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Discussions

A review of seawater intrusion in the Nile Delta groundwater system – the basis for assessing impacts due to climate changes and water resources development

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Abstract

Serious environmental problems are emerging in the River Nile basin and its groundwater resources. Recent years have brought scientific evidence of climate change and development-induced environmental impacts globally as well as over Egypt. Some impacts are subtle, like decline of the Nile River water levels, others are dramatic like the salinization of all coastal land in the Nile Delta – the agricultural engine of Egypt. These consequences have become a striking reality causing a set of interconnected groundwater management problems. Massive population increase that overwhelmed the Nile Delta region has amplified the problem. Many researchers have studied these problems from different perspectives using different methodologies, following different objectives and, consequently, arrived at different findings. However, they all confirmed that significant groundwater salinization has affected the Nile Delta and this is likely to become worse rapidly in the future. This article presents, categorizes and critically analyses and synthesizes the most relevant research regarding climate change and development challenges in relation to groundwater resources in the Nile Delta. It is shown that there is a gap in studies that focus on sustainable groundwater resources development and environmentally sound protection as an integrated regional process in Nile Delta. Moreover, there is also a knowledge gap related to the deterioration of groundwater quality. The article recommends further research that covers the groundwater resources and salinization in the whole Nile Delta based on integrated three-dimensional groundwater modelling of the Nile delta aquifer.

1 Introduction

Among all current global, environmental and social changes, climate change, as predicted by various global climate models (IPCC, 2008), will have severe future impacts in delta areas. There is a wide range of impacts including: sea level rise, rainfall patterns, floods and droughts frequencies, salinization, and settlement of land. These impacts

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may have significant influence on natural resources, especially water resources – either surface or groundwater. This is particularly problematic for the Mediterranean coastal areas, and especially the northern Nile Delta Coast in Egypt, where both natural and socio-economic resources of high value exist and are developed rapidly.

The Nile Delta in Egypt, along with its fringes, covers an area of 22 000 km^2 (EGSA, 1997). It is occupied by the most populated governorates in Egypt. About 60 % of Egypt's population lives in the Nile Delta region (Sherif, 2001). Agriculture activities are predominant in the region (around 63 % of the total agricultural land) due to the nature of the soil (Dawoud, 2004) and an irrigation system in place. The Nile Delta aquifer is a vast leaky aquifer that is located between Cairo and the Mediterranean Sea. The productive aquifer is bound by an upper semi-permeable layer and lower impermeable rocky layer. The aquifer is recharged by infiltration from excess irrigation water and the very limited rainfall that infiltrates through the upper clay layer (Leaven, 1991).

The quality of the groundwater in this area may be strongly affected by the impact of the sea level rise combined with changes of Nile river flows, leading to an increase in the salinity levels of groundwater (Dawoud, 2004). In addition, the current and future human activities, especially extensive and unplanned groundwater abstraction are resulting in deterioration of the available groundwater resources. Serious negative socioeconomic impacts can follow as a consequence. This situation prompts for studying and analyzing the problem thoroughly and identifying flexible adaptation strategies that can not only mitigate the negative effects of climate change, but also lead to capacity development for coping with uncertain future changes.

Many water researchers have been interested in the Nile Delta, and they tackled it from different aspects, focusing on either surface or groundwater. Different tools have been used to characterize, classify and analyze the groundwater aquifer. Most of the studies assure that climate change is a significant issue that should be considered with high priority (Sherif, 2001). A number of researchers investigated the problem of current water quality status of groundwater, but such studies were always local in nature, not covering the whole Nile Delta. Also, most of the strategies for adaptation measures

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focus only on a limited area and do not take into consideration the combined effects that may become apparent when studying the Nile Delta from regional perspective.

This article attempts to identify and analyze the findings of most recent studies regarding climate change and development challenges that the Nile Delta faces with particular focus on its groundwater resources. This analysis should serve as the basis for identifying future research needs. As will be demonstrated, the main drawback of existing research efforts (and the resulting results and recommendations) is their local focus, leading to the need for an integrated approach that takes the whole Nile Delta as a unit for analysis. Furthermore, this article proposes research needs for such an integrated hydro approach that should lead to sustainable solutions. The proposed integrated hydro approach focuses mainly on different hydrological, hydro-geological, geological and hydro-chemical characteristics of the groundwater aquifers in Nile Delta and incorporates them in a three-dimensional groundwater model that can serve as a predictive tool for analyzing possible future sustainable solutions. This approach should also be based on updated data on groundwater salinization for large number of wells covering the whole delta region.

The structure of the article is as follows: in Sect. 2 we provide an overview of the studies related to climate change impacts, particularly sea level rise, on the Nile delta. Section 3 introduces the Nile Delta aquifer and an overview of research studies related to identifying its hydro-geologic, hydrologic and salinity characteristics. Existing modeling approaches and specific groundwater modeling studies of the Nile Delta are introduced in Sect. 4, followed in Sect. 5 by an overview of studies related to possible adaptation and mitigation measures. In Sect. 6 we discuss the identified knowledge gaps, and we conclude the article with a section that proposes further research directions for assessing climate change and development-related impacts on the groundwater resources of the Nile Delta aquifer.

2 Climate change and Nile River

Understanding climate change implications in the Nile basin has attracted many researchers worldwide. The first impact considered is related to potential changes in precipitation and temperature patterns that may lead to changes in the Nile flows. The research findings so far are providing conflicting results. Strzepek and Yates (1996) have combined six climate models with an aggregated monthly water balance model that use precipitation fields generated from the climate models. The results of their research that covers the whole Nile basin indicated that five of the climate models predicted an increase in Nile flow at Aswan. On the other hand, Strzepek et al. (2001) studied Nile flow patterns using nine representative samples from the full range of climate change scenarios. Using water balance models, the results of eight out of nine scenarios in this research showed a high tendency for a decrease in Nile flows. Di Baldassare et al. (2010) discussed a number of studies that dealt with future climate change in the Nile basin and the recent models applied. The authors highlighted that studies of climate change and its influence on flow patterns over the Nile basin provide conflicting evidence for long term trends. Although there is no significant change regarding the overall pattern of flow or precipitation, the trends (increase/decrease) are highly uncertain. The authors therefore emphasized the importance of further climate change impact studies.

