along the Nile delta coast. The SLR is expected to cause a landward shift of salt wedges that could increase the rate of saline seepage to topsoil under the delta. This salinization phenomenon may bring serious problem to agriculture and drainage systems,

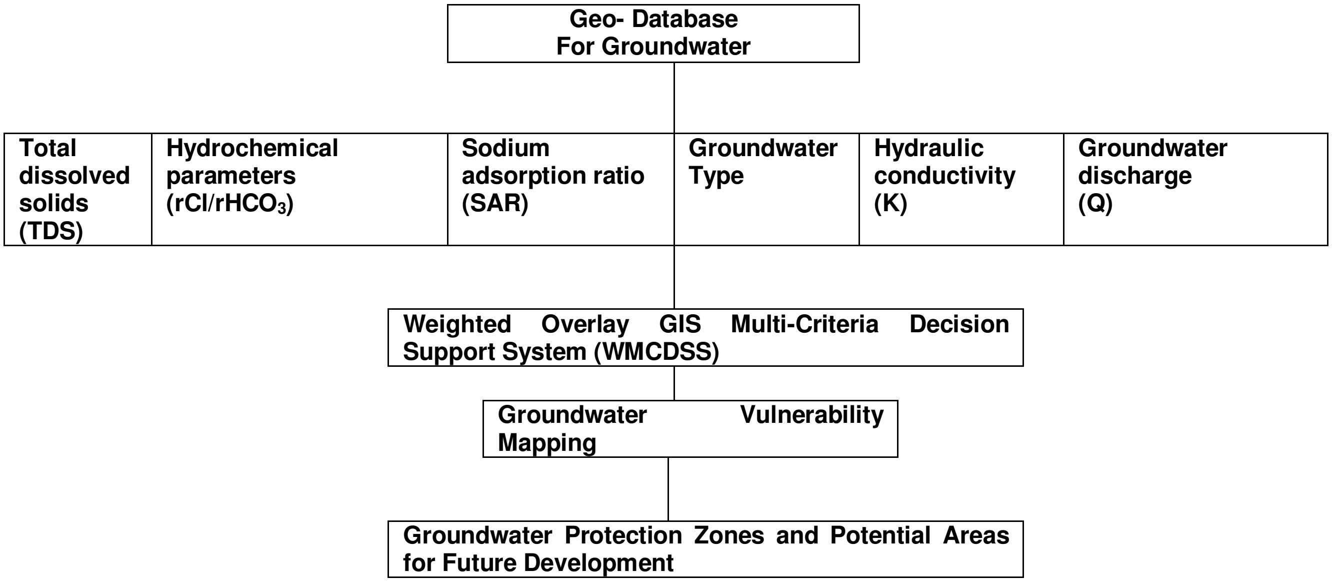

Figure 2. Model methodology flowchart used for this study

Table 1. Chemical analyses results of the groundwater samples from Quaternary aquifer system in the study area.

Sample No.	EC	TDS	pH	K^+	Na^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	rNa / rCl	rCl / $rHCO_3$	SAR	Water type
1	1.26	773	7.7	0.40	3.2	4.9	4.0	7.5	2.60	2.5	0.43	3.00	1.5	Mg-Ca-Cl-SO_4
2	0.94	638	7.7	0.30	3.1	2.6	3.5	4.0	1.40	4.0	0.77	1.00	1.8	Ca-Na-Cl-HCO_3
3	2.78	1727	7.4	0.80	11.0	5.9	10.0	20.0	0.80	6.9	0.55	2.89	3.9	Na-Ca-Cl-HCO_3
4	10.8	6193	7.7	3.40	54.0	18.8	31.0	101.0	0.40	6.0	0.54	16.83	10.8	Na-Ca-Cl
5	3.49	2163	7.4	0.90	15.0	6.9	12.0	25.0	1.90	7.9	0.60	3.18	4.9	Na-Ca-Cl-HCO_3
6	5.22	3130	7.5	0.33	27.8	5.1	17.5	27.3	15.0	6.16	1.02	4.43	8.3	Na-Ca-Cl-SO_4
7	19.1	12182	7.3	2.46	164.4	24.3	17.2	163.7	25.8	10.2	1.00	16.10	36.1	Na-Cl
8	21.2	12202	7.1	2.56	169.6	24.9	18.1	169.0	25.8	4.9	1.00	34.37	36.6	Na-Cl
9	6.00	3587	7.8	0.18	32.2	13.0	12.4	31.0	19.8	6.3	1.04	4.91	9.0	Na-Mg-Cl-SO_4
10	32.0	18400	7.2	2.56	202.6	92.9	27.3	300.3	22.0	2.5	0.68	118.9	26.1	Na-Mg-Cl
11	1.26	855	7.1	0.38	2.8	3.2	5.6	2.8	2.5	6.6	1.00	0.42	1.3	Ca-Mg-HCO_3-Cl
12	1.15	690	7.8	0.51	4.0	2.4	3.2	3.8	2.1	4.1	1.04	0.93	2.4	Na-Ca-HCO_3-Cl
13	1.10	573	7.6	0.33	4.3	2.1	2.0	3.1	1.7	3.4	1.35	0.92	3.0	Na-Mg-HCO_3-Cl
14	1.4	826	7.3	0.56	4.5	2.9	4.0	4.2	3.0	4.8	1.08	.88	2.4	NA-Ca-HCO_3- Cl
15	0.68	424	7.5	0.38	1.8	2.1	1.8	1.8	1.3	3.0	1.00	.59	1.3	Mg-Na-HCO_3-Cl
16	1.29	734	7.5	0.51	4.8	2.0	3.4	4.8	1.8	4.1	1.00	1.16	2.9	Na-Ca-Cl-HCO_3
17	0.45	310	7.5	0.21	1.7	0.9	1.6	1.5	0.6	2.2	1.09	.70	1.5	Na-Ca-HCO_3-Cl
18	0.74	701	8.2	0.41	6.7	1.6	1.6	1.5	7.7	0.79	4.43	1.93	5.3	Na-SO_4
19	0.44	292	7.8	0.23	.85	1.2	2.0	0.9	0.4	2.62	1.00	0.32	0.7	Ca-Mg-HCO3-Cl
20	0.44	726	7.4	0.23	2.26	4.2	4.5	2.5	2.4	5.3	0.90	0.48	1.1	Ca-MG-HCO3-Cl
21	0.88	541	7.3	0.49	2.3	2.6	2.4	2.3	2.1	3.4	1.00	0.65	1.4	Mg-Ca-HCO_3-Cl
22	1.55	1190	8.0	0.49	14.4	0.94	0.97	3.4	3.1	8.9	4.25	0.38	14.7	Na-HCO_3-Cl
23	1.42	780	7.7	0.41	7.3	1.6	2.96	7.3	0.63	3.7	1.00	1.98	4.8	Na-Ca-Cl-HCO_3
24	0.95	440	7.6	0.31	2.62	2.06	1.4	2.62	0.46	3.28	1.00	0.80	2.0	Na-Mg-HCO3-Cl
25	1.03	726	8.4	0.21	3.48	2.88	4.3	2.48	2.27	2.25	1.40	0.47	1.8	Ca-Na-HCO_3-Cl
26	0.72	521	7.8	0.36	1.09	1.64	3.25	1.63	1.79	3.77	1.28	0.43	1.3	Ca-Na-HCO_3-SO_4

