Chapter 3
Mathematical Models Ensuring Freshwater of Coastal Zones in Arid and Semiarid Regions

Ismail Abd-Elaty and Salvatore Straface

Abstract Freshwater resources are limited and account for only 3% of all Earth's water, of which 22% constitute groundwater resources. Sustainable management of groundwater resources is increasingly urgent with the widening gap between demand and available water supply. Water scarcity problems are amplified by climate change (CC). Today, exploitation of nonconventional water resources for water and food security is a major challenge. Brackish water is reliable and low cost; it may be obtained using renewable energy and has a low content of salinity. A mathematical model (SEAWAT) was applied to the coastal region of the Nile Delta, Egypt. Three scenarios were simulated: sea level rise (SLR), reduced surface water hydrographs, and overexploitation. Four management scenarios were considered: optimisation and allocation of abstraction rates (OA); treatment and recharge (TR); abstraction of brackish water, desalination, and recharge (ADR); and treatment of wastewater and recharge, abstraction of brackish water, and desalination (TRAD). The results indicated that SEAWAT is a powerful tool for simulating and predicting groundwater salinity and can be used for sustainable management and control of coastal aquifer salinity.

Keywords Saltwater intrusion · Sustainable water management · Coastal aquifers · Mathematical modelling · Nile Delta Aquifer · Egypt

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3.1 Introduction

About 97% of water in the oceans is saline, while 3% of all water on Earth is represented by freshwater. Most of the freshwater is enclosed in glaciers and polar ice caps of Greenland and Antarctica. Freshwater is also groundwater and surface water of rivers and lakes which we use in our everyday consumption (Gleick 1996). Groundwater accounts for about 22% of all freshwater on Earth, 77% is polar ice and 0.30% is in rivers and lakes (Bear et al. 1999). The role of groundwater resources in the hydrological cycle is illustrated by the distribution of global water supplies (Fetter 2001).

Good water management is essential for life and the well-being of ecosystems, yet it can be very challenging. One of the most concerning global issues is the uneven distribution of water and water shortage, which provokes violations of human rights and issues of injustice and even leads to war. Causal factors of water shortage include climate change, population growth, overuse of water, and industrial pollution (Jones 2011). An efficient, integrated, and sustainable groundwater resource management plan is required. Management of water resources relies on a comprehensive database representing the characteristics of aquifer systems and modelling tools (Dawoud et al. 2005). Demand for water resources for human consumption, sanitation, agricultural irrigation, and production will continue to intensify with population growth and the acceleration of global urbanization, industrialization, and commercial development (Flint and Houser 2001).

Fresh groundwater (FG) plays a prominent role in supplying many areas that do not have sufficient surface water sources. FG supports different types of life forms and helps in the growth of human civilization. Around two billion people depend on groundwater sources. Groundwater sources are a renewable source that is recharged yearly from rainfall (Simlandy 2015). Today more strategies are needed to maintain optimal groundwater quality; the management of this vital natural resource has become a global priority (Andreo et al. 2005). The hydrologic water balance can be used as a preliminary estimate of the total inflow and outflow of groundwater flow systems and the resulting net storage change. The groundwater flow balance equation is applicable when the available data for use in sophisticated numerical groundwater flow models is insufficient (Mukhopadhyay et al. 1994).

3.2 Climate Change and Water Resources

Climate change (CC) is accelerating at an alarming rate as a result of human activity and natural processes. The effect of CC on various water resources and processes is discussed in this section.

3.2.1 Groundwater and Climate Change

Most climatologists believe that human activity contributes to climate change (CC) by increasing greenhouse gas emissions and the Earth's average temperature. Over centuries, CC can be responsible for melting large amounts of ice from glaciers and caps, sea level rise, coastal region flooding, erosion, loss of wetlands, and saltwater intrusion (SWI) as seen in Fig. 3.1. Rise in sea levels contributes to submergence of coastal and small island nations (Abd-Elhamid 2010; El-Raey 2010).

Scenarios within the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) define four storylines within two divergent tendencies: one group varies between strong economic values and strong environmental values, whilst the other is between increasing globalization and increasing regionalization (Nakicenovic et al. 2000). The outcome of the storylines and our current activities is a global rise in temperature of up to 5.8 °C by 2100; local fluctuations may be more or less, depending on their vulnerabilities and activities. Whatever the gravity of CC, impacts on water resources are inevitable.

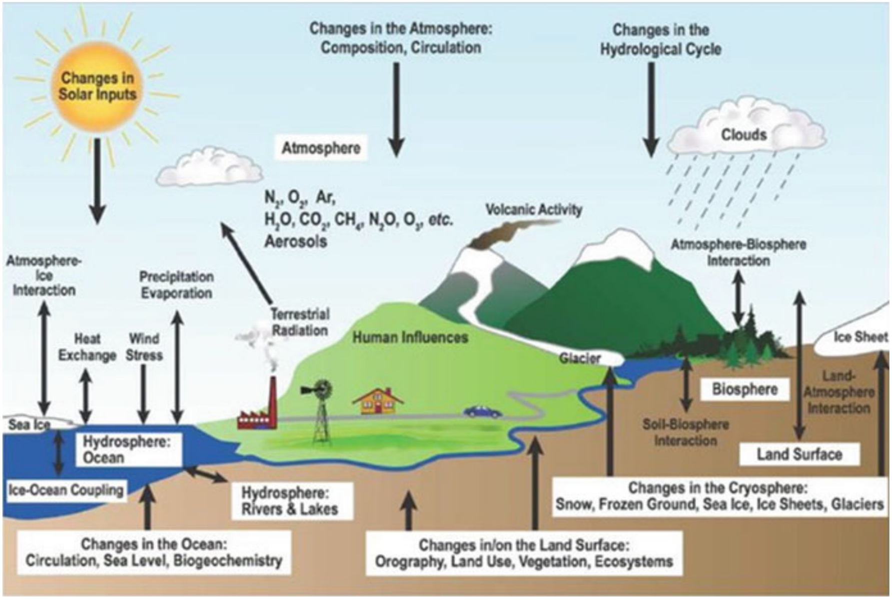

Fig. 3.1 Schematic view of the components of the climate system, their processes, and interactions (Treut et al. 2007)

3.2.2 *Impact of Climate Change on Sea Level Rise (SLR)*

Climate change has a major impact on coastal aquifers, leading to SLR, which directly affects SWI. Increased global temperature warms the land surface, bodies of water, and seas, further leading to decreased atmospheric pressure, which leads to an increase in water levels (IPCC 1996). SLR is a consequence of thermal expansion of oceans and seas and the melting of glaciers, ice caps, and Greenland and Antarctic ice sheets.

Satellite observations have indicated an acceleration of SLR. Field measurements of the tide level showed that the global mean sea level rose between 0.10 and 0.20 m in the twentieth century as shown in Fig. 3.2a.