Another significant impact of climate change is sea level rise (SLR). Egypt is considered among the most vulnerable countries, according to Sestini (1989) and IPCC (2008). Fluctuations in mean sea level (MSL) will affect delta regions causing seawater intrusion and shoreline retreat. That will consequently reduce the sand dunes zone along the coastal aquifer where fresh water is located. The sea level rise along the Egyptian coast has been studied by many scientists, among them, Emery et al. (1988), Stanley (1990), Frihy (1992) and Eid et al. (2007). In their studies they used different climate models to predict sea level rise. The range of sea level rise predicted for the coming 100 yr, lies between 30 and 150 cm along the Mediterranean

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Sea. The most common estimate that is repeated in many reviews is 60 cm (Essink and Kleef, 1993). Alam El Din and Abdel Rahmin (2009) examined the sea level rise in three coastal cities, Alexandria, Portsaid and Suez, using five different statistical models: linear, quadratic, logarithmic, exponential and power models. Their results showed that the sea level rise was not uniform in the three cities. In Alexandria, the annual rate ranged between 1.94 and 2.22 mm yr^{-1}, in Port Said, it was between 2.74 and 3.57 mm yr^{-1}. In Suez on the Red Sea, it ranged between 0.90 and 1.94 mm yr^{-1}. It should be mentioned that some earlier studies showed different future sea level rise and seawater intrusion in the coastal zone of Nile Delta (e.g. Sestini, 1989; CRI /UNESCO/UNDP, 1978; Delft hydraulics, 1992; Stanley and Warne, 1993; El-Raey et al., 1995, 1999, 1997). These studies were based on less reliable data and assumed that sea level rise would be linear in time. However, according to Alam El Din and Abdel Rahmin (2009) sea level rise is expected to accelerate as a function of time.

Different studies have been conducted to analyze the impact of sea level rise on the Nile Delta. Sestini (1989) predicted that the increase in sea level rise in the coastal region of Nile Delta will lead to flooding in the Eastern Delta and a severe damage to harbors. El Fishawi (1993) predicted that a 49 cm sea level rise by the year 2050 is likely to cause salinization in the river mouth of 500–800 mg L^{-1}. El-Raey et al. (1995, 1999, 1997) studied the economic and social impact that could be induced due to seawater intrusion. They found that the sea level rise will lead to the loss of a large area of touristic villages and harbors that have great economic value to Egypt, even more than agriculture.

The above mentioned climate change studies also identify the impact of sea level rise on increased seawater intrusion, but quantification of such impacts is lacking. Moreover, such studies rarely make the assessment whether sea level rise is the only responsible factor for increased sweater intrusion. In the Nile Delta, extensive groundwater abstraction is also a very significant factor that increases seawater intrusion. Groundwater wells which were beyond salinization zones in the past are consequently showing up-coning of saline or brackish water. It is in fact considered the most serious reason behind seawater intrusion in developing regions. Studies showing the degree of climate change and sea level rise impact on seawater intrusion compared to other factors such as development-induced groundwater abstraction do not exist. This assures the need for future research that will assess the impact of climate change versus extensive abstraction as another responsible factor for salinization.

3 Groundwater in Nile Delta

3.1 Aquifer characteristics in Nile Delta

The Nile Delta was extensively studied from geological, hydro-chemical and hydrological aspects. Many research studies have been implemented in different regions of the delta and for different objectives, all leading to identification of the characteristics of the aquifer.

The Nile Delta Quaternary aquifer is considered as a semi-confined aquifer (Ball, 1939). It covers the whole Nile Delta. Its thickness varies from 200 m in the southern parts to 1000 m in the northern parts, (RIGW, 1992a), (Fig. 3). The depth to the groundwater table in this aquifer ranges between 1–2 m in the North, 3–4 m in the Middle and 5 m in the South. Different estimated depths to groundwater table that have been reported by RIGW (2002) and Morsy (2009) are shown in Figs. 1 and 2. Farid (1980) and Wilson et al. (1979) studied the characteristics of Nile Delta aquifer and declared that the top of the Quaternary aquifer is covered by a thin clay layer, which leads to the characterization of this main aquifer as a semi-confined aquifer. The thickness of the clay layer varies from 5–20 m in the south and the middle part of the delta, and reaches 50 m in the north (Diab et al., 1997). The thickness and lithological differences of the clay layer have a great effect on the degree of hydraulic connection between the ground and surface water (Saleh, 1980).

The main aquifer is formed by Quaternary deposits. Farid (1980) attributed the variation of the hydraulic parameters and salinity of the aquifer to the fact that these deposits

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took place under different deltaic conditions. These deposits represent different aggradations and degradation phases that were usually accompanied with sea level changes (Diab et al., 1997). The hydraulic connections among these deposits transformed the Quaternary aquifer to a large storage reservoir that is supplied directly by the Nile water through the extensive irrigation networks, especially in the southern part of Nile Delta (Abdel Maged, 1994). On the other hand, different investigations confirmed that there is no definite hydraulic connection between the Quaternary aquifer and the underlying Tertiary rocky deposits that act as an aquiclude (Saleh, 1980).