Table 1. Continue

27	0.78	479	7.5	0.44	3.0	12.06	1.44	2.76	0.94	3.21	1.08	0.86	2.3	Na-Mg-HCO$_3$-Cl
28	1.0	647	7.6	0.23	3.47	1.86	3.75	3.46	1.08	4.67	1.00	0.74	2.1	Ca-Na-HCO$_3$-Cl
29	56.2	35680	7.1	6.00	489.0	84.0	32.0	550.0	60.0	0.61	0.8	906.8	64.2	Na-Cl
30	16.0	6594	7.4	1.44	62.3	5.35	45.0	108.3	4.03	1.69	0.58	64.14	12.4	Na-Ca-Cl
31	0.35	278	7.8	0.10	1.35	0.91	1.40	0.71	0.21	2.75	1.90	0.26	1.3	Ca-Na-HCO$_3$
32	0.67	360	7.7	0.41	1.41	2.0	1.28	1.41	0.85	2.79	1.00	0.51	1.1	Mg-Na-HCO$_3$-Cl
33	1.02	450	7.7	0.31	2.09	1.68	2.52	1.08	0.94	3.28	1.00	0.64	1.4	Ca-Na-HCO$_3$-Cl
34	0.48	406	7.8	0.23	1.3	1.27	2.72	0.90	0.88	3.66	1.45	0.25	0.9	Ca-Na-HCO$_3$
35	0.49	473	7.7	0.26	2.03	2.06	2.4	1.75	0.85	3.93	1.00	0.44	1.4	Ca-Mg-HCO$_3$-Cl
36	0.75	500	7.8	0.36	2.54	2.4	2.25	2.54	0.90	3.61	1.16	0.70	1.7	Na-Mg-HCO^3-Cl
37	0.65	500	7.7	0.12	2.54	2.4	2.45	2.54	0.79	3.77	1.00	0.67	1.6	Na-Ca-HCO$_3$-Cl
38	2.14	1554	7.6	0.26	13.91	2.45	7.16	12.11	6.46	5.10	1.15	2.37	6.3	Na-Ca-Cl-HCO$_3$
39	17.9	11355	6.8	0.64	101.7	41.5	60.5	158.6	1.10	2.82	0.51	70.43	14.2	Na-Ca-Cl
40	0.56	567	7.7	0.49	3.27	2.20	2.40	3.27	0.88	3.93	1.00	0.83	2.2	Na-Ca-HCO$_3$-Cl

Units: TDS (mg/l), dissolved ions (epm), EC (ds/m)

which can eventually affect the available groundwater resources in the upper Nile Delta. In addition, the water in Manzala Lake may get an increase input of salinity due to stronger influence of tidal flows penetrating the lake. Changes in the salinity conditions of the lake may in turn affect its ecology and fisheries related resources (El-Raey, *et* al., 1999).

METHODOLOGY

Locations of the groundwater samples were digitized as point data and a database for the respective parameters has been constructed using ArcGIS 9.3.3© package. Spatial maps for each criteria (including TDS, Cl/HCO$_3$, SAR, groundwater type, K and Q) have been constructed from point data using the applied ArcGIS 9.3.3© spatial analyst extension. The "Kriging" interpolation method was then applied to obtain the distribution values. Define the most effective parameters for making the weighted in GIS and Multi-Criteria Decision Support System (WMCDSS). Groundwater vulnerability map for the Quaternary aquifer system determining saline and fresh water zones has been prepared. A complete flowchart for the used methodology is explained in Figure 2.