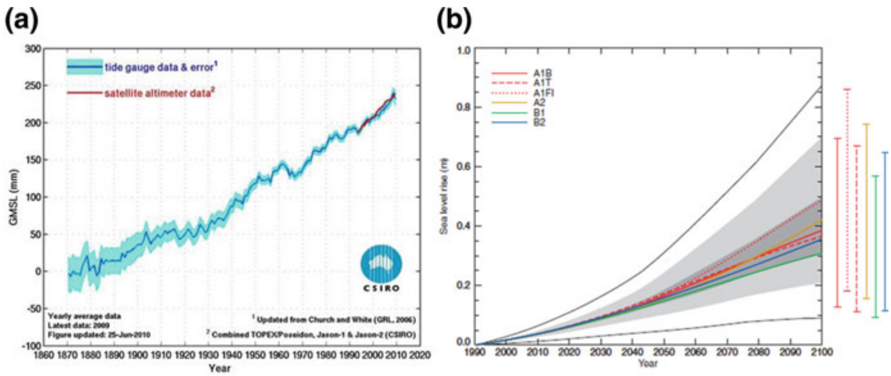

Fig. 3.2 Changing rates of SLR for (**a**) measured global mean sea level (GMSL) over the period 1870–2010 as observed by ground-based and satellite observations and (**b**) prediction for the twenty-first century (IPCC 2001)

The range of SLR reported in the second assessment report (SAR) by IPCC (1996) was 0.13–0.94 m for IS92 scenarios. Simple models have been developed to represent seawater expansion and the melting of ice sheets and glaciers and used in the third assessment report (TAR) for the estimation of the global average SLR, projecting from 0.09 to 0.88 m by 2100 relative to 1990 in SRES scenarios as shown in Fig. 3.2b (IPCC 2001). Moreover, SLR is expected to be between 18 and 58 cm by the end of this century (IPCC 2007).

3.2.3 *Impact of Climate Change on Precipitation*

Precipitation increased by 0.5–1% per decade in the middle and high latitudes of the continents of the northern hemisphere, and by 0.2–0.3% per decade over the tropical (10° N to 10° S) land areas, while it decreased by 0.3% in the subtropical areas of the northern hemisphere (10° N to 30° N). In parts of Asia and Africa, the frequency and intensity of droughts have increased in recent decades. The simulations and

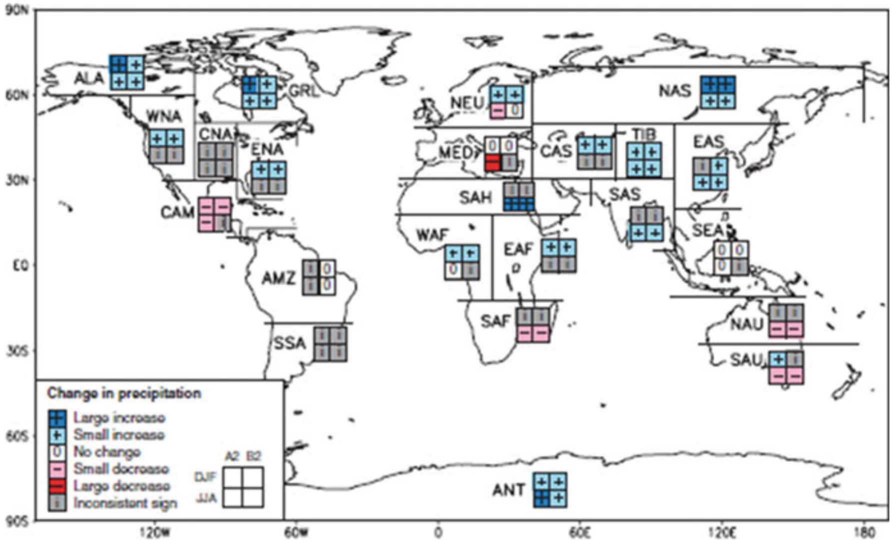

Fig. 3.3 Analysis of inter-model consistency in regional precipitation change (IPCC 2001)

scenarios of the global models are used to predict that the global average water vapor concentration and precipitation will increase in the twenty-first century. In the second half of the twenty-first century, winter precipitation is likely to increase in northern mid-to-high latitudes and in Antarctica, while there are both regional increases and decreases over land areas at low latitudes. Figure 3.3 shows changes in regional precipitation calculated by the IPCC (2001).

3.2.4 Impact of Climate Change on Hydrology and Water Resources

More than one-sixth of the world's population lives in river basins fed by glaciers or snowmelt and is influenced by a decrease in the amount of water stored in glaciers and snow, an increase in the ratio of winter to annual flows, and a decrease in low rivers caused by reduced glacier expansion. It is predicted that increased precipitation intensity and frequency will increase the risk of floods and droughts in many areas. Up to 20% of the world's population lives in river basins and may be affected by an increased risk of flooding in the course of global warming until the 2080s. By the middle of this century, the annual average river runoff and water availability will increase between 10% and 40% in high latitudes and in some tropical humid areas. In contrast, these parameters will decrease between 10% and 30% in some arid regions in mid-latitudes and in arid regions of the tropics, some of which are already water stressed (IPCC 2007; SNC 2010).

The goal of groundwater management is to obtain the maximum quantity of water to meet predetermined quality requirements at least cost. Aquifers can be conceptualized as large natural groundwater reservoirs. The abstraction of groundwater by localized wells can affect the quantity and quality of water that is available elsewhere within an aquifer. To manage FG (fresh groundwater), knowledge of water quantity that can be abstracted is a prerequisite. The equation of hydrologic equilibrium provides a quantitative statement of water balance (Todd 1980).

3.3 Groundwater Reservoirs

Geological formations of groundwater reservoirs are classified as aquifers, aquitards, and aquicludes.

3.3.1 Aquifers

Aquifers are rock or sediment bodies that release significant (economic) amounts of groundwater to the abstraction wells or springs. There are different types of aquifers (unconfined sedimentary, confined sedimentary, and confined fractured lava rock) depending on the geologic material coverage and depth.

Unconfined or free water table (atmospheric) aquifers are without overlying confining layers and are more highly subjected to contamination than confined aquifers. Confined aquifers are those overlain by a confining layer. Artesian aquifers of well flow result from pressure within the aquifer. The hydrogeological conditions subject groundwater to pressure. The artesian flow discontinues when the aquifer pressure is reduced, and the potentiometric surface drops below ground surface level. Partially or confined aquifers can be restricted to parts of their area being more confined than other (uncovered) types (Heath 1983; Berardinucci and Ronneseth 2002).

3.3.2 Aquitards

Aquifers consist of silt, clay, shale, or dense crystalline rock. They can be permeable, enabling flow of significant amounts of water at the regional level, but are incapable of supplying water to a production well. Aquitards store the groundwater but do not provide it in significant or economical quantities. Aquitards have confining layers which retard the vertical movement of groundwater flow, though some can be described as “leaky” (Heath 1983).

3.3.3 Aquicludes/Aquifuges

Aquicludes are impermeable geological units which do not transmit water. They absorb water slowly, can store water but cannot transmit it easily. Examples are metamorphic rocks. Aquifuges are a further even less permeable type where geological formation can neither absorb nor transmit groundwater (Heath 1983).

3.4 Groundwater Contamination

Although groundwater resources are more protected from contamination than surface water, they are still exposed to pollution. Following contamination, restoring it to the original unpolluted state is very hard and costly. Groundwater contamination is usually traced back to environmental, domestic, industrial, and agricultural sources (Bear 1979; EPA 2012).

Environmental pollution occurs by the flow of groundwater through carbonate rock, SWI, or the brackish groundwater invasion from adjacent aquifers. Domestic pollution occurs via accidental fractures in sewers, seepage from septic wastewater tanks, precipitation through contaminated land, and acid rain; additionally biological contaminants (including bacteria and viruses) occur through sewerage treatments. Industrial pollution resides in sewage and may contain heavy metals, non-deteriorating compounds, and radioactive materials. Agricultural pollution occurs through leaching of applied materials such as fertilizers, salts, herbicides, and pesticides.

3.4.1 Saltwater Intrusion

Saltwater intrusion (SWI) is a natural process in which coastal aquifers are connected to the sea due to the greater density of saline water relative to the freshwater in the aquifer. Dense saline water flows under the freshwater and forms a “wedge.” The wedge occupies a position where the density and pressure forces from the sea pushing the wedge inland are balanced by the forces of pressure within the aquifer. Pressure forces are often imbalanced and erode the wedge at the interface between the freshwater and saltwater, as shown in Figs. 3.4 and 3.8. The saltwater wedge becomes a significant problem if it begins to move inland. It can contaminate water supply and/or irrigation wells. Excessive groundwater abstraction from the coastal aquifer causes wedge movement (Harman 2002). Contour maps of total dissolved solids (TDS) are one measure of salinity. The TDS location subjects the area to the influence of SWI (Abd-Elhamid 2010).

