Modelling of paleo-saltwater intrusion in the northern part of the Nubian Aquifer System, Northeast Africa

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Abstract A numerical groundwater model of the Nubian Aquifer System was established to prove the influence of rising seawater levels on the groundwater salinity in northern Egypt over the last 140,000years. In addition, the impact of a groundwater recharge scenario for these 140,000years, involving climatic change, on the saltwater/freshwater interface was investigated. Saltwater intrusion induced by rising water levels of the Mediterranean Sea led to salinisation from the Mediterranean Sea to the Qattara depression. This modeling approach was supported by a density-driven model setup and calculation. The modelled saltwater/freshwater interfaces partially fitted the observed ones, especially in the southern half of the Qattara depression. In other parts of the northern Nubian Aquifer System, the ingression of salt water was modelled adequately, but in the west, small regions of the measured interface were not. The development in the Qattara depression (Egypt) and Sirte basin (Libya) were investigated in more detail. The different behaviour in the Sirte basin may be due to high evapotranspiration rates in some former periods, salt solutions from the pre-Quaternary layers or saltwater infiltration from sabkha-like recent salt-bearing sediments.

Keywords Paleohydrology · Paleoclimate · Salt-water/ fresh-water relation · Nubian Aquifer System · Egypt · Libya

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Introduction

The Nubian Aquifer System in northeast Africa is an important water resource for the eastern Sahara (Struckmeier et al. 2006) and has been the subject of many studies for over a hundred years (e.g. Ball 1927; Sandford 1935; Hellström 1939; Ezzat 1974). Since the end of the 1980s, there has been a consistent development in hydrogeological investigations. The earliest numerical groundwater models were developed for this area based on regional-scale geological investigations (Lamoreaux et al. 1985; Heinl and Brinkmann 1989; Heinl and Thorweihe 1993; Idris and Nour 1990; Thorweihe and Heinl 1999; Ebraheem et al. 2002; Ebraheem et al. 2003; Ebraheem et al. 2004) and enhanced with better modelling techniques (Gossel et al. 2004, 2006, 2008; Sefelnasr 2007). These models focused either on the development of resources from the late Quaternary or the prospective impact of groundwater extraction in development areas, e.g. oases in Egypt and Libya. Until now, the regional numerical groundwater models for the Nubian Aquifer System implemented a boundary condition for the north of the model area; this was built by the saltwater/freshwater interface ranging from the north of the Siwa oasis to the south of the Nile delta. This interface was assumed to have been stable for at least the last hundred years. For long-term models, this is a weak boundary condition because research projects from the last 10 years have shown rising water levels for the Mediterranean Sea over the last 25,000 years, which may have influenced this interface as well. Long-term groundwater models should therefore incorporate this knowledge in the form of a more reliable boundary condition. An overview of the area is given in Fig. 1. The aim of this study was to investigate possible fluctuations in the saltwater/freshwater interface as there are several processes that can lead to ingressions of salt water into the Nubian Aquifer System. These processes and their time scales are listed in Table 1. The table shows the clear necessity for a regional and long-term groundwater model for this area. With this enhancement and the additional variable density approach, the model goes far beyond the former models that only regarded the freshwater and took the saltwater/ freshwater interface as a boundary condition.

All influences of rising saltwater/freshwater interfaces in central and southern parts of the Nubian Aquifer

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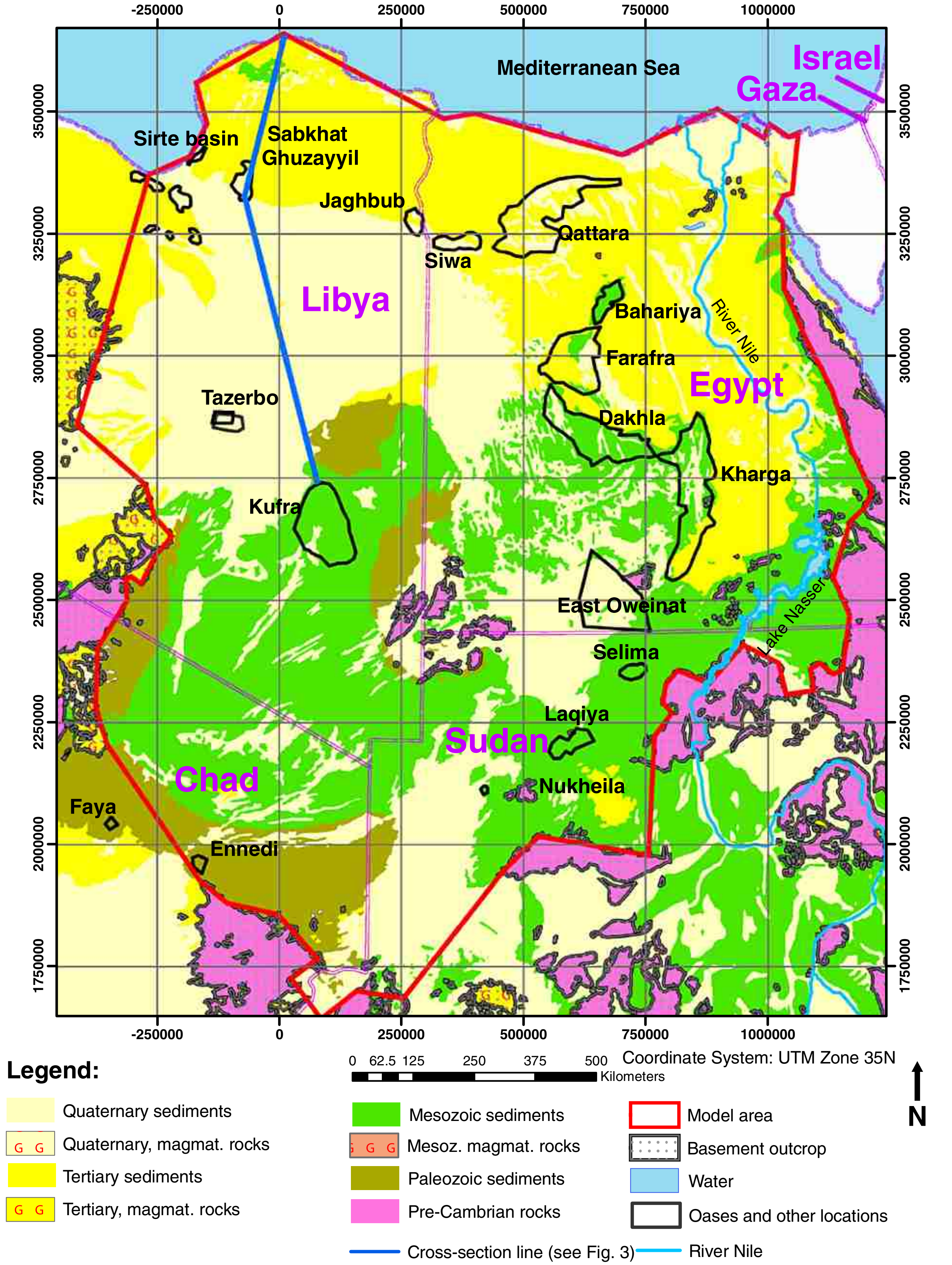

Fig. 1 Geographical and geological overview

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Table 1 Overview of processes influencing the saltwater/freshwater interface in northeast Africa that are the focus of this report. The timescale was estimated but gives an overview of the duration and reversibility of the processes

Process	Effect	Spatial scale	Timescale
Saltwater residues of former marine ingressions	Residues of old salt water	Regional scale $x\times100$ km	X million years
Climatic change: rising seawater levels (Mediterranean Sea)	Intrusion of salt water in case of influent flow conditions, regression of salt water in case of effluent flow conditions	Local scale to regional scale (100 m to $x\times100$ km)	$X\times1,000$ years
Climatic change: varying groundwater recharge (precipitation and evapotranspiration)	Intrusion of salt water dependent on flow conditions	Local scale to regional scale (100 m to $x\times100$ km)	$X\times1,000$ years
Solution of salt in sediments	Increasing salt concentrations in adjacent aquifers	Local scale ($x\times1$ to $x\times10$ km)	$X\times1,00$ years
Solution of recent salt deposits in sabkha sediments	Locally increasing salt concentrations in upper aquifer	Local scale ($x\times1$ to $x\times10$ km)	$X\times100$ years
Evaporation of shallow groundwater	Increase in salt concentration by evapotranspiration	Local scale ($x\times1$ to $x\times10$ km)	$X\times100$ years

System and additional groundwater extraction by pumping are not regarded in this study because the time horizon was set to the past 140,000 years. Therefore, the investigation is meant as a contribution to the discussion of the long-term influence of rising seawater levels on coastal aquifers in a long time range as proposed for a climatic change. For this region, evaluating and differentiating the processes in detail can only be done on the long-term regional scale. Using a numerical groundwater transport and density-driven model, the extent of the influence of different sources can be estimated.