Hydrochemical data collection

Groundwater samples were collected from 40 drilled wells during 2011. On spot measurements were made for groundwater levels, pH values and Electric conductivity (EC). As initial step, all the samples were immediately preserved in the ice tanks after their collections, and then sent to the laboratory to chemically analyze major ions and total dissolved solids. The analyzed chemical data for Quaternary aquifer system are listed in Table 1 and the location map of groundwater samples is shown in Figure 3.

Building GIS database and mapping

The impact of sea level rise and an eventual inland intrusion of seawater could be assessed by performing a GIS-based vulnerability mapping. Several methods have been proposed for this purpose, which can be classified into three categories, namely: overlay and index methods, process based methods and statistical methods (Anthony *et al*., 1988; NRC, 1993; Nobre *et al*., 2007). The DRASTIC model, which falls under the overlay and index category, is the most widely used for vulnerability assessment in regional scale granular aquifers (USEPA, 1993; Aller *et al*., 1987) and for AGPZ in karstic aquifers (SAEFL, 1998).

The present research describes a new approach to assess groundwater vulnerability based on the construction of weighted spatial multi-criteria decision support system (WMCDSS). A multi-layered GIS map has been prepared by including all the decisive parameters or criteria needed for groundwater vulnerability delineation. As a part of this procedure, six thematic layers were first digitally integrated and then assigned with different weights (W_f) and rates (R_f) as tabulated in Table 2. The criteria used for this purpose are based on the hydrochemical parameters such as total dissolved solid (TDS), hydrochemical ratio (rCl/rHCO$_3$), sodium adsorption ratio (SAR), groundwater type and the

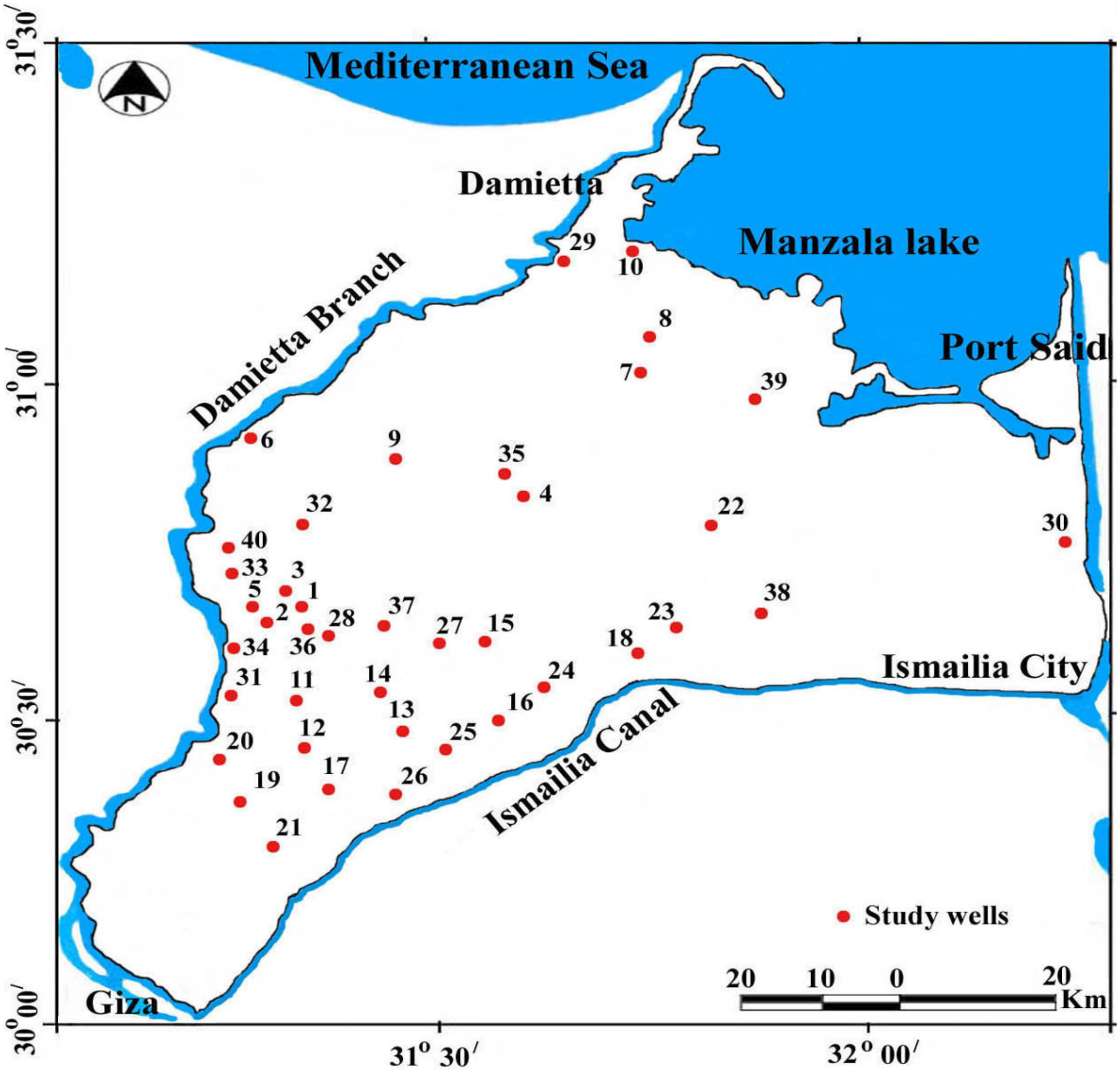

Figure 3. Location map for the studied groundwater wells

Table 2. Rates and weights for different criteria and their influencing classes used for groundwater vulnerability mapping in the WMCDSS model.