SWI is a serious problem in coastal regions. The degree of groundwater salinity depends on several natural and human parameters. The natural parameters include

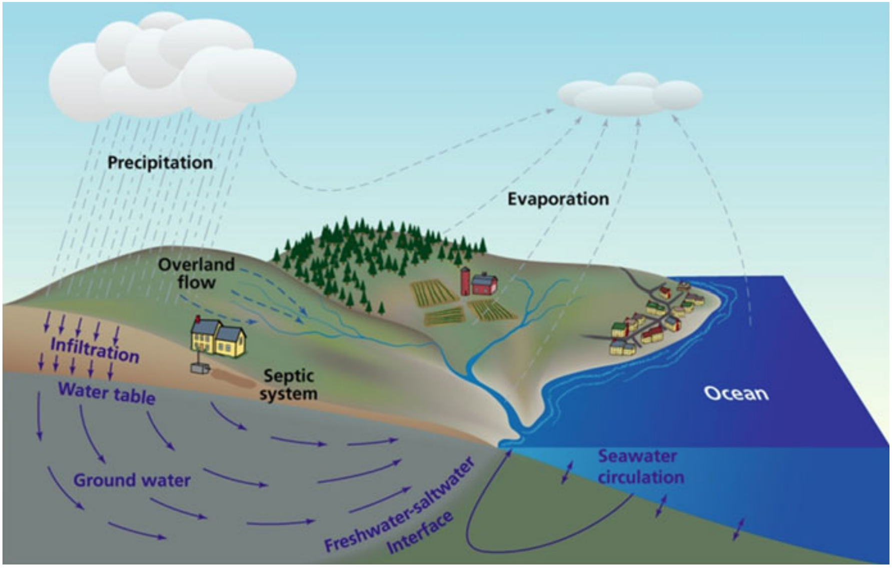

Fig. 3.4 Saltwater intrusion process

the geological aspects, aquifer geometry, sea depth, the hydrogeological and hydraulic parameters (specific yield, specific retention, effective and total porosity, permeability, specific storage and storage coefficient, groundwater heads, groundwater abstraction and recharge), the transport parameters (such as dispersivity, dispersion and diffusion coefficients), reaction processes, and the flow and contamination boundary conditions. Human parameters include overpumping, control of flooding runoff, land use, and artificial recharge of freshwater activities. The five types of SWI are lateral intrusion, downward seepage, upcoming deep saline seawater, alteration to natural barriers, and via improving groundwater quality due to abstraction (Callander 2011).

Coupling of groundwater fluid flow and solute transport models may be used to investigate and predict SWI in coastal aquifers. Problems for groundwater are overexploitation, mining, subsidence, water logging, seawater intrusion, and groundwater pollution (Kumar 2002). Investigation of coastal region salinity requires data of the hydrological and hydro-chemical parameters of aquifers. SWI has been investigated by both geophysical and geochemical methods (Bear et al. 1999). Experimental studies may be carried out in laboratories to ascertain the saline freshwater interface in order to obtain accurate values of the hydraulic heads in freshwater zones. Mathematical studies have been applied to simulate and predict the SWI using analytical and numerical models.

3.4.2 Population and Overexploitation

Over 70% of the world's population resides in coastal zones which are among the most densely populated areas in the world. These regions face serious hydrological problems such as freshwater scarcity, groundwater contamination, and seawater invasion. Coastal zones are subjected to serious hydrological problems including high stress of freshwater, pollution of groundwater by SWI, and overpumping by increasing groundwater abstraction due to growth in the global population (Abd-Elhamid 2010).

3.5 Groundwater Models

The modelling of groundwater enables an understanding of physical problems and entails conversion of physical systems into mathematical terms to quantify and qualify processes taking place in a hydrological system or to answer a specific question (Kumar 2002). The goals and methods of modelling depend on the nature of the query and the properties of the location or system. Details and accuracy of the system depend on the objectives of the natural resource sector. Models of groundwater are used in environmental assessments or other permit requirements. The use of numerical groundwater models enables and helps decision-makers to study and evaluate large and complex water resource development projects.

3.5.1 Classification of Groundwater Models

Groundwater models are used to simplify the hydrological groundwater system, which can be classified by physical or mathematical models. Physical modelling is made by "box tanks" replicating physical processes at smaller scales than in the field. These models are developed and used to simulate the groundwater flow and the solute transport of contamination and pollutants in the groundwater (Barnett et al. 2012). Rausch (2010) states groundwater models can be classified with respect to: (i) physical conditions, (ii) dimensionality, and (iii) solution method.

3.5.2 Types of Mathematical Models

A wide variety of modelling tools are available to simulate groundwater systems. These tools can be roughly grouped into analytical, numerical, and analytic element models.

Analytical models use exact solutions to describe the groundwater flow or the transport equation. To obtain exact solutions, flow or transport equations have to be simplified to apply to hydrological systems. The analytical models' advantage is the ease of use and transparency of such models, while the disadvantage is that application may be limited to relatively simple flow or transport problems (Wels 2012).

Numerical models solve the governing equations of groundwater flow and/or contaminant transport using numerical methods. The advantage of numerical models is that they solve complex systems; multi-layered aquifers have hydraulic parameters and boundary conditions and model time steps. The disadvantages are the cost, the time of solving, and the model complexity which reduces the transparency of calculations and may introduce uncertainty (Wels 2012; Barnett et al. 2012).

Analytic element models use the superposition of closed-form (analytical) solutions to the governing differential equation of groundwater flow to approximate both local (near-field) and regional (far-field) flow (Hunt et al. 1998). The process of selecting the appropriate mathematical model has been described (Bazrkar et al. 2017).

3.5.3 Solution Methods for Differential Equations

The objective of solutions of differential equations which physically govern the hydrological system is to find unknown parameters with associated boundary and initial conditions. Analytical and numerical methods are used to solve these equations.

3.5.3.1 Analytical Solution

The coupled fluid flow and the transport problems in porous media are solved using complex nonlinear partial differential equations. Numerical methods with approximate solutions may be preferred to the use of complex differentials (Abd-Elhamid 2010). However, analytical solutions can be used for simple boundary, initial conditions and homogeneity assumption (Rausch 2010).

3.5.3.2 Numerical Solution

Types of numerical methods used to solve the complex nonlinear partial differential equations of groundwater flow and transport models in porous media are finite difference and finite element methods (Abd-Elhamid 2010).