The influence of climate change is twofold. On one hand, the groundwater recharge varies over time over a wide range; on the other hand, the seawater level in the Mediterranean Sea is connected to the freezing and melting of ice shields during the Quaternary period. The climatic parameters in this area over the last 140,000 years have been reconstructed either by compiling observations or modelling (Claussen 1995; Kubatzki and Claussen 1998; Pachur 1999; Hoelzmann et al. 2001; Claussen and Gayler 1997; Valdes 2005; Claussen 2005; Kubatzki 2002; NCDC 2005). The impact of the mid-Holocene period, during which this region had a warm and humid climate, is described in detail by Kröpelin (1999) and Kuper and Kröpelin (2006); the climatic processes are already quantified but with a low temporal and spatial resolution. This input can also be used for enhancing regional numerical groundwater models.

Methods and modelling approach

Until now, only a few wells have been used to measure the outline of the saltwater/freshwater interface. Thus, the database is very scant, and the genesis of the salt water can only be assumed through isotopic measurements. A numerical groundwater model is more suitable for clarifying the genesis and it can also serve for prognostic development plans. Therefore, the already established and described numerical groundwater flow model for the Nubian Aquifer System (Gossel et al. 2004, 2008; Sefelnasr 2007) was spatially enlarged northward to the Mediterranean Sea. After the expansion, the model has nearly the same outline as the recent boundaries shown by the Centre for Environment and Development in the Arab Region and Europe (CEDARE; Abu Zeid 2005). To meet the needs of transport and density-driven saltwater intrusion models, the structure had to be simplified, especially for high resolution in the Egyptian oases.

The finite element modelling tool FEFLOW (Diersch 2005) was chosen because of its capability to model groundwater flow, transport and variable density; in addition, previous models were set up with this tool. FEFLOW allows for three-dimensional (3D) groundwater flow modelling with spatial and time-dependent groundwater-recharge input, which allows the different influences over the last 140,000 years to be recognised in the model.

For the transport model, only dispersion and diffusion were set because salt is nonreactive. The dissolved salt is not sorbed in remarkable dimensions by clay minerals. Although an ion exchange may be assumed for the salt concentration, especially in the limestone near the coast, this process was not modelled due to the lack of detailed hydrochemical analyses in this area. Biological or radioactive decay can be excluded. In the transport model, the number of layers was reduced due to unstable behaviour, especially for distorted prisms. The transport model is more sensitive to these elements than the flow model. Gossel et al. (2004, 2008) and Sefelnasr (2007) divided all hydrogeological layers into three numerical layers because of the averaging algorithm for hydraulic conductivities between cells. The model described here thus consists of 11 instead of 22 layers (top and bottom layers were divided into 2 layers by Gossel et al. 2004, 2008 and Sefelnasr 2007). Therefore, the new model had to be calibrated again with this hydrogeological structure; however, in general the hydraulic conductivities remained nearly the same.

The density difference between freshwater and saltwater influences the groundwater flow model because of a relevant vertical flow. This phenomenon has been observed, described and modelled at several coastal sites (e.g. Konikow and Reilly 1999). To show the effects of the density driven vertical flow over this long time period, the 3D modelling approach is necessary. Two-dimensional vertical models can not be used here because of the

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changing flow directions due to the changing recharge conditions.

Geological and hydrogeological settings

The structure of the biggest part of the model area has already been described by Gossel et al. (2004, 2008) and Sefelnasr (2007). Available drilling information on the fully penetrated wells until 2001 and the available geological cross sections (e.g. Hesse et al. 1987; Wright et al. 1982; Edmunds and Wright 1979) were digitised and entered into a formulated geographic information system (GIS) database. Additional geological information was derived from Schandelmeier and Wipfler (1999) and Klitzsch and Wycisk (1999).

The whole structure was held in a GIS database. To enlarge the model area to the Mediterranean Sea, some additional literature datasets were necessary. The digital elevation model (DEM) of the SRTM (Shuttle Radar Topography Mission; USGS 2000) at a resolution of 30 arcseconds was used for the top of the model. The base of the whole aquifer system was built by an interpolation of isolines and cross sections. In addition, data for fully penetrated wells up to 2001 were regarded not only for the model base but also for the 3D structure of different layers.

The structure of the basins and uplifts has already been explained by Gossel et al. (2004; Fig. 2); in addition, the northwest basin of the model area was enlarged. The top of the basement rises from −3,500 to 2,500 m above sea level (masl), and the distribution of the top elevation is shown in Fig. 2. The structure of this basin is modelled based on maps from Hantar (1990), and additional information from Mansouri et al. (1993) and Fürst (1993) was used to construct the hydrogeological structure of the enlarged area. However, most of the recent improvements should have only minor effects on the model.

In northwest Egypt, the Paleozoic layers are approximately 2,000 m thick. The lithology of these layers is described as sandstone and mainly continental (Hantar 1990; Edmunds and Wright 1979). The Jurassic and Lower Cretaceous layers also consist mainly of sandstone; the Jurassic is divided into the Wadi el Natrun and Bahrein (Lower Jurassic), Khatatba (Middle Jurassic), and Masajid (Upper Jurassic) formations. The Masajid formation already contains limestone and shale. The Lower Cretaceous layer is also mainly continental with sandstone and shale (Hantar 1990). Only the upper part (Alamein formation) is built up by dolomite. The Bahariya formation in the Middle Cretaceous layer consists of marine sandstone and shale, whereas the Upper Cretaceous layer (Apollonia, Khoman and Abu Roash formations) consists of limestone and dolomite. A thick shale is intercalated in the Eocene and Oligocene layers (Dabaa formation), and the topmost modelling layer is the Moghra aquifer, which is a limestone from the Miocene age. The layers overlying the Moghra aquifer are not set in the model because they are only partially saturated.

The geological structures, given in several cross sections by Edmunds and Wright (1979) and the contours from Hantar (1990), were digitised and used as a base for interpolation. The layers fading out were substituted by overlying or underlying layers with shifts in hydraulic conductivities. The same procedure was used for faults. The whole structural model of slice elevations and parameters was held in a GIS database to access input parameters during the calibration process. A hydrogeological cross-section in the western part of the model area is given in Fig. 3.

Groundwater flow model

The 3D structure of the hydrogeological layers was taken for the biggest part of the area (Sefelnasr 2007) without using the high resolution in the development areas.

Each layer consists of 42,747 triangular elements and 21,853 nodes. The model covers an area of 2.18 million (M) km² and has a volume of 3.6 Mkm^3. The area of the triangles ranges from 15 to 500 km². The horizontal discretisation is shown in Fig. 4.

In the north, the structure and parameters were completed by cross sections and the contours of the layer bottoms, as described in the previous. As an example, the distribution of the hydraulic conductivity in the third hydrogeological layer above the basement is shown in Fig. 4. It is an aquifer comprised mainly of Paleozoic sandstone; in the northern part of the model area, the hydraulic conductivity is reduced due to intercalation of finer sediments. An overview of the structure and parameters of the 11 hydrogeological layers is given in Table 2.

The boundary conditions are mostly set to no-flow boundaries (see Fig. 2). In the east, south and west of the model area, basement outcrops define the outline without any input; to the north, the Mediterranean Sea is set to a defined head boundary. In addition, the Nile River is used as an internal boundary condition with defined heads in the eastern part of the model area.