Parameter layers (criterion)	Vulnerability class	Average rate (R_f)	Weight (W_f)	Effectiveness degree (E)
	I	90		27
	II	70		21
Total dissolved solids (TDS)	III	50	0.30 (30%)	15
	IV	30		9
	V	10		3
	I	90		13.5
	II	70		10.5
rCl/rHCO3	III	50	0.15 (15%)	7.5
	IV	30		4.5
	V	10		1.5

Table 2. Continue

Sodium adsorption ratio (SAR)	I	90	0.15 (15%)	13.5
	II	70		10.5
	III	50		7.5
	IV	30		4.5
	V	10		1.5
Groundwater type	I	90	0.10 (10%)	9
	II	70		7
	III	50		5
	IV	30		3
	V	10		1
Hydraulic conductivity (K)	I	90	0.15 (15%)	13.5
	II	70		10.5
	III	50		7.5
	IV	30		4.5
	V	10		1.5
Well discharge (Q)	I	90	0.15 (15%)	13.5
	II	70		10.5
	III	50		7.5
	IV	30		4.5
	V	10		1.5

Note: Vulnerability class I (Very high), II (High), III (Moderate), IV (Low), V (Very low)

hydrogeological parameters such as hydraulic conductivity (K) and well discharge (Q). Spatial analyses of these space-dependent criteria were performed by spatial analyst method using the ArcGIS 9.3.3 software (ESRI, 2007). This module is an extension of ArcGIS that provides spatial modeling and analytical features. It allows the creation, querying, mapping and analysis of cell-based raster data and an integrated vector-raster analysis. Results from refined model ultimately lead to better decision-making and appropriate selection of groundwater zones that need special management practices to protect and maintain their sustainability for future use.

The multi-criteria decision support system has been built using the GIS infrastructure database for 40 groundwater wells. As a necessary step, validation, editing and error removal from the maps and tabular data have been made to obtain high level of precession for the given assumptions and parameters. Interpolation of data parameters was then performed by Kriging method (Cressie, 1993).

RESULTS AND DISCUSSION

The rate of erosion by coastal retreat, which is more pronounced in Damietta Promontory areas, varied from 44 m/y in 25 years period (1925-1949), 40.28 m/y in 59 years (1925-1984) to 41 m/y in 75 years (1925-2000). Although, this record indicates a variable rate of regression, the trend generally reveals sea level fluctuation (Sestini, 1992). Erosion of the coastal line during the past decades has its own bearing on the degradation of Quaternary aquifer system.

As mentioned in the above sections, groundwater vulnerability mapping could be achieved by investigating the efficient criteria revealing the water salinization. These criteria are related to saltwater intrusion (i. e., TDS, $rCl/rHCO_3$ and water type), the influencing factors (K, Q) and the usability of water in different zones (SAR). The criteria controlling groundwater vulnerability to saltwater contamination are different in space and time. The total dissolved solid (TDS) in groundwater reflect their salinization through seawater intrusions. Hydrochemical ratio $rCl/rHCO_3$ is considered as a good indicator for groundwater genesis and saltwater intrusions. Sodium adsorption ratio (SAR) differentiates between various classes of groundwater in the vulnerability map, which could be used in settling-up adaptation policies and management practices for groundwater protection. Hydrochemical facies (groundwater type) are indicators of the groundwater genesis, which could be used to detect a trend of salinization in the mixing zones. Hydraulic conductivity (K) is a controlling factor determining the degree of susceptibility to seawater intrusion as well as the aquifer

