Groundwater Resources of the Nubian Aquifer System NE-Africa

Synthesis

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Abstract

In the Eastern Sahara, in south-eastern Libya, north-eastern Chad, northern Sudan and Egypt the Nubian Aquifer System occurs, which is formed by predominantly continental sandstone of Mesozoic and Palaeozoic age (pre-Senonian strata). Its major structural elements are the Kufra Basin in south-eastern Libya and the Dakhla Basin in south-western Egypt, each with an aquifer system up to 4000 m thick. Based on effective porosities of 7 to 10 % of the sediments, the total groundwater storage amounts to 150 000 km³, a giant groundwater resource, which has been developed partially since 1960 in particular project areas in the Kufra Basin in Libya and in major oases of the New Valley in Egypt.

In the frame of a joint research programme on geoscientific problems in arid and semi-arid areas, carried out in the eighties by the Universities of Berlin and different partners in the region, the evaluation of the groundwater resources in the Nubian Aquifer System – its development history and utilisation strategy – was one major emphasis of investigation. In that programme, the groundwater research was based on two scientific sectors: isotope technique and numerical flow simulation. The isotopes have proven, that the groundwater in the Nubian Aquifer System was formed by wet Atlantic air masses transported by western drift. Groundwater recharge has taken place during different wet periods in the past. Radiocarbon age dating indicates the groundwater formed in the Late Pleistocene older than 20 000 years and in the Holocene between 14 000 and 4 000 a b.p. This distribution of periods of groundwater recharge is in accord with the Quaternary geological findings in the region as well as in areas in central and western Sahara.

1 Introduction

The Nubian Aquifer System is the Sahara's most easterly groundwater province. It covers south-east Libya, Egypt, north-east Chad, and north Sudan with a total area of about two million square kilometres. To the east, the border is formed by basement outcrops of the Nubian Plate, to the south and west by the basement outcrops of the Kordofan Block and the Ennedi or Tibesti Mountains (Fig. 1). In the north and north-west, the pore volume of sediment is filled with saline water that entered the system either via an intrusion of Mediterranean sea water from the north or is groundwater that has not flushed out since the sedimentation of marine deposits. This interface between fresh and saline water forms the system's border in the north and north-west and is considered spatially stable in its position although slow movement is conceivable. The Nubian Aquifer System is therefore a broadly closed system. Only in the south-east there is a groundwater inflow from the Blue Nile/Main Nile Rift System (SALAMA, 1985).

The Kufra Basin in south-eastern Libya, north-eastern Chad and in furthest north-western Sudan, and the Dakhla Basin in south-western Egypt are the dominant elements of the aquifer system. Both contain sediments with thicknesses of 4 000 to 4 500 m and maximum aquifer thicknesses of about 3 500 to 4 000 m. Compared to them, the Aswan Platform, which is east of the Dakhla Basin, and the North Sudan Platform, which borders to the south, contain comparatively small groundwater resources due to the low sediment thickness of a few hundred meters only. North of the Dakhla Basin lies the Northwestern Basin of Egypt, with sedimentary thicknesses of over 4 000 m. Only the southern part of this structure, however, is within the Nubian Aquifer System, and is
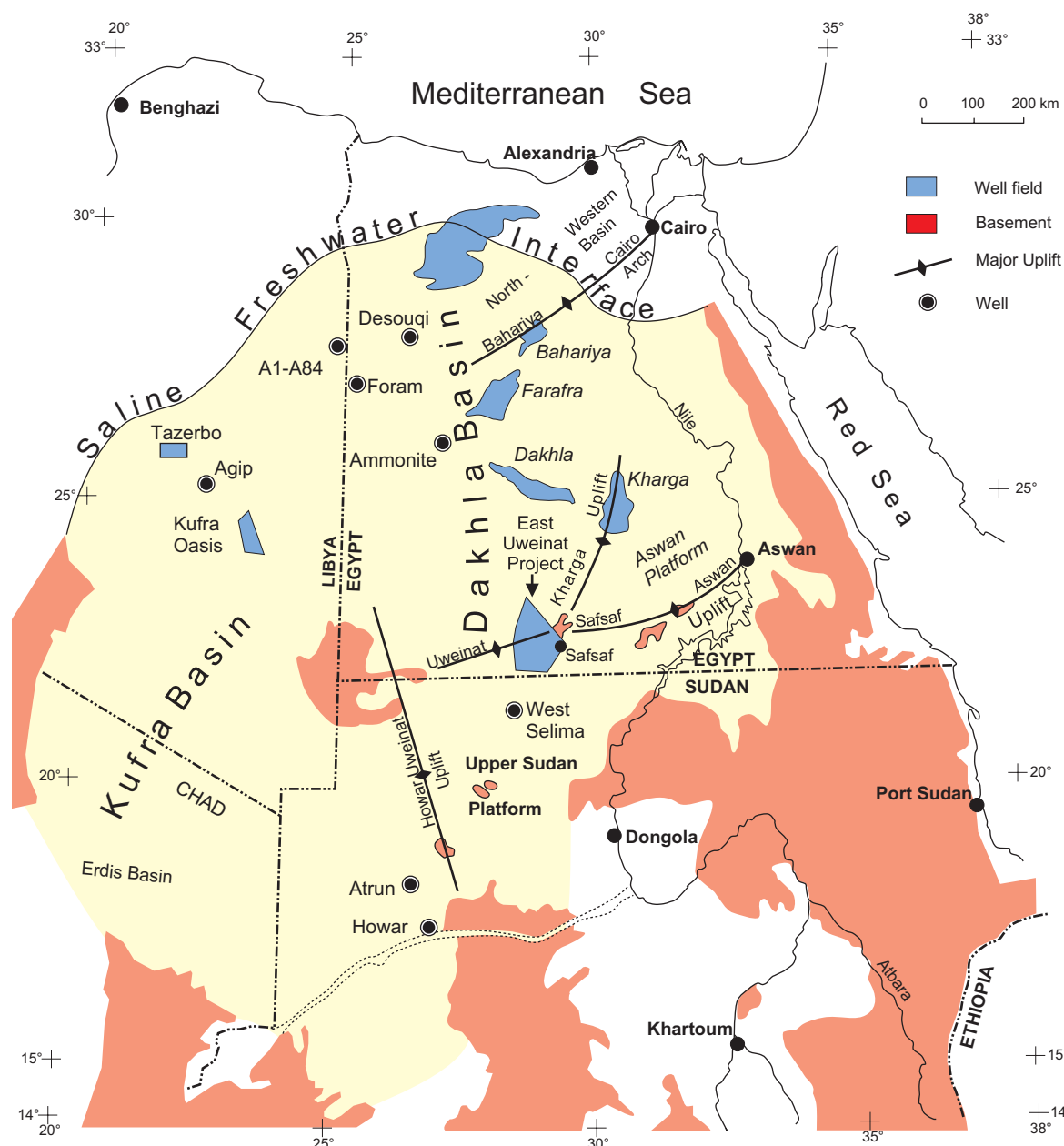
Fig. 1: General map of the Nubian Aquifer System area. (Position of saline-freshwater interface after: KLITZSCH, 1972; BGR, 1976)