The boundary conditions of first kind for the Mediterranean Sea and Nile River need some detailed explanation. During the 140,000 years being modelled, the level of the Mediterranean Sea changed dramatically, especially in the time spans between 120,000–140,000 and 5,000–25,000 years BP. Archaeological and geological research has shown that since the maximum of the last glacial (approximately 20,000 years BP), the level of the Mediterranean Sea has risen by approximately 120 m (Doumenge 1996; McCoy 1978). Figure 5 shows that the rising sea level was not a linear process but mainly occurred between 5,000–18,000 years BP. This also resulted in rising water levels of the lower Nile River. The sedimentary processes leading to the deposits in the Nile Delta could not be modelled in this groundwater

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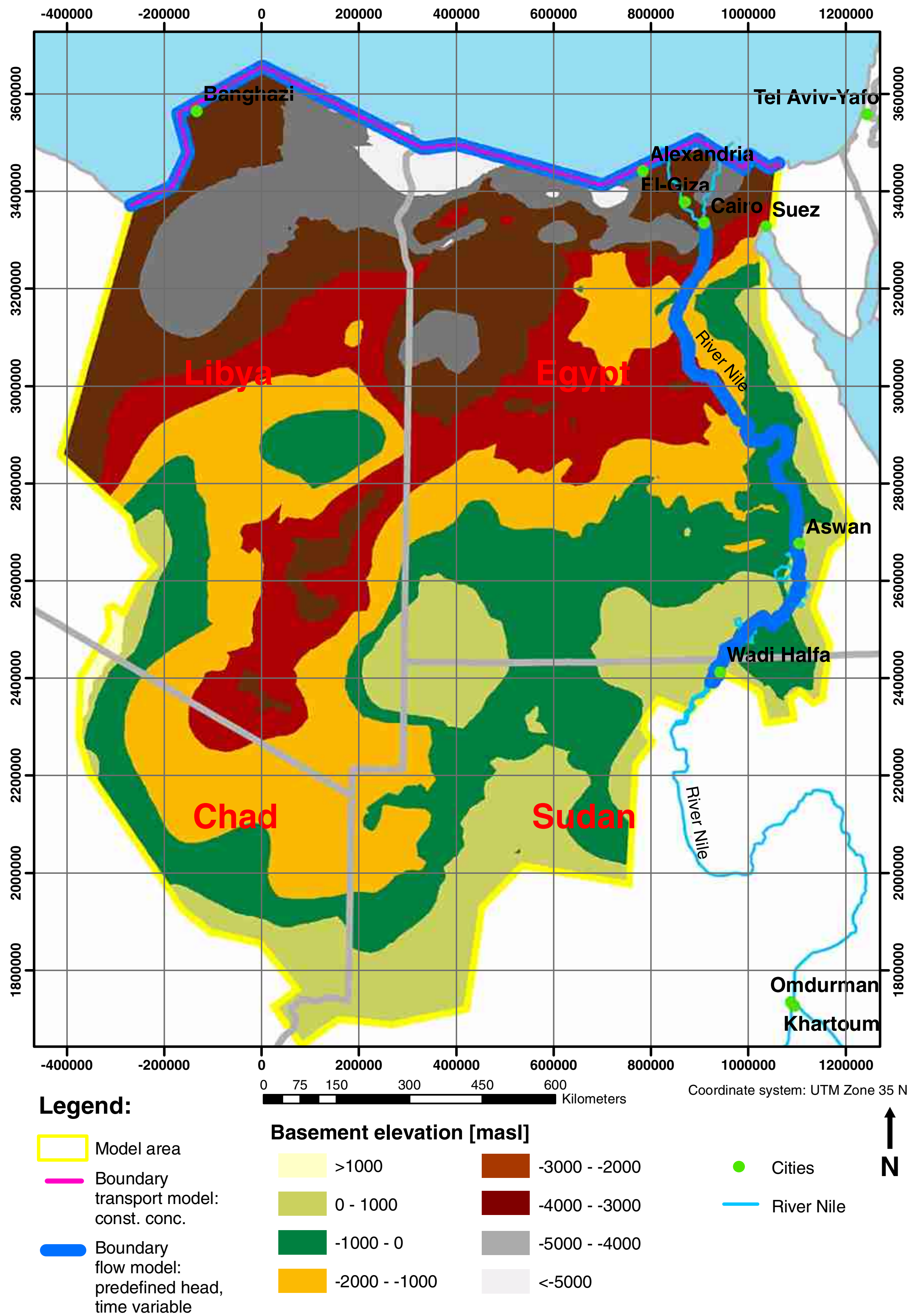

Fig. 2 Elevation map of the top basement and boundary conditions in the model area

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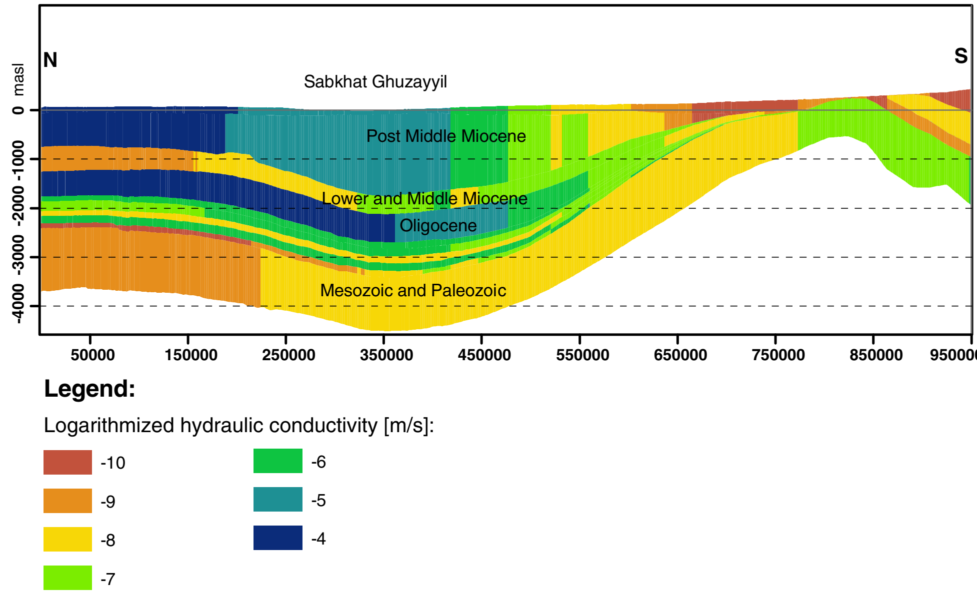

Fig. 3 Hydrogeological cross-section of the Eastern part of the model area–Mediterranean Sea to Kufra (see cross-section line in Fig. 1). The stratigraphical units are inserted according to Edmunds and Wright 1979

model. The water level of the lower Nile River was interpolated automatically as time dependent.

The initial water levels were set by a steady-state model of this area with the water levels of the Mediterranean Sea at the model start 140,000 years BP. The climatic data for the period between 10,000 and 140,000 years BP were extracted from the National Climatic Data Center (NCDC 2005). Only a very rough database of global climatic data is available for that time. Therefore, the recharge modelling is not as detailed and reliable as it is for the last 10,000 years. Nevertheless, this long period is necessary to understand how salt water intruded into the aquifer; therefore, the weak climatic data were taken and translated into the recharge values shown in Fig. 6. The wet and dry periods have been set to discrete values. Because of the high sensitivity to recharge data that was shown already in Gossel et al. (2004, 2008), the values do not vary too much.

The climatic change over the last 10,000 years as reported by Pachur (1999) and Kuper and Kröpelin (2006) was implemented by groundwater recharge in an enhancement of the recharge modelling by Gossel et al. (2006). For 20,000–25,000 years BP, there was a wet period that was followed by a dry period of approximately 10,000 years. Approximately 5,000–10,000 years BP, there was another wet period with a remarkable groundwater recharge. The minimum groundwater ages for the Nubian Aquifer System were determined to belong to this period so that all groundwater is older than 5,000 years and there was (nearly) no groundwater recharge after this wet period. On the other hand, discharge and evapotranspiration in the oases continued through this entire period, and these were at a higher level during the dry periods as compared to the wet periods. An overview of the groundwater recharge and evapotranspiration is shown in Fig. 6.