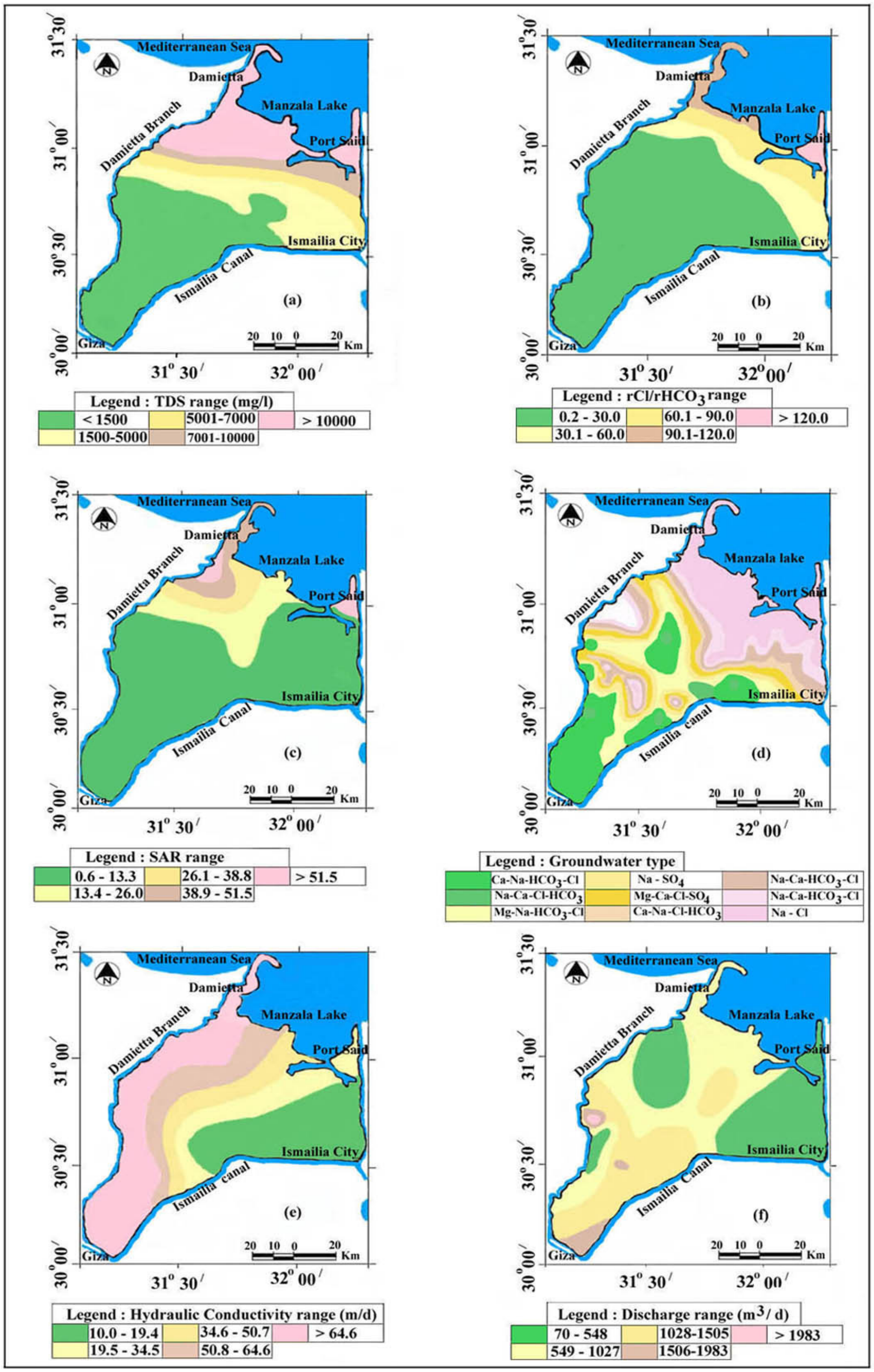

Figure 4. Thematic layers criteria (a) TDS; (b) rcl/rHCO$_3$ ratio; (c) SAR; (d) groundwater type; (e) hydraulic conductivity; (f) well discharge (Q).

infiltration. Well discharge (Q) is an influencing criterion for the groundwater genesis and saltwater intrusion.

The necessary criteria for the success of groundwater vulnerability mapping, which also justify the GIS-based WMCDSS, are the real groundwater conditions in terms of piezometric levels and the water quality in the production wells. Therefore, the influencing and symptomatic criteria on groundwater vulnerability were identified and digitally mapped as thematic layers. The integration of these factors in the GIS multilayer system with the help of ArcGIS 9.3.3 software enabled us to make the WMCDSS model and construct the groundwater vulnerability map. Four classes of groundwater vulnerability to contamination are described in this map, ranging from very low to high.

For the first time, this study focuses on the most influencing criteria or layers for groundwater vulnerability mapping in the northeastern part of the Nile Delta. In this respect, it should be taken into account that these factors are geographically dependant and having a spatial variation from one area to another. Systematic integration of these factors will result in a precise groundwater vulnerability map for a number of categories. All these criteria do not have the same degree of influence on groundwater vulnerability, but have different levels of influence. As given in the following sections, six WMCDSS parameters have been used to evaluate the Quaternary aquifer system in the study area.

Parameter 1

Total dissolved solids (TDS) criterion

Parameter related to total dissolved solids (TDS) gave a variable response between the northern and southern parts of the study area. The northern zone, which is classified as very highly salinized, has a TDS values over 10000 mg/l. However, relatively low values of TDS (less than 1500 mg/l) have been recorded in southern part of the study area. The salinization trend revealed by the TDS map envisaged the impact of saltwater intrusion on fresh water degradation, which is extremely saline in northern parts of the study area compared to middle and southern parts (Figure 4a). Therefore, the Quaternary aquifer system between the middle and northern parts should be treated to bring back a suitable salinity level for irrigating certain crops in the area.

As a result of saltwater intrusion, the continuous irrigation of crops in the affected area using highly saline groundwater produces progressively higher residue of salt in the soil. These salts residue remains there even after the aquifers recharging, resulting in the acceleration of desertification, as evident from areas in southern Europe (Calvache and Pulido-Bosch, 1994). To improve water quality of the production wells in the degraded areas for municipal supply and coastal rehabilitation, the use of desalination techniques has become a common practice in many parts of Egypt. A layer related to this criterion is given a weightage of 0.30 (30%) in the WMCDSS model (Table 2).