The hydraulic parameters of the main aquifer have been investigated by many researchers. Table 1 summarizes the hydraulic parameters estimations of the Nile Delta aquifer made by various authors. The high hydraulic conductivity values are attributed to the fact that the aquifer is composed mainly of sand and gravel (Marotz, 1968). Some parameter ranges are quite close across different studies, e.g. porosity. However, other parameter ranges are quite different, e.g. transmissivity. As indicated in the table, almost all of the studies gave an average value of hydraulic conductivity for the whole delta, which was subsequently used in further studies (including development of groundwater models), which gives only a rough estimation. A regional area like the Nile Delta is characterized with spatially varying hydraulic conductivity for different locations and layers, which needs to be taken into account for more accurate representation of the study area. There are not too many studies with estimations of the hydraulic parameters for the overlying clay layer in literature. Farid (1980) reported that its vertical hydraulic conductivity at 0.0025 m/day while Leaven (1991) reported it at 0.0484 m day^{-1}. With slightly lower values Wolf (1987) reported it as 0.0011 m day^{-1} and Arlt (1995) at 0.0046 m day^{-1}. On the other hand, Sherif et al. (2012) reported the vertical hydraulic conductivity to be about 0.67 m day^{-1}. Due to lack of data, subsequent studies used uniform value of vertical hydraulic conductivity all over the Nile Delta, not taking into consideration that the clay characteristics are spatially varying in the Nile Delta.

DRI (1989) reported the average percolation to the Quaternary aquifer at about 0.8 mm day^{-1}. Warner et al. (1991) reported that the percolation rate ranges between

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0.25 and 0.8 mm day^{-1} in the central and southern part of the delta, depending on the type of soil and irrigation and drainage practices. In the desert areas to the west, percolation rates are dominant that range from 1.0 to 1.5 mm day^{-1} for furrow irrigation. However, lower rates were found for drip and sprinkler irrigation that ranged from 0.1 to 0.5 mm day^{-1}. The percolation rates ranged between 0.2 mm day^{-1} and 5 mm day^{-1} in the large reclamation projects in the Eastern parts of the Delta due to the subsurface drainage that prevailed (RIGW/IWACO, 1990a). Those percolation rates have been used widely in modeling studies.

Average rainfall in the delta is very small and ranges from 25 mm yr^{-1} in the South and middle part of the Delta to 200 mm yr^{-1} in the North (RIGW, 1992a). From literature review, it can be concluded that the rainfall-induced recharge is neglected in almost all groundwater modeling studies because it is very small, compared to the recharge from the returned irrigation flow, in particular in the light of the high potential evapotranspiration rate of about 2000 mm yr^{-1}.

Another significant influence to the recharge of the main aquifer comes from the water levels in the irrigation canals. These water levels are also a significant factor in groundwater modeling, because they influence the surface water-groundwater interaction. The literature review shows that in most modeling studies these were represented with a constant average water level value along the canals (e.g. RIGW, 2003). On the other hand, water levels of the canals vary from one month to another and throughout different sectors of the canals, which needs to be taken into account for more accurate representation of the interactions between the aquifer and the surface water in the delta.

The previous work that has been carried out has provided a better understanding of the aquifer. It has formed the basis for many researchers that have used the reported results as valuable input in groundwater modeling and simulation studies for different environmental problems that face the Nile Delta aquifer. However, these hydrological data should be always monitored and updated in order to be integrated in groundwater modeling and give reliable findings. Only then the resulting groundwater models

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may be considered as strong tools for groundwater management, addressing different environmental problems (especially salinization) in the Nile Delta.

3.2 Groundwater salinization studies in the Nile Delta

Many researchers used chemical and isotopic analyses to detect the salinity of the groundwater aquifer as diagnostic tools for identifying the origin of the dissolved salts. Seawater intrusion was the primary cause to explain the increase in salinity of groundwater especially in the northern parts. However, some other causes such as salinization coming from soil formations were also documented. Atta (1979) analyzed the groundwater salinity and found that the range of groundwater salinity is between 227 ppm and 15 264 ppm. The lower salinity values are found in the southern parts of the Nile Delta region and near the canals of the Nile River due to soil salinity. His results agreed with (Farid, 1980) that the northern zone is highly saline due to seawater intrusion. Sakr et al. (2004) analyzed the historical records and concluded that salinity of groundwater is changing with changing water levels of the canals. He mentioned that from 1957 till 1984, the water salinity records showed that it was enhanced and the freshwater was dominating and overcoming seawater intrusion. He found that the groundwater heads were increasing during this period and he attributed that to the construction of High Aswan Dam. After 1984, the groundwater salinity started to increase due to extensive abstraction and reduction in the flow of the Nile. When the Nile water flow increased in 1990, the salinity of groundwater reduced again to its former levels. However, in 2000, the salinity of groundwater increased again due to extensive abstraction and new reclamation projects. This interpretation of the historical data provided a clear general picture about the evolution of the Quaternary aquifer status in Nile Delta.

The above mentioned researchers where among the pioneers that provided a very good description of the groundwater aquifer and their results formed the base from which a large number of subsequent researches branched. Chemical analyses by themselves are good tools to detect salinity in given conditions, but they are insufficient for forecasting future salinity conditions. Salinization analysis of the aquifer with all the hydrological dimensions is very complicated, and it is severely impaired by the lack of continuous monitoring data. Highly populated regions like the Nile Delta faced with a persisting issue of seawater intrusion require aquifer management based on prediction of future conditions that can be provided by groundwater modeling accompanied with continuous monitoring.