Due to this definition of the boundary conditions and the additional differentiated groundwater recharge data, a transient flow model had to be run. For this long time period, it was important to have a modelling tool with an automatic time step control. The groundwater flow model was already calibrated by Gossel et al. (2004, 2008) for the period before groundwater extraction began in developing areas in 1960, while Sefelnasr (2007) calibrated the model for water levels after 1960. For the time period 5,000–10,000 years BP, Kuper and Kröpelin's proxy data (2006) were used. In the areas shown by Kuper and Kröpelin (2006), the model gave a good fit for the depth to groundwater of only a few meters up to >1,000 m. Thus, the model is reasonable, although a direct fit to proxy data could not be achieved.

The extension of the model area northward did not affect the water levels in most of the previous model area. At the northern edge, there was a slight deviation in the water levels, showing a further flow in the northern direction that had been suppressed by the no-flow boundary in the former models.

Results of the groundwater flow model

The results of the groundwater flow model allowed for the calculation and analysis of water levels, flow directions and balances. Due to the purpose of the model, the focus was set on analysing the results at the northern boundary condition.

The water levels show the influence of the rising water level of the Mediterranean Sea on the groundwater (Fig. 7). This is supported by the outline of the flow directions. In Fig. 7, the results are shown for the period immediately before the wet period approximately 10,000 years ago. The pathlines shown in Fig. 7 for this period also show the influence of the Mediterranean Sea on the groundwater; however, the velocities were very low, and therefore, the total influx could only be estimated

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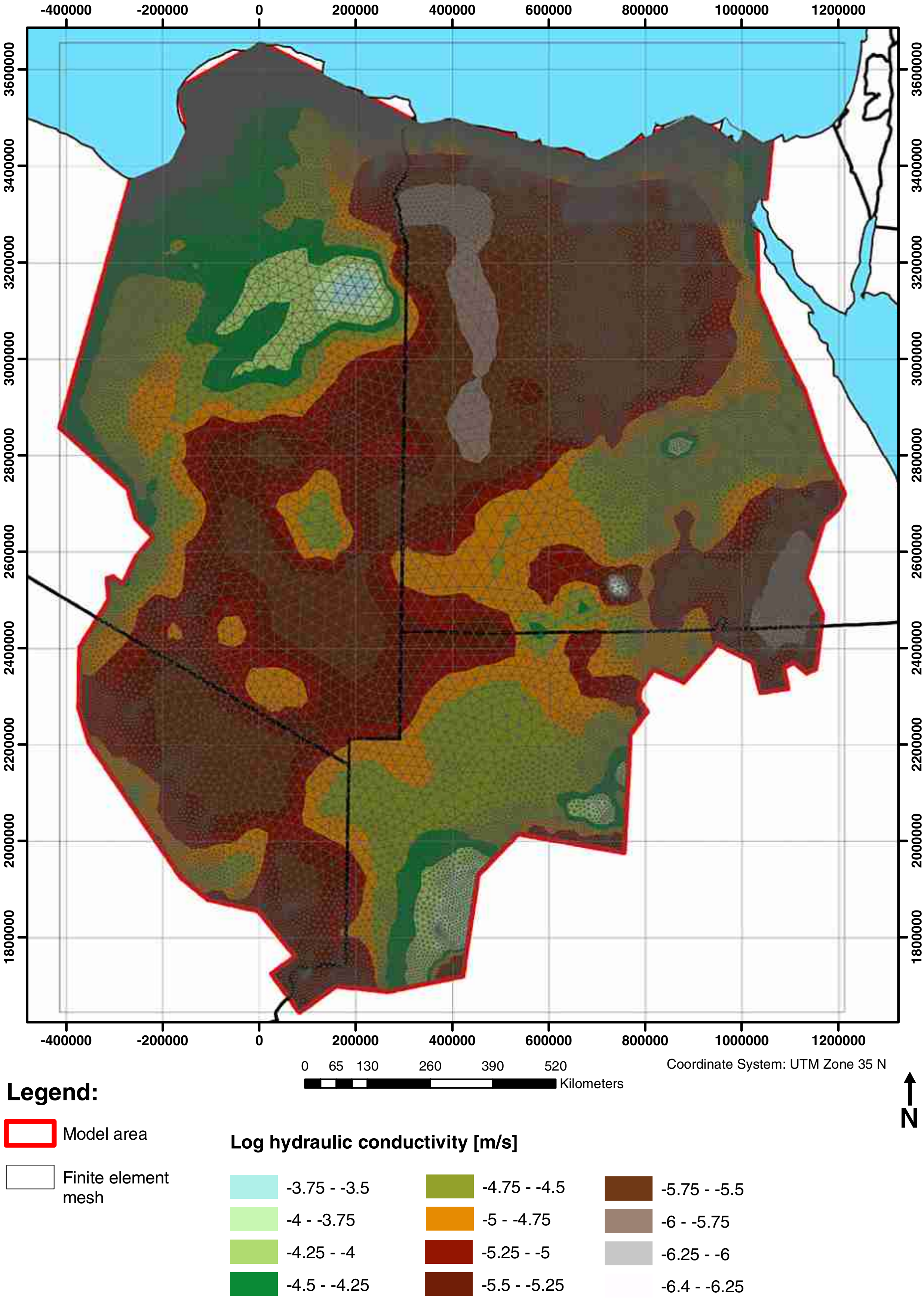

Fig. 4 Finite element mesh and distribution of the hydraulic conductivities of the third hydrogeological layer above the basement

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Table 2 Overview of the 10 hydrogeological layers (the top of the uppermost layer, slice 1, is the ground surface; the bottom of layer 10, slice 11, is the basement top). The minimum thickness is 0.1 m. *SD* standard deviation

Layer number	Mean layer thickness [m]	Max. layer thickness [m]	SD layer thickness [m]	Min. log(kf)	Max. log(kf)	Mean log(kf)	SD log (kf)
1	257	3,187	365	−6.4	−3.6	−5.3	−3.6
2	391	1,905	402	−6.4	−3.5	−4.7	−3.6
3	462	3,344	425	−6.5	−3.8	−4.7	−3.6
4	374	1,238	235	−6.4	−3.8	−4.9	−3.7
5	51	795	61	−6.4	−3.6	−4.7	−3.6
6	275	2,010	390	−6.4	−3.3	−3.9	−3.3
7	139	1,715	195	−6.5	−3.4	−4.0	−3.3
8	170	1,291	214	−6.7	−3.6	−4.2	−3.3
9	144	1,057	170	−6.9	−3.3	−4.0	−3.1
10	1,030	4,238	1,029	−6.4	−3.7	−5.1	−3.7

by the calculation of balances. The total influx during this period was 3–10 Mm^3/d for the entire coastal boundary of the Mediterranean Sea, with a length of approximately 1,600 km. For the coastline in the north of the Qattara depression, the time dependent influx, outflux and difference values are shown in Fig. 8. For a length of 315 km, the average influx from the Mediterranean Sea to the groundwater is ~30.1 Mm^3/d (influent conditions) and from the groundwater to the Mediterranean 30.5 M m^3/d (effluent conditions), so that the balance is 1% of the total fluxes. In parts of this long coastline there is a long-term influent flux and in other parts effluent flux. The intruded salt water can not be repelled by this small amount in the balance and so it remains in the aquifer, also during effluent flow conditions.

Balances of the exchange with the Nile River before 1960 were reported by Gossel et al. (2004, 2008). This model shows for the whole stream from Aswan to Cairo a recent flow of 85,000 m^3/d from the Nile River into the Nubian Aquifer System and a total flow of 225,000 m^3/d from the Nubian Aquifer System into the Nile River. More detailed analysis considering the exchange between Lake Nasser and the Nubian Aquifer System are reported in Sefelnasr (2007).