Parameter 2

Hydrochemical ratio ($rCl/rHCO_3$) criterion

Chloride has been selected as a fingerprint element for seawater intrusion because it is chemically conservative (Hem, 1989; Somay and Gemici, 2009). The $rCl/rHCO_3$ concentration map indicates a steady increase of salinization towards the north, which is clearly reflected by increase in Cl- value (Figure 4b). This layer is given a weightage of 0.15 (15%) in the WMCDSS model (Table 2).

Parameter 3

Sodium adsorption ratio (SAR) criterion

As described by Ayers and Westcot (1985), the two most common water quality factors that influence the normal rate of infiltration are the salinity of water and the relative concentrations of sodium versus magnesium and calcium ions in the water; known as the SAR. The SAR of irrigation water is a good indicator to understand the occurrence of sodium in the soil. In the study area, salinization initially started in the north and gradually spread towards south. As a result of increased salinization, the current SAR level is well above the tolerance limit of 15 in the northern areas (EPA, 1986). However, the observed SAR values are below this level in the south, indicating the freshness of Quaternary aquifer system in this area (Figure 4c). SAR is a function of salinity, which register an increase due to high evaporation rate in the dry season compared to rainy season. This layer has been given a weight of 0.15 (15%) in the WMCDSS model (Table 2).

Parameter 4

Groundwater type criterion

This criterion is used to segregate different zones affected by seawater intrusion. It is one of the efficient tools to determine the mixing zone properties from the salt dispersion during the advancement of seawater tongue. In most cases, the fresh and saline water interface is characterized by a thick zone of brackish water (Mg-Ca-Cl-SO_4, Na-HCO_3-Cl, Na-Ca-HCO_3-Cl, Mg-Na-HCO_3-Cl), which extends from fresh water zone to the complete saline water zone occurring in the direct contact with the sea (Na-Cl). In this study, the freshwater zone currently occupies the middle – southern parts (Ca-Na-HCO_3-Cl) of the area, which is the first evolutionary stage of continental genesis as a result of recharging from Ismailia Canal (Figure 4d). A weight of 0.10 (10%) has been allotted to this layer in the WMCDSS model (Table 2).

Parameter 5

Hydraulic conductivity (K) criterion

The hydraulic conductivity (m/d) value determines the degree to which brackish water penetrate the Quaternary aquifer system in the study area (Mehnert and Jennings, 1985). For this parameter the obtained values are in a range between10 m/day and 76 m/day (Figure 4e), which carry a weight of 0.15 (15%) in the WMCDSS model (Table 2). The interpolated values obtained through Kriging Method reveal an increase in hydraulic conductivity from east to west for the studied aquifer systems. This type of behavior could be attributed to nature of the depositional cycles and grain size variation in the Nile sediments near and far from the Damietta Branch. The enhanced hydraulic conductivity values near the Manzala Lake in the north reinforce seawater intrusion at different magnitudes.

Parameter 6

Water well discharge (Q) criterion

The development of agriculture and public water supply very much depends on groundwater extraction from coastal aquifer in the semiarid area, which received an increased salinization in the past decades (Carnoda et al., 2004; Somay and Gemici 2009). The distribution of groundwater discharge (m^3/d) in the study area is shown in Figure 4f. According to the WMCDSS model for this area, a weight of 0.15 (15%) has been estimated for this parameter (Table 2). In the north, the degraded soil due to salinization is accompanied by low to moderate withdrawal policies (550 - 1030 m^3/d). As a well-know fact, a strong connection between increase in salt contamination and a decrease in piezometric level is attributable to groundwater overdraft and/or a decrease in natural groundwater discharge (Polemio, 2005). As shown in Figure 5, the constructed piezometric map of the study area shows a good compatibility. The areas with lower piezometric level (0.5-2.5 masl) are well pronounced in the northern parts, indicating their suffering from saltwater intrusions**.** In the middle and southern parts of the study area, the piezometric levels increase steadily (10 – 10.5 masl), indicating a decrease in seawater intrusion. Groundwater overdraft of the Quaternary aquifer system may have caused steady advance of seawater front further inland, making it necessary to apply some management practices for alleviating the effect of sea level rise.

Assessing groundwater vulnerability in the Quaternary aquifer system

Five WMCDSS classes have been ranked according to their level of contribution to groundwater vulnerability/degradation. They are categorized from high to very low in terms of contribution and then used them for mapping groundwater vulnerability to degradation (Table 2; Figure 6). The output map has been constructed with a number of classes indicating different categories of groundwater vulnerability (very high, high, moderate, low, and very low). As evident from this map, contributions from different parameters to groundwater vulnerability are not similar, but the role of TDS is much stronger and effective than the rCl/rHCO_3, SAR, K and Q parameters.

The groundwater type, which reflects the hydrochemical facies of groundwater, represents the least effective and non-quantified among the six parameters. Although, all the described parameters have a role in in groundwater degradation, the TDS has shown highest level of contribution as it directly reflects the trend and space of salinization. On the other hand the well discharge indirectly affects the vulnerability assessment, by much more of groundwater abstraction, the possibility of the advancement of the seawater intrusion increase. Keeping in view their level of contributions to groundwater vulnerability, specific weights have been given to these parameters. In addition to geostatistical normalization and cross-validation (quantitative methods) using the ArcGIS platform (Chachadi and Lobo-Ferreira, 2005), these weights and rates were adopted and optimized. Cross-validation helps in making a decision as to which model is the best for prediction. The calculated statistics serve as diagnostics that indicate whether the model and/or its associated parameter values are reasonable. The weights and rates were modified based on the relations between each of the WMCDSS classified layers. Therefore, the criteria (parameters) used in this