4 Modeling of groundwater salinity

4.1 Brief overview of available models

A thorough overview of all aspects of groundwater salt intrusion (SI) problems, including modeling approaches, is provided in the recent article of Werner et al. (2012). We will therefore not go in detailed overview of these modeling approaches, for which the readers are advised to access the mentioned references. It is of importance, however, to mention that out of the two distinct approaches for modeling SI, namely the sharp interface approach and the variable density approach, the applicability of the sharp interface approach for the integrated modeling of the Nile Delta aquifer is quite limited. The reason for this is the fact that the transition zone between salt and fresh water in this aquifer (characterized with varying density) is quite large and needs to be captured by the intended model. This brief overview of available modeling codes will therefore present only most widely used variable density codes (see Table 2), by borrowing again from Werner et al. (2012).

As can be seen from Table 1 one of the most popular codes in recent years has been SEAWAT, which uses the concept of equivalent fresh water head for simulating density dependent flows, where the flow calculations are performed by the popular MODFLOW code and MT3DMS is used for the solute transport. This code has shown very good results in seawater intrusion modeling studies in several different applications. Given its features and application potential, SEAWAT may be a good candidate code for developing the kind of integrated three-dimensional model of the Nile delta aquifer that

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is argued for in this article. Some experiences with applications of SEAWAT are briefly presented as follows.

The original SEAWAT code was written by Guo and Bennett (1998) referred to as version 1. It was applied to simulate groundwater flow and saltwater intrusion in coastal environments. It was modified by Langevin and Guo (1999). Guo and Langevin (2002) presented the formal documentation for version 2 of SEAWAT code. Langevin et al. (2004) implemented SWIFT2D coupled with SEAWAT to simulate the hydrological processes in coastal wetlands. They concluded that the integrated code gave very good results and could be widely used in seawater intrusion problems. Afterward, Dausman and Langevin (2004) conducted a study to evaluate the relation between water-level fluctuations and saltwater intrusion in Broward County, Florida, using SEAWAT. The model was used to simulate movement of the saltwater interface resulting from changes in precipitation, abstraction, sea-level movement, and upstream canal stage. The results indicated that the canal control structure and sea level have major effects on groundwater flow. They concluded that SEAWAT code provides very reliable results. Masterson and Garabedian (2007) used SEAWAT code to analyze freshwater and saltwater flow. They found that the subsurface geology greatly affects the position and movement of the underlying freshwater/saltwater interface. Moreover, the authors concluded that pumping from large-capacity municipal-supply wells increases the potential of impacts on surface-water resources that are affected by pumping and wastewater disposal locations. They also stated that SEAWAT code is accurate and consequently can be used to represent hydrodynamic surface-water flow and variable-density groundwater flow for multi-year periods.

These studies indicate that SEAWAT has been successfully used for model-based analysis of a wide range of saltwater intrusion problems that have similar characteristics to those in the Nile Delta aquifer. Like with other variable density codes the main problems that researchers could face when using SEWAT are in determining the right trade-off between required complexity that is needed for interpreting the predicted salinity distribution and long running times, and the efforts needed for model

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calibration. Nevertheless, such modeling codes have allowed possibilities for simulating three-dimensional variable-density groundwater flow and predicting the magnitude and direction of saltwater intrusion under changed future conditions.

4.2 Groundwater salinity modeling studies in Egypt

Various numerical techniques were used to assess and simulate the seawater intrusion in the Nile Delta. Earlier studies were mainly focused on determining the freshwater thickness of the Nile Delta aquifer using (semi- analytical) models based on the sharp interface modeling approach. Examples of such studies can be found in Wilson et al. (1979), Amer and Farid (1981), Farid (1980, 1985) and Sakr et al. (2004). Most of these studies were rather theoretical in nature as there were not enough records of salinity of the aquifer. As we have mentioned earlier, in case of the Nile Delta the transition zone is relatively large, characterized by the dynamic relation between fresh and seawater. Consequently, the variable density numerical models are better suited for simulating the interactions of the freshwater and sweater in the aquifer. In reset years, such models have been developed either as two-dimensional vertical models for selected cross sections of the delta, or two-dimensional horizontal models for parts of the Nile delta aquifer. Given that the potential sea level rise impact on salinization of the Nile Delta aquifer have been only recently recognized, most of the developed variable density models in the past were focused on determining the impact of increased groundwater abstractions on the salinization of the aquifer.

This focus of the existing studies is understandable because groundwater abstraction is a major cause of seawater intrusion in coastal aquifers. Increased abstraction leads to reduced freshwater head, which allows progression of the seawater further in land. In Egypt extensive unplanned abstraction causes the deterioration of the Quaternary aquifer, especially in the northern coast. Historical records show a continuous increase in the abstraction rates over the last 30 yr (during the period of 1980–2010), which is summarized in Fig. 4. The overview of the groundwater modeling studies using variable density numerical models needs to be presented in this context of continuous increase of groundwater abstractions.

In 1980, the Research Institute of Groundwater in Egypt (RIGW) launched a primary study to estimate the safe yield of the Nile Delta aquifer. Two dimensional finite difference models were applied to determine the effect of abstraction on the water levels and the safe yield of the Nile Delta aquifer. However, this model did not take into account the seawater intrusion phenomena. The research declared that the total annual abstraction rate in 1980 was estimated at about $1.6 \times 10^9\,m^3\,yr^{-1}$. In addition, the net recharge rate to the Quaternary aquifer was estimated to $2.6 \times 10^9\,m^3\,yr^{-1}$. The results from chemical analyses of the groundwater did not show increase in its salinity, in spite of the reduction in the amount of annual outflow to the sea and the increase of abstraction rates, compared to rates of abstraction in 1960. Consequently, the study concluded that both salt and freshwater status was in dynamic equilibrium. The study recommended that the annual abstraction rates should increase by $0.5 \times 10^9\,m^3\,yr^{-1}$. They attributed this to the need to lower the groundwater head in order to prevent water logging and soil salinization. Farid (1985) used a two dimensional finite element model called AQUIFEM1, a 2-D horizontal finite element model code based on movable sharp interface depending on abstractions. The model results estimated an optimal annual groundwater extraction that should not exceed $4.8 \times 10^9\,m^3\,yr^{-1}$. Official reports from RIGW confirmed significant increase patterns of abstraction, which reached around $2.6 \times 10^9\,m^3\,yr^{-1}$ in 1991. The numbers of wells have doubled from 5600 in 1958 to 13 000 in 1991 (RIGW, 1992b).