Parameters and boundary conditions of the groundwater transport and density dependent model

The groundwater transport model was established to consider the intrusion of salt water from the Mediterranean Sea over time. At the coastline, a constant concentration of 35,000 mg/L was set for all layers according to recent salt concentrations in seawater. The initials for the salt concentration were set to 35,000 mg/L at the coastline and 0 elsewhere in the model area so that it was a real starting point of a new saltwater intrusion.

For this large area, high heterogeneity was assumed; therefore, the dispersivity was set to high values. For the total area, longitudinal and transversal dispersivities were set at 500 and 50 m, respectively. Due to the nonreactive transport of salt, neither sorption nor decay was set. Molecular diffusion only affected small areas, and stand-

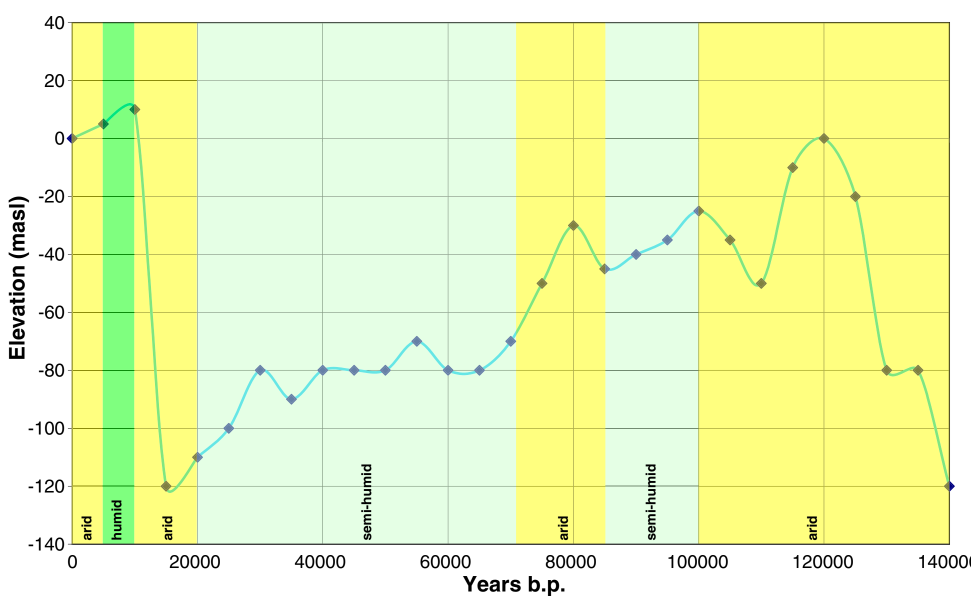

Fig. 5 Hydrograph of the Mediterranean Sea over the last 140,000 years (after NCDC 2005; and McCoy 1978)

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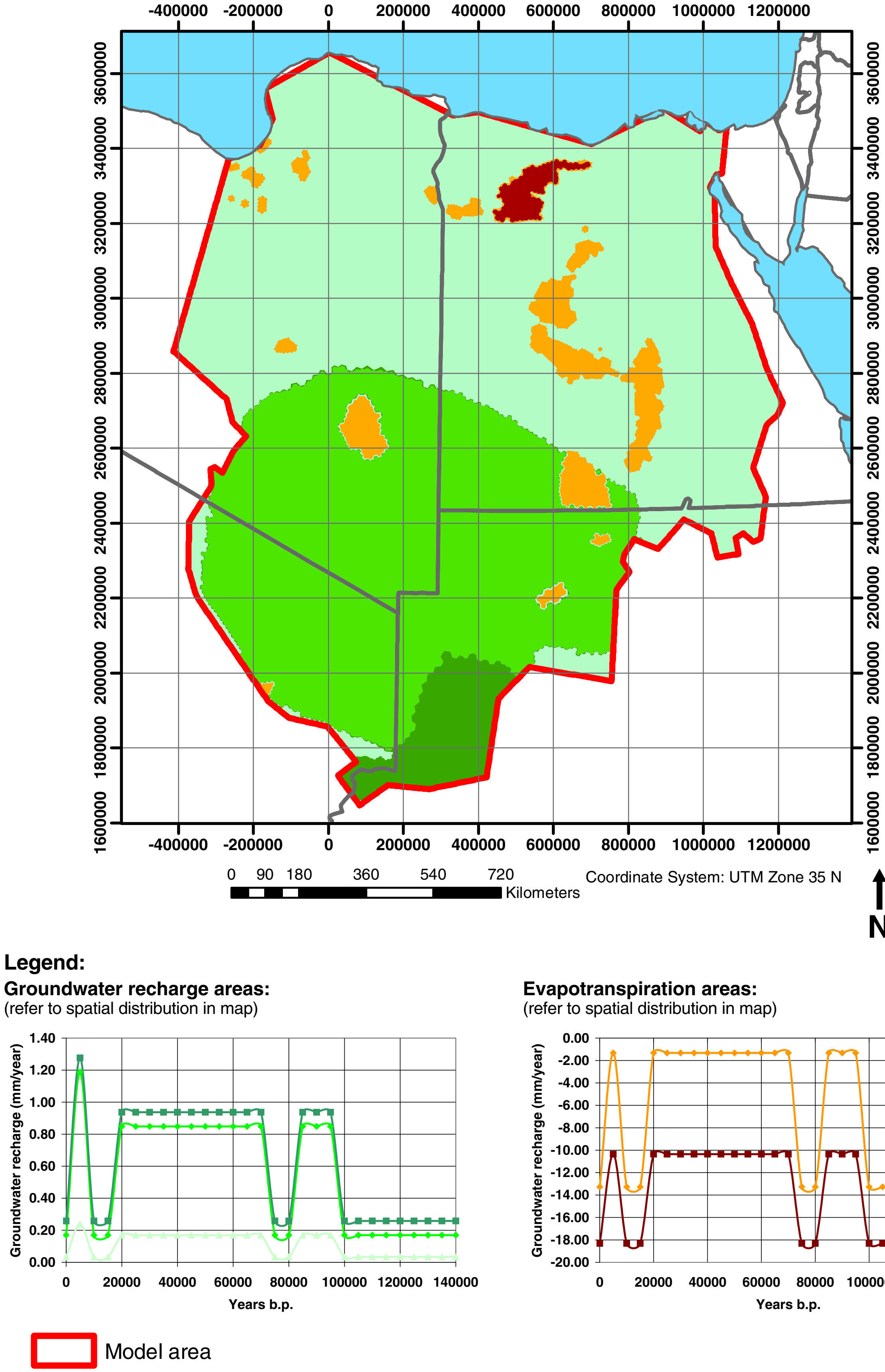

Fig. 6 Overview of spatial and temporal distribution of groundwater recharge areas and evapotranspiration areas. The *colours* of the spatial distribution in the map and of the hydrographs are related