Finite difference method (FDM) is most frequently used in simulation of numerical groundwater flow and transport models. In most FDM models, the domain of space and time are divided on a rectangular grid (Fig. 3.5a), and model parameters such as hydraulic parameters and the hydrological boundary conditions are specified

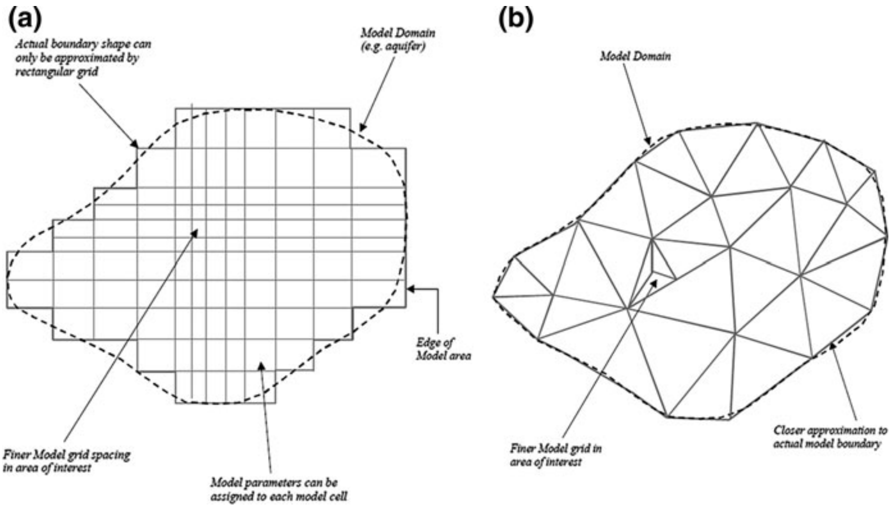

Fig. 3.5 Illustration of (**a**) finite difference method (FDM) and (**b**) finite element method (FEM) (NGCLC 2001)

by cell. The grid spacing represents the degree of accuracy of the model, representing lateral or vertical changes in the property values describing the system. The advantage of the FDM is its use for simple or regular geometry, while the disadvantage is that it may be less accurate for irregular model domains such as anisotropic and heterogeneous aquifers with irregular boundaries. In addition, it is difficult to change the grid spacing to increase model precision (Wels 2012; Istok 1989). FDM can be solved using a computer program or a spreadsheet, such as MODFLOW and SEAWAT.

Finite element method (FEM) uses a mesh of elements to divide the problem domain (Fig. 3.5b). FEM is a powerful numerical tool for the solution of a wide range of engineering problems. In the 1970s, the FEM was first used to solve flow and transport problems in porous media (Istok 1989). The fundamental idea of FEM is to produce a set of algebraic equations for each element and then collate all elements using a procedure called assembly to form the global matrix statement (Baker and Pepper 1991). A polynomial function may be used to approximate the variation in a model parameter across the model element. Complex geological boundary model domains are defined much better than in FDM. The mesh is easily modifiable and achieves great precision. Models of finite elements are less susceptible to numerical dispersion than finite difference models (Wels 2012). FEM is very popular (Logan 2002) as it may be used to simulate irregular and curved geometric domains, variable node spacing, variable element size, boundary conditions, anisotropic and heterogeneous porous media, nonlinear behavior, and dynamic effects (Cheung et al. 1996).

3.5.4 Numerical Model Codes

Numerical model code is used in groundwater modelling to solve groundwater flow or solute transport problems. The code facilitates the recording of the relevant input parameters of model such as model grids, aquifer hydraulic and hydrological parameters, and boundary conditions. Table 3.1 details code names and descriptions.

Numerical dispersion and numerical instability are the most common problems for groundwater solute transport models (Wels 2012).

Numerical dispersion problems are caused by insufficient discretization in space and time. Distortion effects are more pronounced in the vertical direction than horizontal. Reduced numerical dispersion can be achieved by using Lagrangian methods, decreasing the model grid spacing and time steps for the models solved by Euclidean methods, choice of initial or starting conditions, and convergence criteria.

Numerical instability can lead to numerical oscillations in space and time. Peclet and Courant numbers are used to estimate the maximum grid size and time step for solute transport models. In addition, sensitivity analyses may be used to check the effect of grid spacing and time step (Wels 2012).

Table 3.1 Available groundwater modelling codes (Barnett et al. 2012)

Serial	Model codes	Simulation type	Description
1	MODFLOW (McDonald and Harbaugh 1984)	Saturated groundwater flow	Open-source software of the US Geological Survey, based on FDM
2	MT3DMS (Zheng and Wang 1999)	Transport of multiple reactive solutes	Open-source software coupled with MODFLOW for coupling flow and transport
3	SEAWAT (Guo and Bennett 1998)	Saturated flow, transport of multiple solutes and heat	Open-source software combining MODFLOW and MT3DMS for density-coupled flow and transport
4	MODFLOW 2000	3D groundwater flow and contaminant transport	Commercial software supports MODFLOW packages, MODPATH, SEAWAT, MT3DMS, MT3D99, RT3D, PHT3D, MGO, PEST, MODFLOW-SURFACT, and MIKE 11
5	SUTRA (Voss 1984)	Saturated and unsaturated flow, transport and heat	Open-source software based on FEM, designed for density-coupled flow and transport
6	FEFLOW (Diersch 1996)	3D saturated and unsaturated flow, transport and heat, with integrated GUI	Commercial software based on the FED coupling to MIKE 11 to simulate flow in river and stream networks
7	GMS	GUI	Commercial software supports MODFLOW packages, MODPATH, MODAEM, SEAWAT, MT3DMS, RT3D, PEST, and FEMWATER

3.5.5 Water Modelling Packages

Visual MODFLOW 2010.1 is a 3D groundwater flow and solute transport model; it integrates MODFLOW-2000, SEAWAT, MODPATH, MT3DMS, MT3D99, RT3D, VMOD 3D-Explorer, WinPEST, Stream routing package, Zone Budget, MGO, SAMG, and PHT3D.

The main component of the governing groundwater flow equation is the law of mass balance plus Darcy's law (Kumar 2002). The mathematical treatment for the groundwater flow equation through a porous medium depends upon an equation that captures the essence of the physics of flow (Vandenbohede 2003). The partial differential equation of groundwater flow for constant density groundwater flow may be applied (McDonald and Harbaugh 1984) and is given in Eq. (3.1):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_{\mathrm{s}}\frac{\partial h}{\partial t}\pm q \tag{3.1}$$

where K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, h is the potentiometric head, t is time, and q is volumetric flux per unit volume representing source/sink terms, with $q < 0$ for flow out of the groundwater system and $q > 0$ for flow in. S_{s} is the specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material.

The mechanism of the equivalent freshwater head in a saline aquifer is based on the following assumptions: (i) validation of Darcy's law, (ii) it is applicable to specific storage in a confined aquifer, (iii) the diffusive approach based on Fick's law is applied, and (iv) prevailing isothermal conditions. The porous medium is assumed to be fully saturated with water. A single, fully miscible liquid phase of very small compressibility is also assumed (Guo and Langevin 2002).

The theory of variable-density groundwater flow is usually developed in terms of fluid pressure and density with an Eq. (3.2) developed in terms of equivalent freshwater head and fluid density. Figure 3.6 indicates the two piezometers which represent an aquifer containing saline water in which Piezometer A contains freshwater while Piezometer B contains saline aquifer water at point N.