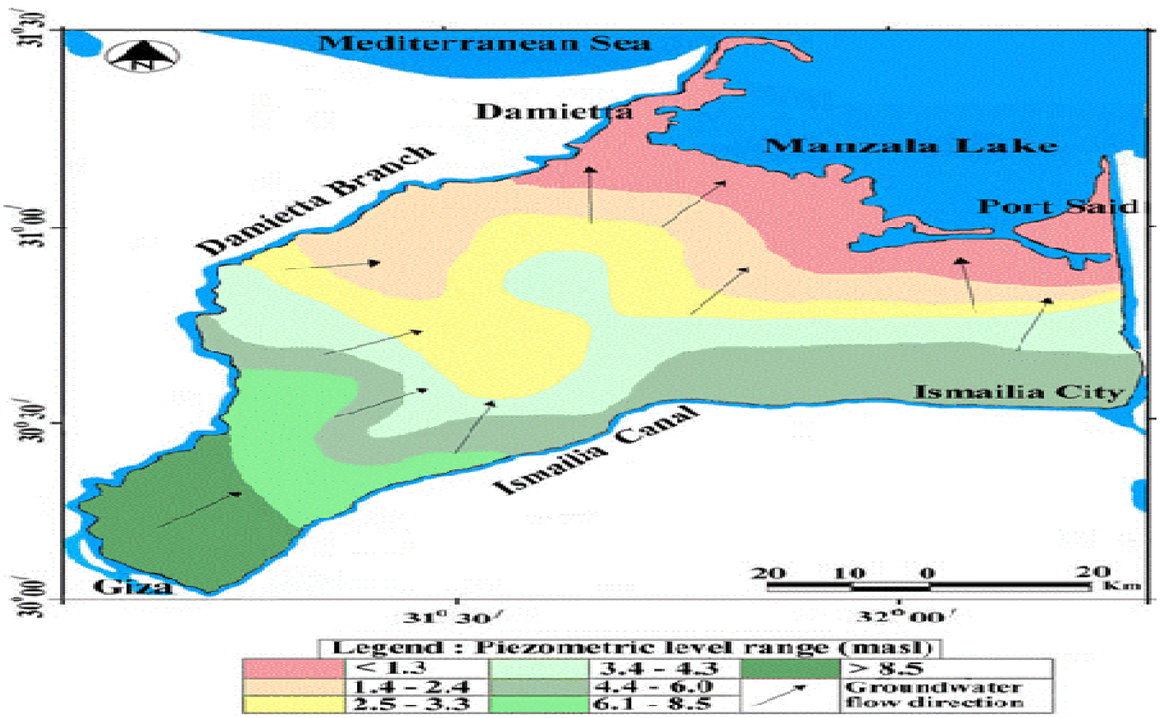

Figure 5. Spatial distribution of the piezometric levels for the Quaternary aquifer system in the study area.