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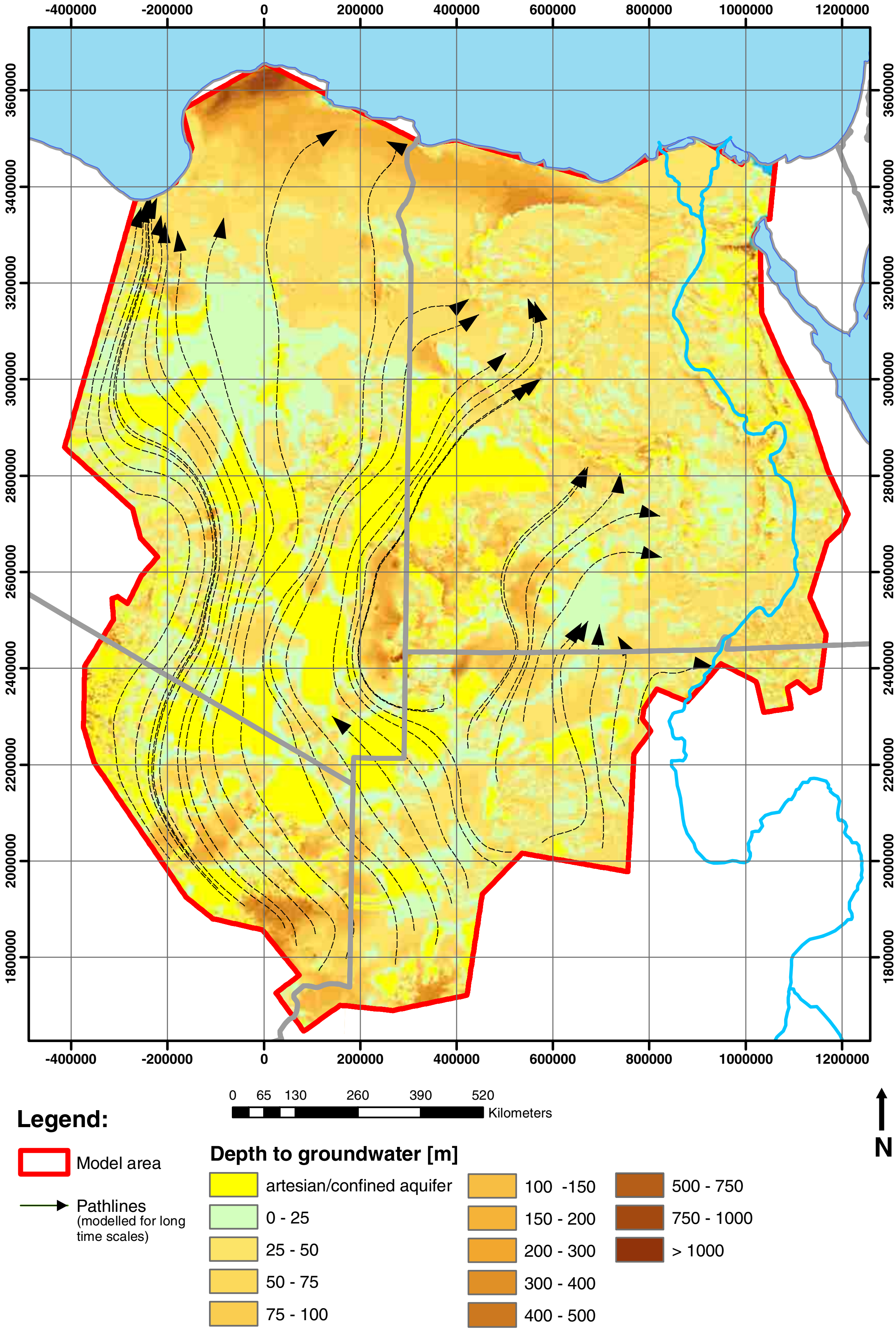

Fig. 7 Depth to groundwater and pathlines (10,000 years BP). The recharge from the south does not exist today, so these pathlines are only valid for the long-term flow regime

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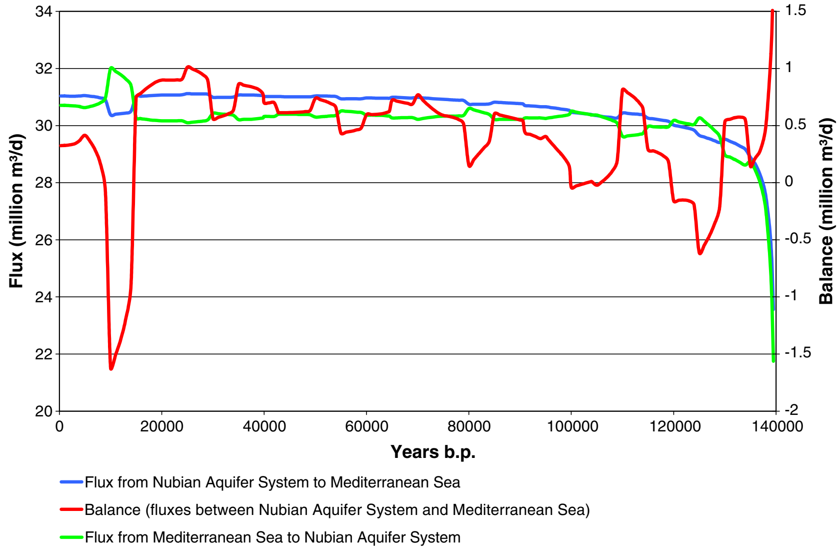

Fig. 8 Time-dependent modelled fluxes and balance between Mediterranean Sea and groundwater in the Nubian Aquifer System at the coast to the north of the Qattara depression

ard values were taken because there was no influence from water with high temperatures. For the transport model, the porosity is an important parameter. It was set according to the results of a few aquifer tests in wells in the oases collected by Sefelnasr (2007). The values range from 0.125 to 10% according to the depth of the layers and the distributions of hydraulic conductivities.

For the calculation of density-driven phenomena, a density of 1,020 g/L for the salt concentration in seawater is set. The density was corrected automatically by the modelling tool according to the salt concentration calculated by the transport model. Due to numerical problems in calculation, the time step length had to be restricted to a maximum of 1 year. The automatic time-step control of FEFLOW only sets additional steps when there are large changes between the previous and the next calculated time steps.

Results of the transport model

The transport model exhibited a differentiated reaction to the diverse climatic conditions and the hydrograph for the Mediterranean Sea. In general, intrusions of seawater were observed during periods of rising seawater levels. In periods of falling seawater levels, the process was reversed but in a spatially differentiated manner. These reversible ingressions and regressions of saltwater intrusion were very slow and had a time lag of a few thousand years. The first period of rising seawater levels led to an intrusion in northern Egypt from the Mediterranean Sea towards the Qattara depression, which has high evaporation. This is supported by the groundwater contours; in addition, the density of the seawater led to spreading of saltwater in the lower aquifers. These processes took approximately 60,000 years (80,000–140,000 years BP) due to the long distances between the coast and the centre of the Qattara depression. Other oases such as Jaghbub or Siwa were not so effective due to their narrow shapes and the longer distance to the Mediterranean Sea. After this time period, a retreat of the saltwater/freshwater interface, as indicated by the 2,000 mg/L salt concentration in Fig. 9, was observed in the western parts of the model area. This can be related to the change in climatic conditions and the turn of the seawater level; the higher groundwater recharge started approximately 95,000 years BP, and the water level of the Mediterranean Sea began to sink approximately 115,000 years BP. In northern Egypt, especially around the Qattara depression, the ingression continued, although it was slightly retarded. Approximately 15,000–20,000 years BP, the intrusion began again, especially in the western parts of the model area. At this time, the level of the Mediterranean Sea was rising rapidly and the groundwater recharge was very low. This process has continued up to present times, although the period of high groundwater recharge approximately 5,000–10,000 years BP led to a reduced velocity.

In general, the density effect could be observed; however, it was not as effective as the evapotranspiration process. In particular, during the intrusion of salt water, the front in the deep parts of the aquifer is faster than in the shallow parts. The maximum difference between the front in the upper and deeper parts of the aquifer was approximately 10 km.

The Qattara depression and Sirte basin were explored in greater detail due to their different behaviour. The high evapotranspiration in the Qattara depression is explained by the ground surface of about −70 to −80 masl corresponding to groundwater levels of −150 to −200 masl. In times of high groundwater levels, parts of the depression were flooded and the evapotranspiration increased dramatically. The groundwater levels of −150 to −200 masl led to a nearly permanent gradient from the Mediterranean Sea to the lowest parts of the depression, and thus to a saltwater intrusion (Fig. 10). Only at very low water levels in the Mediterranean did this process slow down. Therefore, the intrusion nearly continuously