The principle of mass conservation for fluid and solute is the rate of accumulation of mass stored in the reservoir and is equal to the algebraic sum of the mass fluxes across the faces of the element and the mass exchange due to sinks or sources. The governing equation for variable-density flow (Guo and Langevin 2002) in terms of freshwater head as used in SEAWAT is as follows in Eq. (3.2):

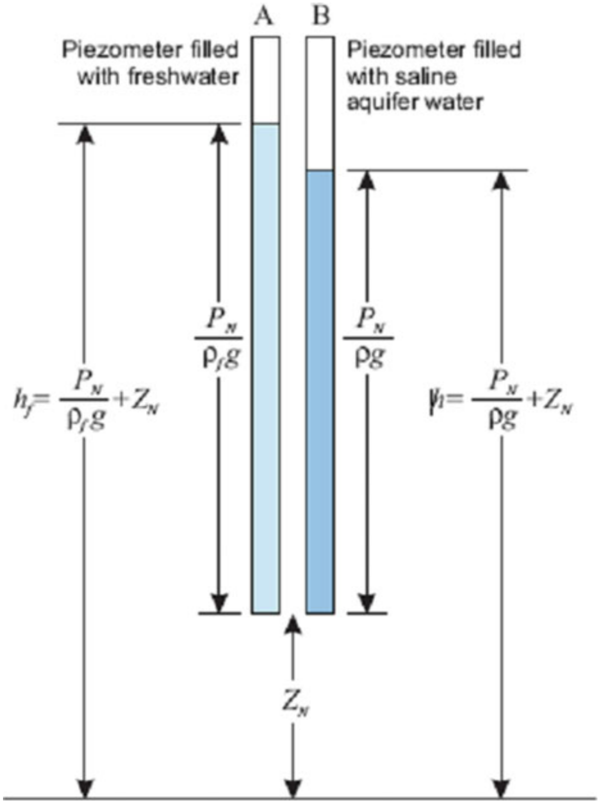

Fig. 3.6 Equivalent freshwater head in a saline aquifer (Guo and Langevin 2002)

$$\frac{\partial}{\partial x}\left(\rho K_{\mathrm{fz}}\left[\frac{\partial h_{\mathrm{f}}}{\partial x}\right]\right)+\frac{\partial}{\partial y}\left(\rho K_{\mathrm{fy}}\left[\frac{\partial h_{\mathrm{f}}}{\partial y}\right]\right)+\frac{\partial}{\partial z}\left(\rho K_{\mathrm{fz}}\left[\frac{\partial h_{\mathrm{f}}}{\partial z}+\frac{\rho-\rho_{\mathrm{f}}}{\rho_{\mathrm{f}}}\right]\right)$$
$$=\rho S_{\mathrm{sf}}\left(\frac{\partial h_{\mathrm{f}}}{\partial t}\right)+n\left(\frac{\partial \rho}{\partial C}\right)\left(\frac{\partial C}{\partial t}\right)-\frac{\rho}{q_{\mathrm{s}}} \quad (3.2)$$

where h_{f} is the equivalent freshwater head, h is the head, P_N is the pressure at point N, ρ is the density of saline groundwater at point N, ρ_{f} is the density of freshwater, S_{sf} is the specific storage in terms of freshwater head or the volume of water released from storage in a unit volume of aquifer per unit decline in freshwater head, t is time, n is the porosity (dimensionless), and C is solute concentration (parts per million).

Numerical models of groundwater are a strong and powerful tool to simulate groundwater in both flow and solute transport systems; they provide support in planning, design, and management of groundwater resources. Derivation of the advection-dispersion equation (ADE) is based on the law of conservation of mass. The derivation is based on Ogata (1970) and Bear (1972) and is presented in Freeze and Cherry (1979) and assumes that the porous medium is homogeneous, isotropic, and saturated, the flow is steady state, and Darcy's law applies.

The effects of pore pressure on fluid density are included in the storage term. An empirical relation between the density of saltwater and concentration (Baxter and Wallace 1916) is shown in Eq. (3.3):

$$\rho = \rho_{\mathrm{f}} + E * C \tag{3.3}$$

where E is a dimensionless constant having an approximate value of 0.7143 for salt concentrations ranging from zero to that of seawater at ρ_{f}, i.e., the freshwater density equal to 1000 kg/m^3.

3.6 Case Study: The Nile Delta Aquifer (NDA), Egypt

The Nile Delta Aquifer (NDA) is one of the largest groundwater reservoirs in the world and is subject to severe seawater intrusion from the Mediterranean. It has direct hydraulic contact with the ocean on its northern boundary (Negm et al. 2018; Abd-Elaty et al. 2021a). Groundwater resources in the Nile Delta are an important water supply for domestic, industry, and irrigation uses (Abd-Elaty et al. 2021b). Increasingly intensive agriculture practices require greater application of fertilizers in order to sustain food production, resulting in higher concentrations of pollutants in groundwater (Abd-Elaty et al. 2020a). The evaluation of water quality indicators is crucial in integrated water resource management, since potable water is an essential resource for world health and sustainable development (Abd-Elaty et al. 2019a).

A number of studies were carried out following various extraction rate scenarios. Voss (1984) and authors used a SUTRA code to identify the optimal distribution for additional production wells from the NDA. It was concluded that additional abstraction rates should be applied in the Middle Delta accompanied with a reduction in abstraction from eastern and western parts. Sherif and Al-Rashed (2001) investigated the quality of groundwater in the northern part of the Nile Delta and found that water quality has deteriorated over the last few decades due to excessive pumping. El Didy and Darwish (2001) simulated the SWI in the NDA using SUTRA code considering the effect of freshwater storage in the northern lakes of Manzala and Burullus, and confirmed that SWI occurred in the northern part despite freshwater lakes minimizing intrusion around the influence zone. Nowadays, Egypt is entering a new phase in which human food needs must harmonize with environmental and sustainable principles (Abd-Elaty et al. 2017).

Figure 3.7 shows the location of the NDA, with its contact with the sea on its northern boundary. Sefelnasr and Sherif (2014) simulated the effect of SLR on SWI in the NDA using a 3D finite element variable density FEFLOW model. Abd-Elaty et al. (2014a, b) used a 3D model (SEAWAT) considering scenarios featuring a rise in sea levels, reduced surface water systems, increased abstraction from production wells, and a combination of the three scenarios. Results indicated damage to the aquifer and a loss in quantity of freshwater due to SWI.

Fig. 3.7 The Nile Delta Aquifer (NDA), Egypt

Figure 3.8 shows the cross section of the NDA. Building on the established basic principles (Theis 1935), Abd-Elhamid et al. (2016) applied a 2D variable density model, and three scenarios were studied: SLR, reduction of freshwater heads due to increasing the abstraction at the land side, and the combination of the two scenarios. Results indicated that SWI was increased when the boundary conditions are altered. Moreover, Abd-Elhamid et al. (2016, 2018, 2019) and Abd-Elaty et al. (2018, 2019b, 2021c, d) investigated SWI in coastal aquifers using SEAWAT.

The NDA geometry and boundary conditions were presented by Abd-Elaty et al. (2014a, b). Figure 3.9 shows the NDA head boundary conditions using river and drain packages, while the brackish lakes including Idku, Burullus, and Manzala with direct connection to the Mediterranean Sea were assigned a constant head boundary.

A constant concentration value of 35,000 mg/L total dissolved solids (TDS) was assigned along the Mediterranean Sea, while the initial concentration of the groundwater was set to 0 mg/L. The model was calibrated; the results of the calculated groundwater head are shown in Fig. 3.10, the groundwater level between 14 m in the south and 0 in the north is in agreement with Abd-Elaty et al. (2014a). Figure 3.11 shows the solute transport where the intrusion length of iso-concentration line 3.5E4 intruded in the aquifer by a distance of 63.75 km from the shoreline. However, the iso-concentration line 1.0E3 in the NDA intruded to 93.75 km from shoreline with a transition zone of 30 km (Fig. 3.12).