In 1999, a project entitled "Water Resources Management under Drought Conditions" studied the Nile Valley and Delta aquifer system using the TRIWACO model code, a finite element variable density numerical model. They found that, there is an alarming danger that urgently needs a comprehensive management plan for drought mitigation based on limiting abstraction rates all over Egypt. They reported that the annual abstraction reached around $3.02 \times 10^9\,m^3\,yr^{-1}$ in Nile Delta. In 2003, the total annual abstraction reached $3.5 \times 10^9\,m^3\,yr^{-1}$ (RIGW, 2003). In 2010, it reached about

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4.6×10^9 m^3 yr^{-1}. Following the trend of the increase of abstraction in Nile Delta, as shown in Fig. 4, it can be noticed that it increases linearly by about 0.1×10^9 m^3 per year, except from the period of 2003 till 2010 where the abstraction increases dramatically by rate of 0.2×10^9 m^3 per year. This demonstrates the need to control abstraction in Nile Delta otherwise, the Nile Delta aquifer will be surely threatened with severe depletion, deterioration and salinization.

In this situation, a number of recent modeling studies focused on analyzing the impact of increased abstraction on the salinization of the Nile Delta aquifer. Gaame (2000) used the SUTRA model code to simulate the behavior of the transition zone of Nile Delta under different abstraction intensities. He declared that the northern part of the Middle Delta is more salinized than the southern part. The model tested the impact of pumping freshwater and brackish water simultaneously which is known as the scavenger well scheme. He concluded that a unique saline well could be used in order to control a number of four or more fresh water pumping wells at a certain distance (circle of influence) to maintain the transition zone at its equilibrium position. El Didy and Darwish (2001) studied seawater intrusion in the Nile Delta aquifer under the effect of fresh water storage in the northern lakes of Manzala and Burullus. The authors simulated the system using SUTRA model and a Lake model called LAKE. They confirmed that there is seawater intrusion in the northern part where the fresh water of the lakes minimizes the intrusion around their zone of influence.

Among the scientist that adopted the variable density approach to study salt water intrusion were Sheriff et al. (1988, 1990), Darwish (1994), Sherif and Singh (1997) and Sherif (1999). They outlined the freshwater-seawater interface in the horizontal and vertical cross sections. Most recently, Sherif et al. (2012) discussed the concept of equivalent freshwater head in successive horizontal simulations of seawater intrusion in Nile Delta. The authors used FEFLOW, a 3-D finite element variable density model. However, due to the unavailability of data, the simulations were performed as 2-D sequences (vertical layers). Their results clearly demonstrate that the location of the transition zone moves towards land side as moving down with depth.

Except for the last study (Sherif et al., 2012), most of the above identified studies were either local in nature, or if they attempted to cover the whole delta region, they used 2-D models in the horizontal directions, or vertical 2-D models for selected cross sections. Such approaches cannot capture the full dynamics of the freshwater-seawater interactions in 3-D. Future research should clearly be oriented towards development of a fully 3-D variable density model of the Nile Delta aquifer that can serve as a predictive tool for analyzing future mitigation and adaptation measures.

5 Mitigation and adaptation measures

Last set of studies that were analyzed in this paper relate to mitigation and adaptation measures for coping with increased salinization of the Nile Delta. In case of the Nile Delta, existing studies were predominantly focused on adaptation measures. Very few existing studies have discussed mitigation measures related to groundwater salinization. Mitigation measures were more studied in relation to the erosion of the coastal strip of Nile Delta, which is another problem that can increase in the future due to sea level rise and more severe weather events. Table 3 summarizes a number of adaptation and mitigation measures proposed by different researchers and their advantages and disadvantages. Generally those studies were dealing with salinization of groundwater on different deltas around the world.

Most of the work that has been carried out in the above proposed adaptive measures is directed towards a specific location in the Nile Delta. The disadvantage of this is that the proposed adaptation plan could negatively influence another region of the Nile Delta. Unfortunately most of the proposed adaptation and/or mitigation measures in Nile Delta stop at the phase of recommendation. A comprehensive strategy for adaptation schemes that is proposed as a result of model-based analysis and evaluation is missing. Also, the effect of integrating two or three adaptation methods together has not been studied. Model-based analysis of such combinations may indicate a possible way forward. In addition, strong institutional capabilities to implement some of the proposed

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alternatives could be a huge constraint in Egypt, as is the case in many developing countries. The need for embedding proposed adaptation and mitigation measures in a broader groundwater management strategy will be further addressed in the following section.

6 Discussion

As we have seen, climate change and its impact on the Nile Delta was the subject of many comprehensive studies for the past 30 yr. Most of the research studies were focused on determining the impact of climate change on precipitation and temperature patterns affecting the Nile basin flows that are critical for the Nile Delta. However, the results from these studies are far from conclusive and further research is needed. Studies of sea level rise due to climate change have mostly focused on quantifying impacts on the Nile Delta coast and surface water. Sea level rise impacts on groundwater in terms of increased salt water intrusion have been clearly recognized, but quantification of these impacts is lacking. Integrated groundwater model of the whole Nile Delta aquifer that includes freshwater-saltwater interactions could serve as a tool for quantification and characterization of these impacts.