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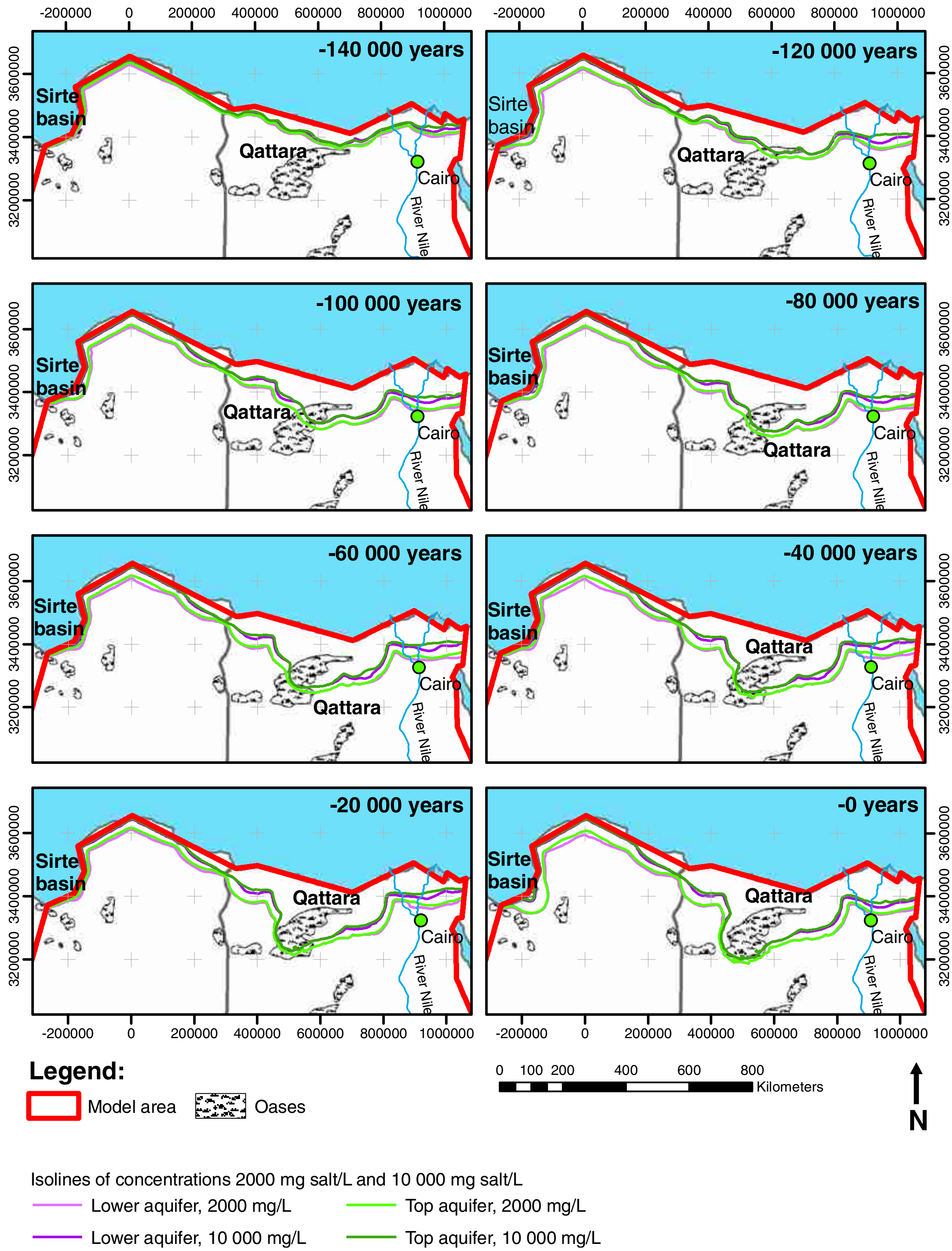

Fig. 9 Overview of saltwater intrusion in northeast Africa. The saltwater intrusion in the lower aquifer reaches only a few kilometres more to the south than the intrusion in the upper aquifer

penetrates the aquifer until it reaches the outline of the recent interface. The progress of the saltwater/freshwater interface in the Nile Delta is nearly stopped at the recent outline. However, the model results for the Nile Delta were quite weak and were restricted to the deeper aquifers. The erosion and sedimentation processes for the Quaternary period with water level changes in the Mediterranean Sea could not be adapted to the groundwater model. The density-driven processes played a minor role in this area, as shown in Fig. 10.

The saltwater intrusion in the Sirte basin exhibited a more complex response to variations in seawater levels and groundwater recharge. The observed (and measured) saltwater intrusion (Wright et al. 1982) indicated spread-

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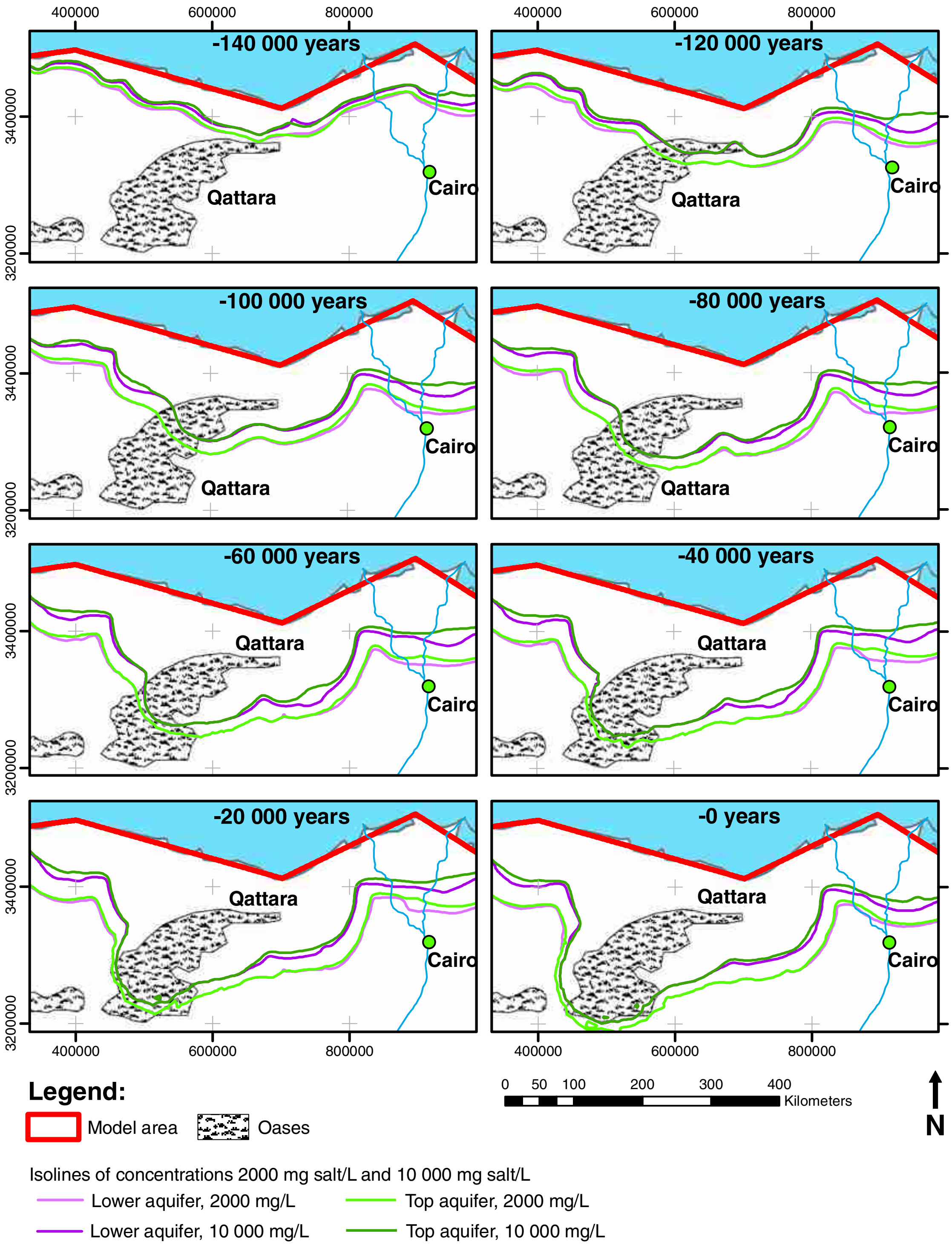

Fig. 10 Local saltwater intrusion in northern Egypt. In the Qattara depression, a continuous advancing front of salt water was observed, whereas in the Nile delta, the intrusion remained constant over a long time at the observed outline

ing far to the southeast. This was not matched by the model. The salt water in this region intruded very slowly, so it may simply require more model time; on the other hand, it also exhibited a wide variation. Figure 11 clearly shows the saltwater progress during times of high seawater levels and retreat when there are low seawater levels. The role of groundwater recharge during more humid climatic conditions is also obvious. Effluent flow conditions push the interface back nearly to the coast. In this highly dynamic system, the recent saltwater distribution is met only by chance. To the east of the Sirte basin, the described distribution (Wright et al. 1982) was not met at all; therefore, the impact of additional processes must be discussed.