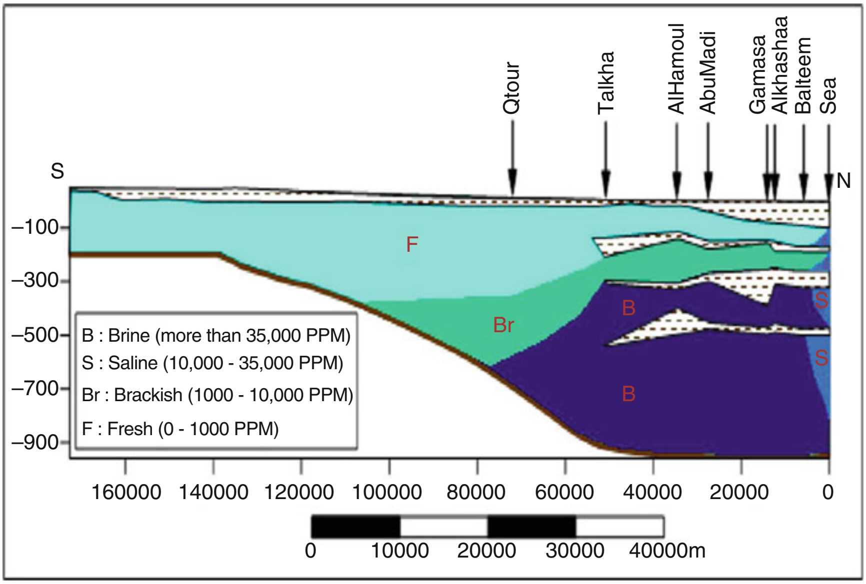

Fig. 3.8 Multi-wedge system of seawater intrusion in the Nile Delta Aquifer (NDA) (Nofal et al. 2015)

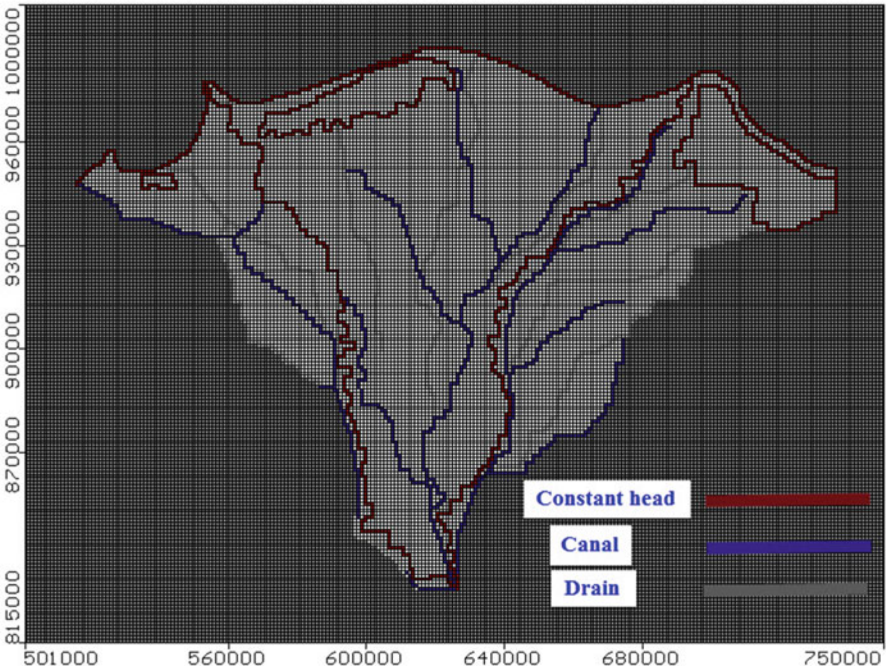

Fig. 3.9 Head boundary conditions for the Nile Delta Aquifer (NDA) in the numerical model

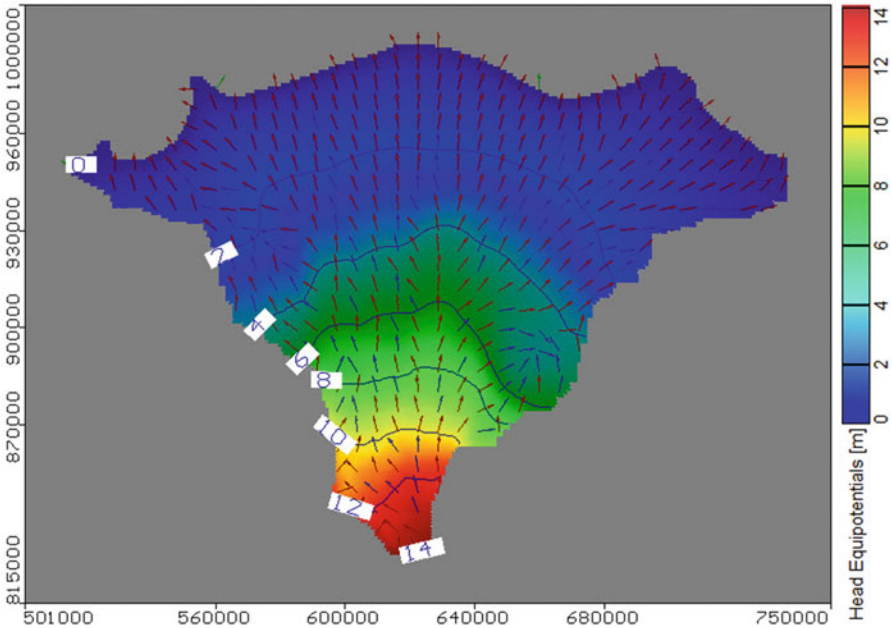

Fig. 3.10 Calculated groundwater level in the Nile Delta Aquifer

3.6.1 Simulations of Saltwater Intrusion (SWI) in the Northern Delta Aquifer

The case study continues to show the numerical code simulated on the NDA for the three cases of increasing sea level, reduction in surface water hydrograph, and increased aquifer abstraction rates. The results of these scenarios are presented in Table 3.2. The investigation of SWI under SLR, decreasing recharge, and overpumping concords with Abd-Elaty et al. (2014b).

Management scenarios were developed for sustainable water resources in coastal aquifers including optimisation and allocation of wells, treatment and recharge, and abstraction and desalination of brackish water. Further results are discussed in the remaining parts of the section.

3.6.1.1 Impact of Sea Level Rise

The results of increasing sea level by 50 cm are presented in Fig. 3.13.

In this scenario the intrusion reached 67 km from shoreline for iso-line 3.5E4, while it reached 96.25 km for iso-line 1.0E3.

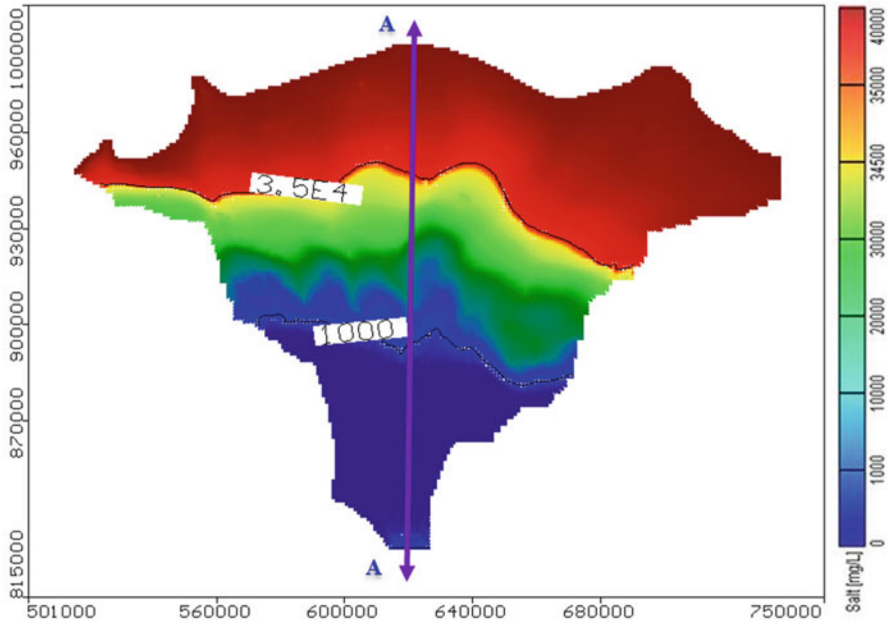

Fig. 3.11 Distribution of TDS in the NDA, on average depth ranges from 450 m in the north to 100 m in the south

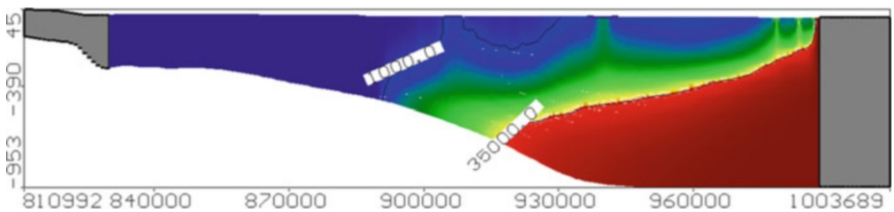

Fig. 3.12 Vertical distribution of TDS in the NDA for base case from the south to the north at section A-A

3.6.1.2 Impact on the Surface Water Hydrograph

The following scenario was developed by decreasing the surface water level by 50 cm. The results are shown in Fig. 3.14.