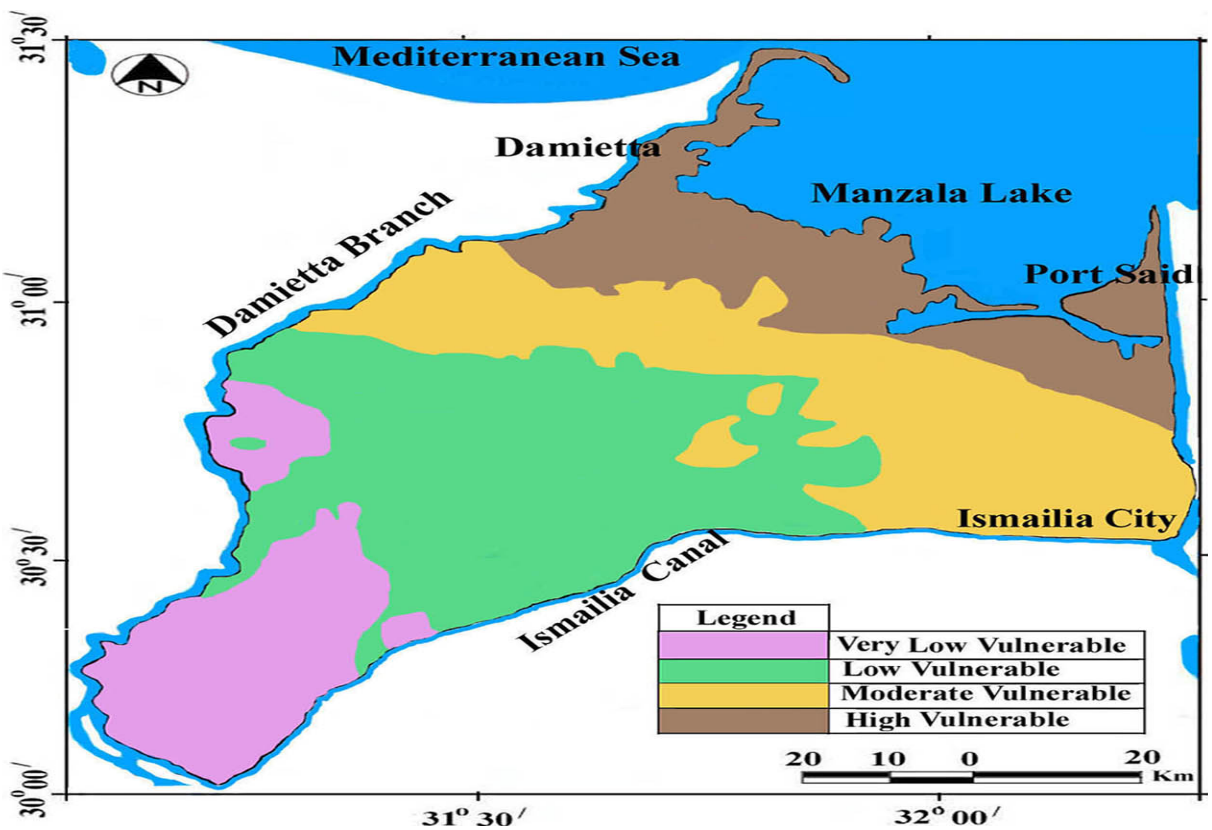

Figure 6. Groundwater vulnerability to degradation map for the Quaternary aquifer system

Table 3. Classes of groundwater vulnerability to degradation in terms of cover area

Vulnerability class	Area (Km^2)	Area %	Total study area (Km^2)
I (Very high)	--	--	
II (High)	1335	17.57	
III (Moderate)	2185	28.75	7600
IV (Low)	2730	35.92	
V (Very low)	1350	17.76	

study were given the following weights: TDS (30%), $rCl/RHCO_3$ (15%), SAR (15%), groundwater type (10%), k (15%) and Q (15%). In addition to the weight assignment, categorization has been made in five classes for each criterion. According to their importance with respect to seawater intrusion and vulnerability (Table 2), these classes have been categorized from 1 (very high vulnerability) to 5 (very low vulnerability). Manipulation of data enabled us to evaluate how effective each criterion is. It also provides a comparative analysis between different data layers. Therefore, it is obvious from the obtained results (Table 2) that class-I in the TDS (E = 27) represents the most influential criterion for groundwater vulnerability as compared to other least influential classes, such as V (E = 1) in the water type or E = 1.5 in $rCl/rHCO_3$, SAR, K and Q.

An arithmetic overlay approach from ArcGIS 9.3.3© Spatial Analyst Model Builder has been adopted for the WMCDSS. This arithmetic approach accepts both continuous and discrete grid layers, while the derived data are in continuous grid layer. The resulting map with four classes of groundwater vulnerability to degradation by saltwater intrusion is graded from very low to high, such as <10 % (very low), 10 – 30 % (low), 30 – 50 % (Moderate) and 50 -70 % (high). The level above 70% (very high vulnerability) is not represented in this study (Figure 6).

The constructed groundwater vulnerability map for quality degradation suggest that the promising localities for groundwater usage (under certain control of consumption rates) are located in the areas where very low to low vulnerability level could be seen. This relatively safe zone covers an area of 4080 km^2, making 53.68% of the total study area. The zone having moderate and high groundwater vulnerability cover an area of 3520 km^2 (46.32% of the total study area), indicating that nearly half of the study area is already deteriorated in terms of groundwater quality (Figure 6), which need special treatment and cropping pattern before use. The adaptation techniques should be applied by sowing certain crops, which consume less water and environmentally adapted to these conditions. The zone of moderate groundwater vulnerability occupies an area of 2185 km^2 (28.75% of the total study area), which highlights a need for preservation and groundwater management practices (especially controlled consumption) in order to maintain or improve the soil conditions. Management practices could be useful to prevent the spread of groundwater quality deterioration further to the south (Table 3).

The high vulnerability zones in the study area are characterized by increased chloride concentration associated with high calcium and low sodium. The saline water in these areas is coming from seawater intrusion in the northeastern Nile Delta, which is characterized by relatively low Na/Cl and high (>1) $Ca/(HCO_3+SO_4)$ and Ca/SO_4 ratios.

SUMMARY AND CONCLUSIONS

Seawater intrusion, which has been considered as one of the major threat to freshwater resources in the study area, is attributed to sea level rise and an extensive withdrawal of groundwater. These factors have lowered the regional piezometric level and thereby induced the inland migration of seawater into the Quaternary aquifer systems through their submarine exposures in the Mediterranean offshore. This research presents a modeled approach in the shape of map to integrate the factors governing the groundwater vulnerability, and thus to reveal the resulting spatial variation with different responses to groundwater vulnerability in the northeastern part of the Nile Delta. The constructed map can be considered as an important component needed for the sustainable development of the northeastern Nile Delta. The application of GIS and WMCDSS as modern techniques has been found highly effective in the construction of the mentioned map. Six thematic layers have been introduced to build the WMCDSS model, which gave high accuracy to the map. These layers are total dissolved solids (TDS), $rCl/rHCO_3$ ratio, sodium adsorption ratio, groundwater type, hydraulic conductivity (K) and well discharge (Q). The constructed groundwater vulnerability map for the northeastern part of Nile Delta distributes the area between very low and high in terms of their vulnerability to degradation. Among the total study area, 1350 Km^2 (17.76%) are represented by very low, 2730 Km^2 (35.92%) by low, 2185 Km^2 (28.75%) by moderate and 1335 Km^2 (17.57%) by high vulnerability. The promising localities for groundwater usage (under certain control of consumption rates) are mostly located in areas where very low to low vulnerability levels have been observed.

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