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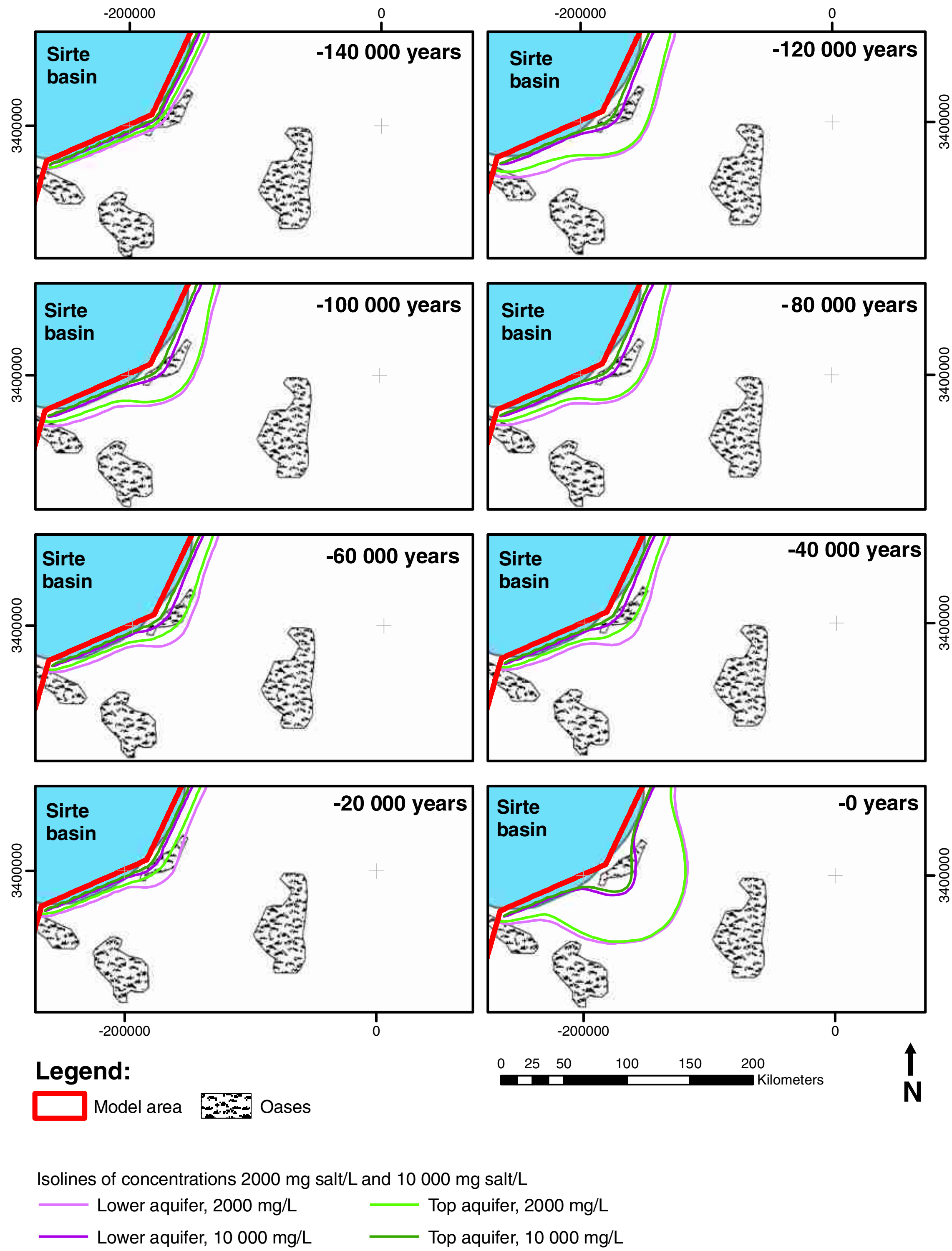

Fig. 11 Local saltwater intrusion in northern Libya. In the Sirte basin, an ingression and regression of the saltwater front is outlined by the model. The measured distribution (Wright et al. 1982) was not explained by the model and must be explained by other processes

Discussion

The period of saltwater intrusion may have started several hundred thousand years ago, even before the modelled time. The intrusion in the region in and around the Qattara depression was spatially very stable after the first influx. Only the concentrations varied with time. This can be understood by the constant function of this area characterised by high evapotranspiration. The effectiveness of the evapotranspiration process on saltwater ingression in this area can also be derived from a comparison with other areas. In addition to the Sirte basin, for other coastal

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aquifers, the ingression only reached a few kilometres, and not a few hundred kilometres as in case of the Qattara depression.

The Sirte basin exhibited only a very slow intrusion of salt water. Different processes may have led to the observed and described outline of salt concentrations higher than 2,000 mg/L:

- A longer ingression period may be assumed, and the behaviour in the modelled time period shows that the process may perhaps have occurred over the entire Quaternary period.
- Another possible reason may be that the saltwater is resident from the time of sedimentation or flooding in previous periods.
- Wright et al. (1982) also mentioned the possibility of salinisation by evapotranspiration.
- Further possible reasons are a recharge by water that infiltrated via salt layers at the surface or by solution of salt layers surrounding the aquifers (IAEA 2007). Real salt layers are very rare in the stratigraphy of this area, but a few are documented.

Although hydrochemical analyses may solve this question, none have been carried out thus far. In the Nile delta area, the intrusion reaches far to the south around Cairo. The literature is not consistent on this topic. Kashef (1983) stated that an intrusion occurred approximately 70–80 km to the south of the coast, while Baumann and Moser (1992) measured and interpolated nearly the same spatial distribution for the intrusion. Struckmeier et al. (2006) reported that the interface is drawn very far to the south, approximately 450 km from the coast of the Mediterranean Sea. The model results therefore do not exactly match the values observed by Kashef (1983) and Baumann and Moser (1992), but in this area, the model layer resolution was not adapted to the complex structures of the Quaternary layers; in the deeper layers, the difference is only a few kilometres. In addition, the impact of irrigation over the last 3,000 years was not regarded in the model. The irrigation may have led to increasing salt concentrations due to the evapotranspiration processes. On the other hand, the drainage system also led to a washing out of salt during and after floods of the River Nile. The complete processes and their balances were not considered in detail in this study for this area.

Conclusions

The model of the saltwater intrusion in northeast Africa very clearly shows the saltwater intrusion process, the recent outline of the saltwater/freshwater interface, and the dependency on climatic conditions and the level of the Mediterranean Sea. This model therefore allows a prognostic calculation of the impact of climatic change or groundwater extraction in the development areas of northern Egypt and Libya. Work on these additional topics will be continued in the future. Although the resolution of the model does not meet the needs of local problems, it can serve as a framework for more detailed investigations. The database must be enhanced to a higher resolution through new geological and hydrogeological investigations. In particular, the question of drain-fillable porosities is important for water balances. This could be achieved by enhanced modelling and by further measurements which were not applied in this study. Modelling approaches exist but they are weak and the suitability for this aquifer system is not proven.

To enhance and verify the results of the model, several investigations could be carried out: The investigation of groundwater ages could lead to better results especially in the Sirte basin. Thus, the actual outline of the interface could be better understood in this part of the aquifer system. The available reports of the geological structure in the north of Egypt and Libya are from the beginning of the 1990s and the recent results of drilling for oil and gas in this region have not been published. This information could also help to enhance the quality of the model especially if the permeabilities are also reported. Additionally the interface is not observed continuously and the exact outline is not determined. In the desert between Egypt and Libya, there is a gap in information that could be closed by a few wells. Perhaps they are already drilled in the frame of the "Great Man-Made River" project in Libya (Anonymous 2010) but they are not reported or publicly available. Structural, hydrogeological and hydrochemical investigations in this area are vital for a further enhancement of the study.

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