The intrusion reached 67 km for iso-line 3.5E4 and 96.50 km for iso-line 1.0E3, respectively. The decrease of the surface water level leads to an increase of SWI in the aquifer.

Table 3.2 Scenarios to investigate and control SWI in the Middle Nile Delta Aquifer (NDA)

Case	Scenario	Scenario description	Intrusion length (Km)	
			Iso-concentration line 3.5E4	Iso-concentration line 1.0E3
Investigation of SWI	I_1	Current situation	63.75	93.75
	I_2	50 cm by SLR	67	96.25
	I_3	50% by decreasing recharge	67	96.50
	I_4	50% by overabstraction	66.50	101.25
Management of SWI	M_1	50% recharge by treated wastewater (TR)	66.25	89
	M_2	50% recharge by desalinated brackish water (ADR)	67.75	90
	M_3	50% recharge by treated wastewater and desalinated brackish water (TRAD)	65.50	84.75

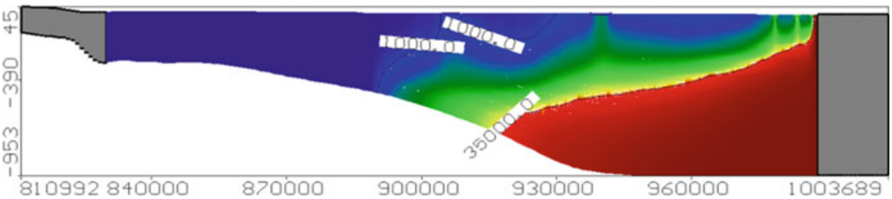

Fig. 3.13 Vertical distribution of TDS in the NDA due to a 50 cm sea level rise (SLR)

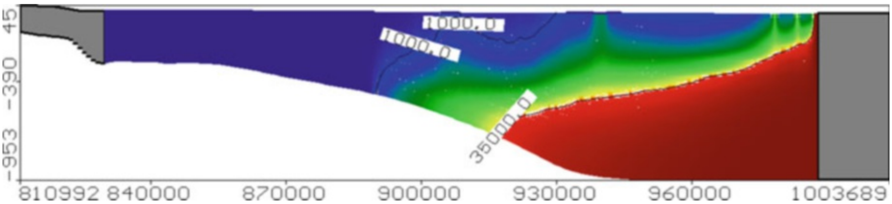

Fig. 3.14 Vertical distribution of TDS in the NDA due to a 50 cm decrease of the surface water hydrograph

3.6.1.3 Impact of Abstraction Rates

In the following graph the abstraction rates from groundwater were increased by 50% (Fig. 3.15).

The figure shows increasing extraction rate for increasing SWI in aquifer. Intrusion reached 66.50 km from shoreline for iso-line 3.5E4 and reached 101.25 km for iso-line 1.0E3, respectively.

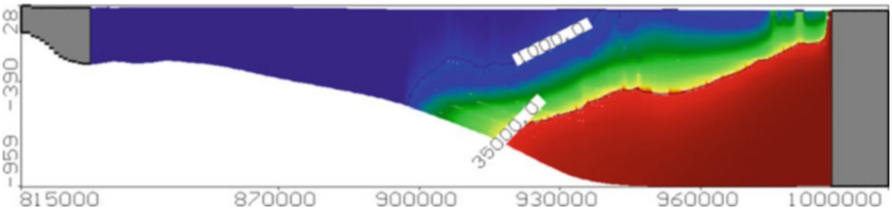

Fig. 3.15 Vertical distribution of TDS in the Nile Delta Aquifer (NDA) due to overpumping by 50%

3.6.2 Management of Saltwater Intrusion (SWI) in Coastal Aquifers

The identified future scenarios provided valuable information for prediction of the sustainable management of the NDA freshwater and for achieving food security. Subsequently, in Egypt, four techniques were applied to control SWI and protect the freshwater aquifer from salinity: optimisation and allocation of abstraction rates (OA); treatment and recharge (TR); abstraction, desalination, and recharge (ADR); and treatment and recharge, abstraction, and desalination (TRAD). Coastal aquifer mitigation is essential to increase the fresh groundwater resources in these regions (Abd-Elhamid et al. 2020).

3.6.2.1 Optimisation and Allocation of Abstraction Rates (OA)

Simulation-optimisation models (SOM) may be used to manage and control SWI in coastal aquifers. The numerical model of SEAWAT may be used to investigate the groundwater heads and salt concentrations for transient density-dependent cases, while the genetic algorithm optimisation technique estimates the optimal well locations, depths, abstraction, and recharge rates to minimize the total costs of the system construction and operation. The iterations of trial and error have been used to solve the optimisation problem, while the numerical simulation models overcame and examined a limited number of design options (Mohamed 2004; Abd-Elhamid 2010). SOM approaches also reduce the remediation costs of polluted land in numbers of a real case study with global coverage (Zheng and Bennett 2002).

Cheng et al. (2000) developed SOM to manage and optimise the abstraction for SWI mitigation based on a sharp interface. Hong et al. (2004) carried out SOM to examine the optimal well pumping rate and locations to achieve the sustainable water resources in coastal zones. Qahman et al. (2005) simulated the SWI using the SEAWAT code with SOM in the Gaza Aquifer, Palestine; also the model was used to study the different pumping rates on aquifer salinity. Reichard and Johnson (2005) carried out SOM to manage the SWI in the west coast basin of Los Angeles, USA, using recharge of freshwater via well injection and surface water ponds. Park et al. (2008) used SOM to optimize the abstraction rates in the aquifer to protect the fresh groundwater by reducing pumping rates. Dokou et al. (2016) developed SOM to manage SWI in two unconfined coastal aquifers in Crete, Greece, by optimising the abstraction rates with fixed SWI using a GWM code. Rearrangement of abstraction wells can reduce the SWI and upconing (Abd-Elhamid and Javadi 2008), though it is costly; construction and placing of wells pose problems.

For the NDA in Egypt, total annual abstraction rates of 7 billion cubic meters in 2016 were reached (Molle et al. 2016). Such abstraction should be managed to optimise the uses of water resources and protect the aquifer from depletion. The NDA may be managed using linked SOM to control SWI rather than with the traditional methods of reduction.

3.6.2.2 Treatment and Recharge (TR)

TR is used to increase aquifer storage by treating wastewater and recharging it to the fresh groundwater, helping to increase groundwater storage and control of SWI. The recharge systems can be realized by means of infiltration surface ponds or deep wells. In regions of high abstraction rates, this system is costly and ineffective (Narayan 2002). Narayan et al. (2003) simulated the groundwater salinity using SUTRA in the Burdekin Delta Aquifer, Australia, for different abstraction and recharge conditions. The study indicated that the variation in pumping rate, artificial and natural recharge, affects the dynamic of SWI. Vandenbohede et al. (2006) simulated the SWI and control methods in the western Belgian coastal plain using natural recharge of ponds for sustainable water management. Abd-Elaty et al. (2021e) developed a numerical study to simulate the use of different well systems in the NDA in Egypt by reduction of current abstraction, treated wastewater recharge, abstraction of brackish water for desalination, and combination of these systems. The study indicated that these techniques are effective in the management of SWI.