Increased and largely uncontrolled groundwater abstractions are potentially more serious threat to the salinization of the Nile Delta aquifer. Historical trends demonstrate continuous increase of groundwater abstractions over the last three decades. Most modeling studies reported in literature simulated the Nile Delta aquifer for studying the deterioration and salinization of the aquifer due to this – already recognized threat. At the same time, however, the majority of reported modeling studies were of local nature, implemented in specific regions to analyze the problems of a particular zone and interpret the results in terms of impacts caused by local causes (abstractions). However, all Nile delta parts are connected and should be integrated together in order to identify their relations and influences. A substantial regional analysis of the whole Nile Delta is lacking in literature.

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Past modeling work was mainly carried out using 2-D vertical (cross sectional) or 2-D horizontal models. An important restriction of 2-D vertical models is that the representative cross sections should be selected carefully and that results are not transferable to other areas of the delta. The 2-D horizontal models provide spatial results in horizontal dimensions, but they give less accurate location and shape of the transition zone between fresh and saltwater in vertical dimension. This situation indicates that future research should focus on development of fully 3-D models, but due to their complexity, data needs and long computational time, such models are rarely developed for seawater intrusion problems, and no such model has been developed for the whole Nile Delta aquifer. Yet, such models are clearly needed. First, they can be used for hypothesis testing and for better understanding of the overall system behavior in three dimensions. Second, these models can be used for an integrated assessment of all potential threats to salinization of the whole Nile Delta aquifer. Finally, once fully developed, such models can became central components of future planning platforms and decision support systems for evaluation of different adaptation and mitigation measures.

A significant problem that prevents scientist from advancing research in this area is the lack of data of sufficient quality. Wells that monitor seawater intrusion (especially deep wells) are lacking (Sherif et al., 2012). Drilling a number of deep wells that cover the Nile Delta aquifer would provide additional information on the salinity of the deep zone of the aquifer. Such salinity data are needed for calibration and validation of models and without these data the accuracy of modeling results remains doubtful. Continuous monitoring of data from all wells is also needed, but it is significant that this is missing in most of the analyzed research studies (Dawoud, 2004).

Data gathering campaigns in Egypt are usually temporary in nature, depending on available funding for particular projects. Furthermore, as in many other countries, existing data are available from different agencies and other organizations and their collation requires considerable effort. A continuous and comprehensive monitoring system of all groundwater data integrated with existing monitoring network of meteorological and hydrological data is therefore crucial challenge for the future. It can be argued, however, that the development of a 3-D integrated model for the Nile Delta aquifer needs to start using all presently available data. Even if the quality of such model would be somewhat impaired because of lack of data, the model itself can be of assistance for designing and implementation of the needed monitoring system, e.g. by identifying critical, vulnerable areas which require denser monitoring network.

The issue of groundwater vulnerability for some parts of the delta has been addressed by few researchers, either by using modeling results (e.g. El Raey et al., 1999) or by GIS analyses of existing data (e.g. Morgen and Shehata, 2012). However, further and more accurate identification of the vulnerable zones in the whole Nile Delta can be supported by the proposed 3-D variable-density groundwater model. Although there is extensive abstraction in Nile Delta, little is known in terms of spatial vulnerability conditions due to combined influences of sea level rise and development-related groundwater abstractions.

Regarding adaptation and mitigation measures, the analysis of previous studies shows that their combined implementation at regional scale is not addressed. Currently proposed measures are studied individually and only focusing on a certain region rather than covering the whole Nile Delta. Also, current adaptations proposed are only addressing objectives of individual stakeholders (e.g. cultivating rice). Studies are rarely based on a multidisciplinary assessment covering both natural and associated social and economic changes. In fact, the adaptation and mitigation measures need to be analyzed within an integrated regional plan accompanied with effective monitoring, evaluation and assessment system. Various schemes proposed (e.g. hydraulic barrier, physical barrier, air or fresh water injection, etc.) should then be extensively studied with the view of economic perspective and applicability. For example, in case of hydraulic injection, the availability and type of injected water, or in case of abstraction of brackish water, the method of disposal of this water without harming the ecosystem, should be carefully analyzed. A comparative performance study could then be established taking into account the time that each method would take for completing the

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mitigation and remediation. Multi-criteria analyses could be carried out by taking into account the complete economic and environmental feasibility objectives for a whole set of measures and these results could then be presented to decision makers. This type of research would link numerical modeling results with socioeconomic constraints together with ecosystem interaction as this has been so far highly neglected. These objectives could be achieved by integrating all required components (data, numerical models, multi criteria analysis tools) in a comprehensive Decision Support System (DSS) that can be used by the relevant authorities and stakeholders.

The envisaged groundwater management plan within which the effectiveness and feasibility of the proposed measures is to be assessed should include additional measures for controlling the excessive abstractions and establishment of pumping regulations. Location-dependent limits of maximum abstraction rates need to be incorporated in such a plan, which should be determined following additional vulnerability studies. Strict monitoring and assessment strategy should be incorporated as a separate component of the DSS to be used by the authorities. Although development of legal regulations and associated strategies (e.g. to restrict development in areas vulnerable to salinization) should provide the broad framework for this approach, this aspect has not been addressed in existing research.

7 Avenues for future research

We conclude this article with several ideas about the possible future research directions that may provide useful inputs for sustainable management of groundwater resources from the Nile Delta aquifer and prevent further salinization problems. From the previous section it becomes apparent that the key research activities in future would be reasonable to aim at developing a regional 3-D variable density numerical model of the Nile Delta aquifer. The multiple benefits of developing such a model have been presented in the previous sections. The popular SEAWAT model code, based on MODFLOW and MT3DMS is a good candidate for setting up such a model. Given the large area of the

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Nile Delta, the envisaged model would still have rather coarse discretization in horizontal direction (1–2 km per grid cell) and sufficiently fine discretization in vertical direction for capturing the transition zone between fresh and seawater (10–30 vertical layers). Such decisions will need to be made by considering the length of computational time, which is an issue for most seawater intrusion models.