In the NDA of Egypt, the use of recharge ponds was simulated using SEWAT to control SWI. The recharge water can be collected from treated water or storm water. The scenario of increasing the recharge by 50% was introduced. Results are shown in Fig. 3.16 where the intrusion length reached 66.25 and 89 km from shoreline for iso-line 3.5E4 and 1.0E3, respectively.

3.6.2.3 Abstraction, Desalination, and Recharge (ADR)

ADR involves abstraction of brackish water, desalination using renewable energy with novel desalination (reverse osmosis (RO), forward osmosis (FO)), and recharge using surface ponds or deep recharge wells. Developed by Abd-Elhamid and Javadi (2008), ADR can mitigate SWI in coastal aquifers. The method has low energy consumption, costs, and environmental impact and is capable of retarding SWI.

Abd-Elhamid and Javadi (2011) report the combined system (ADR) and individual abstraction or recharge technique; considering the total cost and salt

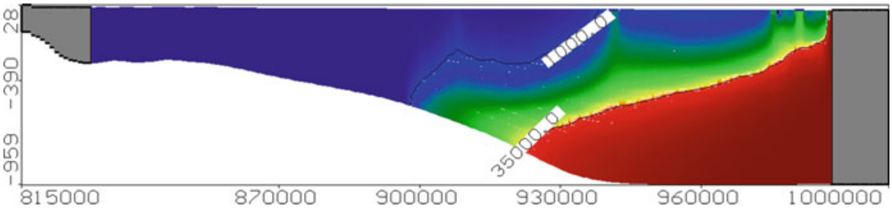

Fig. 3.16 Vertical distribution of total dissolved solids (TDS) in the Nile Delta Aquifer (NDA) due to 50% recharge by treated wastewater

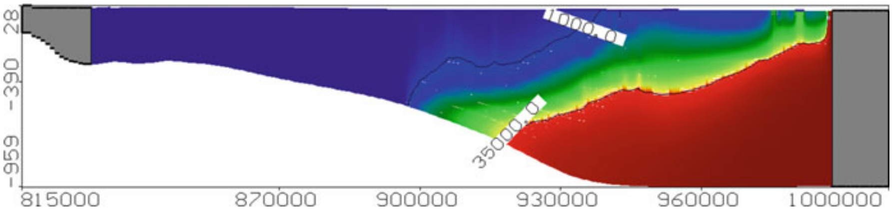

Fig. 3.17 Vertical distribution of TDS in the Nile Delta Aquifer (NDA) due to 50% recharge by use of desalinated abstracted water

concentration can reduce the aquifer salinity. The ADR system was significantly more efficient and sustainable than other systems. Javadi et al. (2013) simulated the SWI using SUTRA with a genetic algorithm (GA) to optimise the management of SWI in unconfined aquifers by combining abstraction of desalinated brackish water and recharge using surface ponds.

For the NDA of the case study in this chapter, control of SWI was developed by abstraction of brackish water by 50% from the total abstraction rates of aquifer. The SEWAT code was simulated (Fig. 3.17).

The iso-line 3.5E4 and 1.0E3 reached 67.75 and 90 km from shoreline, respectively, and the width of the transition zone covered 22 km.

3.6.2.4 Treatment, Recharge, Abstraction, and Desalination (TRAD)

This method is used to mitigate the SWI in coastal aquifers. It includes the treatment of wastewater, recharge to the aquifer to increase the storage of fresh groundwater, abstraction of brackish water to reduce the volume of saline water, and desalination to produce freshwater. The TRAD method overcomes the limitation of other methods, because the source of recharge systems includes the use of treated wastewater, storm water, or the desalinated water of desalination plants. Desalinated water may be used for different purposes to support the water demand or source aquifer freshwater recharge managing SWI. The technique of abstraction and recharge can control SWI toward the sea. Disposal of brine from the desalination plant can be used to produce salt or used in irrigation of certain crops or fisheries. The method has low

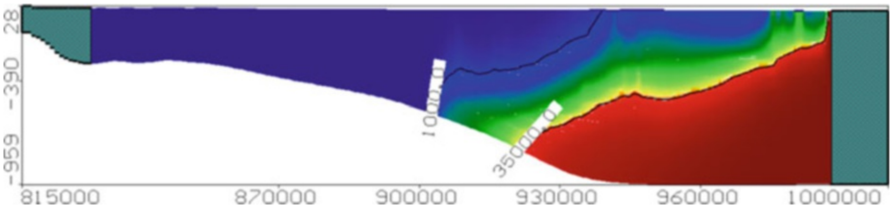

Fig. 3.18 Vertical distribution of total dissolved solids (TDS) in the Nile Delta Aquifer (NDA) due to 50% recharge by treated wastewater and desalination of abstracted water

cost and low environmental impacts, resultantly increasing the groundwater abstraction rates for freshwater supplies and managing flows to the sea (Abd-Elhamid 2010).

Javadi et al. (2015) developed a GA optimisation tool and simulated a SUTRA code to investigate the efficacy of TRAD method to manage SWI. The TRAD technique is efficient and mitigates SWI with low cost and produces the lowest salinity in the aquifer. Abd-Elaty et al. (2021f) used the SEAWAT code to investigate and manage SWI in coastal aquifers under climatic changes of humidity and hyper-aridity using the TRAD technique. The results showed that this system effectively manages SWI.

Abd-Elhamid and Abd-Elaty (2017) simulated the NDA of the chapter case study salinity using this method and found that it could be useful to control SWI where treated wastewater is used for recharge and the abstracted brackish water is used for desalination. The simulation was carried out for the NDA for a recharge and abstraction from brackish water increase of 50%. The results indicated that the iso-line 3.5E4 decreased to 65.50 km, while the iso-line 1.0E3 decreased to 84.75 km as shown in Fig. 3.18. Abd-Elaty et al. (2020b) applied the TRAD technique using a SEAWAT code in the Gaza Aquifer, Palestine, using TRAD with abstraction of brackish water and recharge of treated wastewater. The study showed that this system could retard intrusion of saline water and achieve management of SWI.

3.7 Conclusions

Today, the sustainable management of water resources is a key target for hydrological scientists around the world due to shortage of water resources and increases in water demands as a result of climatic change (CC) and overpopulation. SWI is a major challenge in the management of groundwater resources in coastal regions. Treatment of wastewater has a positive impact and overcomes the scarcity of water in arid regions. Desalinating brackish water using renewable energy sources such as solar energy in combination with reverse osmosis (RO) is an efficient methodology that requires relatively simple equipment and low energy. The freshwater in coastal aquifers must be protected. Nowadays overpumping effects the growth in water demands from increasing coastal populations, increasing the SLR and aquifer salinity, threatening available groundwater supplies. The current study used a SEAWAT code to investigate the sustainable management of water resources in the NDA, Egypt, with mathematical advances. The latter developed a number of approaches – optimisation and allocation of abstraction rates (OA); treatment and recharge (TR); abstraction, desalination, and recharge (ADR); and treatment and recharge, abstraction, and desalination (TRAD). TRAD is a new and valuable method which pushes saline water toward the sea and improves environmental conditions of the aquifer in Egypt; we recommend its application (with adaptation) elsewhere to potentially ensure or contribute to water sustainability amidst increasingly extreme changes present on Earth today.

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