First step in this research would be collection and synthesis of all existing data. It is important that enough reliable and updated data sets on different physical, hydrological and hydro-geological variables and parameters are gathered that will enable the development of the conceptual and the numerical model of the delta. A well calibrated model could then provide useful insights in terms of groundwater heads, water budgets, flow directions and the position and the movement of the freshwater/saltwater interface for the present conditions of the Nile Delta aquifer. This model could also be used for analysis future conditions through scenario simulations. In addition to producing a useful predictive tool, the model development process would contribute to improving our understanding of the hydro-geological processes in the Nile Delta aquifer and especially of the processes related to seawater intrusion.

Given that the main drivers for further deteriorating impacts on the aquifer are identified to be climate change (i.e. sea level rise and changed hydrological conditions in the river Nile) and increased development-driven groundwater abstraction, further analysis with the developed model should be carried out on quantifying changes in groundwater heads, water budgets and especially salinity conditions in the aquifer as induced by these two external drivers. Existing climate change scenarios could be used to formulate possible future sea level and hydrological conditions, while development plans within Egypt could offer information for estimating future levels and spatial distribution of groundwater abstractions.

Special emphasis should be put on extreme conditions/combinations of sea level rise and groundwater abstractions. Possible future changes in Nile river flows at the inflow to the delta could have to be examined as these would be reflected in different boundary conditions of the model (e.g. water levels in irrigation canals), while scenarios with

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changes in irrigation practices could be analyzed by modifying levels and spatial distribution of groundwater recharge zones. The results of the model-based analysis could be used in identification and assessment of the most vulnerable areas, which could serve as primary targets for introduction of possible future mitigation and adaptation strategies.

The possible effects of mitigation/adaptation measures on the basis of the model-generated results could then be quantified and different measures evaluated. Strategies for groundwater conditions could be assessed with and without combinations of mitigation and remediation measures. A combination of several methods could be investigated. The most appropriate adaption and/or mitigation scenarios could then be recommended to be considered for implementation.

These proposed lines of research will contribute to a comprehensive framework for development of long-term planning for sustainable management of groundwater resources in the Nile Delta. Once the model is available and its usefulness is confirmed through the applications described above, further steps could be made towards development of a DSS for groundwater planning and management in the Nile Delta, as discussed in Sect. 6. This will encompass many more than only physical aspects of groundwater management, for instance, management options for the conjunctive use of water resources, socio-economic assessment of alternatives etc.

The model proposed for the Nile Delta could also serve as an example for similar areas around world. New insights provided by this research may lead to application of the investigated methodologies in other comparable deltas, since the problems that the Nile Delta faces nowadays will very likely be future problems encountered in other deltas elsewhere in the world (e.g. Bucx et al., 2010; de Vries et al., 2010).

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Table 1. Reported hydraulic parameters of the Quaternary aquifer in the Nile Delta.

References	Transmissivity ($m^2 day^{-1}$)	Hydraulic Conductivity ($m\,day^{-1}$)	Porosity (%)
Shata and El Fayoumy (1970)	71 800	86	26
Farid (1980)	72 000	112	40
UNDP (1981)	20 000–103 000	55–103	–
Mabrook et al. (1983)	–	72–108	21–30
Zaghloul (1985)	–	119	30
Shahin (1985)	2500–25 900	50	25
Laeven (1991)	10 350–59 800	150	25–30
RIGW (1992b)	15 000–75 000	35–100	25–40
Bahr (1995)	–	25–40	25
Sollouma and Gomaa (1997)	–	23–65	25–40
RIGW/IWACO (1999)			
Southern Nile Delta	5000–25 000	50–100	25–30
Northern Nile Delta	–	Less than 50	More than 30
Sherif et al. (2012)	2000–15 000	36–240	25–40

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Table 2. Most widely used SI modeling codes (adapted from Werner et al., 2012).

SI Modeling System	Basic model features*	Practical SI applications
2D/3DFEMFAT	FE, SU	Zhang et al. (2004)
FEFLOW	FE, SU, GUI	Gossel et al. (2010); Watson et al. (2010); Yechieli et al. (2009)
FEMWATER	FE,SU,GUI	Datta et al. (2009) Carneiro et al. (2010)
HYDROGEOSPHERE	FE, SU	Thompson et al. (2007); Graf and Therrien (2005)
MARUN	FE, SU	Li and Boufadel (2011); Abdollahi-Nasab et al. (2010); Boufadel et al. (2000, 2011)
MOCDENS3D	FD, S, GUI	Bakker et al. (2004); Oude Essink (2001b, c); Oude Essink et al. (2010a); Giambastiani et al. (2007); Vandenbohede and Lebbe (2006, 2007); Vandenbohede et al. (2010, 2008a, b, c)
MODHMS	FD, SU, GUI	Werner and Gallagher (2006)
SEAWAT	FD, S, GUI	Cherubini and Pastore (2011); Bakker et al. (2004); Langevin et al. (2010); Vandenbohede and Lebbe (2011); Webb and Howard (2011); El-Bihery (2009); Lin et al. (2009); Mao et al. (2006a, b); Kourakos and Mantoglou (2009, 2011); Abdullah et al. (2010); Praveena et al. (2010); Praveena and Aris (2010); Luyun et al. (2009); Goswami and Clement (2007)
SUTRA	FE/FD, SU, GUI	Nishikawa et al. (2009); Pool and Carrera (2010)
SWI	FD, S, IF	Bakker et al. (2004)

* FD – finite difference; FE – finite elements; IF – interface flow; S – saturated flow only; SU – saturated-unsaturated flow; GUI – dedicated graphical user interface available.

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Table 3. Advantages and disadvantages of different adaptation and mitigation measures for groundwater salinization in Deltas worldwide.

Measure	Advantage	Disadvantage	Conclusion
a. Adaptation			
1. Rice Cultivation (El Gunidy et al., 1987; Kotb et al., 2000)	Soil salinization patterns decrease considerably	Needs a large amount of water which is already a scarce resource.	Not recommended as it is uneconomic
2. Permitting 10 to 20 % of the freshwater of irrigation to leach the soil (Abrol et al., 1988)	No salt accumulation, salt export will match salt import and will eventually prevent salt infiltration to groundwater.	This could be risky because it might cause salt returning to the root zone again.	Not recommended
3. Cultivating salt tolerant crops (FAO, 1985)	Tolerant crops can withstand salt concentration in the north	Very limited types of plants.	Highly recommended
4. Creating wetlands in salinized areas (IPCC, 2008)	Egypt has four lakes in the northern coast of the Nile Delta which could be considered as natural adaption.	Only applicable in low lying deltas of the Nile Delta	Highly recommended in Egypt
5. Extraction of saline groundwater (Oude Essink, 2001a)	Getting rid of saline water.	Disposal of extracted saline water could cause another environmental problem.	Not recommended in shallow coastal aquifers
6. Increasing land reclamation (Oude Essink, 2001a)	Increase freshwater recharge	Need of land and fresh water	It is recommended
b. Mitigation measures			
1. Artificial Recharge (Bray and Yeh, 2008; Richard and Johnson, 2005; Luyen et al., 2011; Carrera, 2010)	Increase freshwater outflow to the aquifer. The degree of efficiency of this method depends on pumping/injection rates, depth of the wells, the coastal aquifer properties and the location of the wells.	Needs a large amount of water which is already a scarce resource.	It is recommended in case of water abundance as it is a highly effective method.
2. Physical Barriers (Fanos et al., 1995; Oude Essink, 2001a)	This method stabilizes the coast and decreases saltwater intrusion. The height of the barrier has a very significant role in the degree of flushing rates.	It is one of the most expensive methods either using sheet piles or clay trenches. Nevertheless, it is only applicable in shallow aquifer because of its huge cost	Economic feasibility is the cornerstone
3. Air Injection (Dror et al., 2004; Werner et al., 2012)	This method minimizes the aquifer permeability and decreases the discharge temporary.	In experimental stage and not fully developed.	Further experiments on bigger scale is needed

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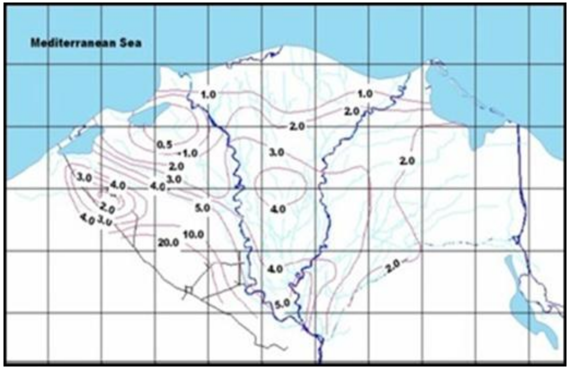

Fig. 1. Average depth to groundwater in the Quaternary aquifer recorded in 2002 (RIGW, 2002).

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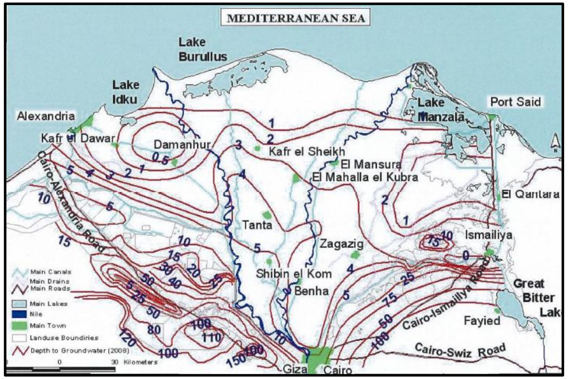

Fig. 2. Average depth to groundwater in the Quaternary aquifer recorded in 2008 (Morsy, 2009).

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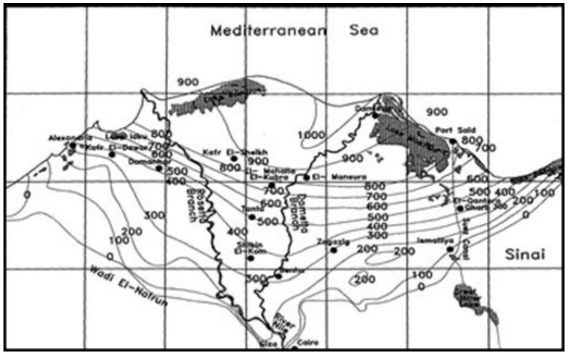

Fig. 3. Depth of the base of the Quaternary aquifer recorded in 2008 (Dahab, 1993).

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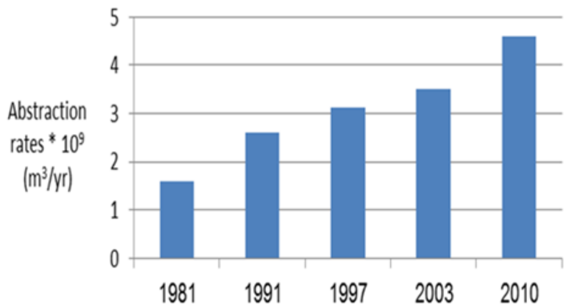

Fig. 4. Abstraction rates versus time in Nile Delta (RIGW, 1980, 1992b, 1999, 2003, and 2010).

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