therefore only of marginal importance for the hydrogeology of the study area.

Since the early 1960's, groundwater has been developed to a great extent for agricultural and to a lesser degree for mining purposes in the Kufra Oasis in Libya and in the oases of the New-Valley in Egypt, a chain of depressions in the Dakhla Basin that runs roughly parallel to the Nile and includes the Kharga, Dakhla, Farafra and Bahariya Oases.

During planning it has been generally assumed that the groundwater inflow from the south more or less balanced the groundwater discharge in the depressions. In other words the groundwater flow was in a steady-state, which would not be disturbed by artificial groundwater extraction. However, hyper-arid climatic conditions prevail in the study area, except in the most southern areas of the Nubian Aquifer System. Groundwater recharge from recent precipitation is only conceivable in mountainous areas or south of the Wadi Howar (SONNTAG, 1985.) Even without precise knowledge of the hydraulic parameters, based on Darcy's law the estimated groundwater flow time from there to the

development projects is several hundred thousand years. During this time different wet periods have occurred during which groundwater formation by local precipitation has taken place over the entire area. Due to these climatic changes from humid or semi-arid conditions to arid climates and vice versa, the groundwater system cannot attain a steady-state flow.

It must be assumed that even with regional groundwater inflow from present infiltration areas the groundwater in the Nubian Aquifer System is fossil. In other words, it is a ground-water deposit that would be depleted through natural and artificial processes. For this reason, choice of development area and production rate must be planned carefully even during the exploration phase, in order to avoid a breakdown in groundwater exploration projects over short- or long-term.

Responsible use of the groundwater requires a profound study of its origin and formation taking into account the quantitative hydraulic parameters of the aquifer system and the development of the groundwater flow considering extractions already started.

Fig. 2: Basement outcrops form the boundaries of the Nubian Aquifer System in the East (Red Sea Hills), in the South (Darfur Block, Ennedi Mountains) and in the West (Tibesti Mountains). In the North and Northwest the system is geologically open. (Clip of Geological Map of Africa, UNESCO, 1975.)

2 Geological Outline

The dominant geological units of the Nubian Aquifer System, the Kufra and Dakhla Basins, have undergone different geological development. The formation of the Kufra Basin began in the Early Paleozoic and was completed at the end of the Lower Cretaceous. Through regional marine transgressions during the Lower Silurian and Upper Carboniferous, which intercalated the far-reaching continental sedimentation, thick, vastly differentiated predominantly Paleozoic sediments are found here. On the other hand, the Dakhla Basin was presumably formed at the beginning of the Cretaceous, at least its southern part. North of the Dakhla Oasis latitude, Paleozoic sedimentation can be found.
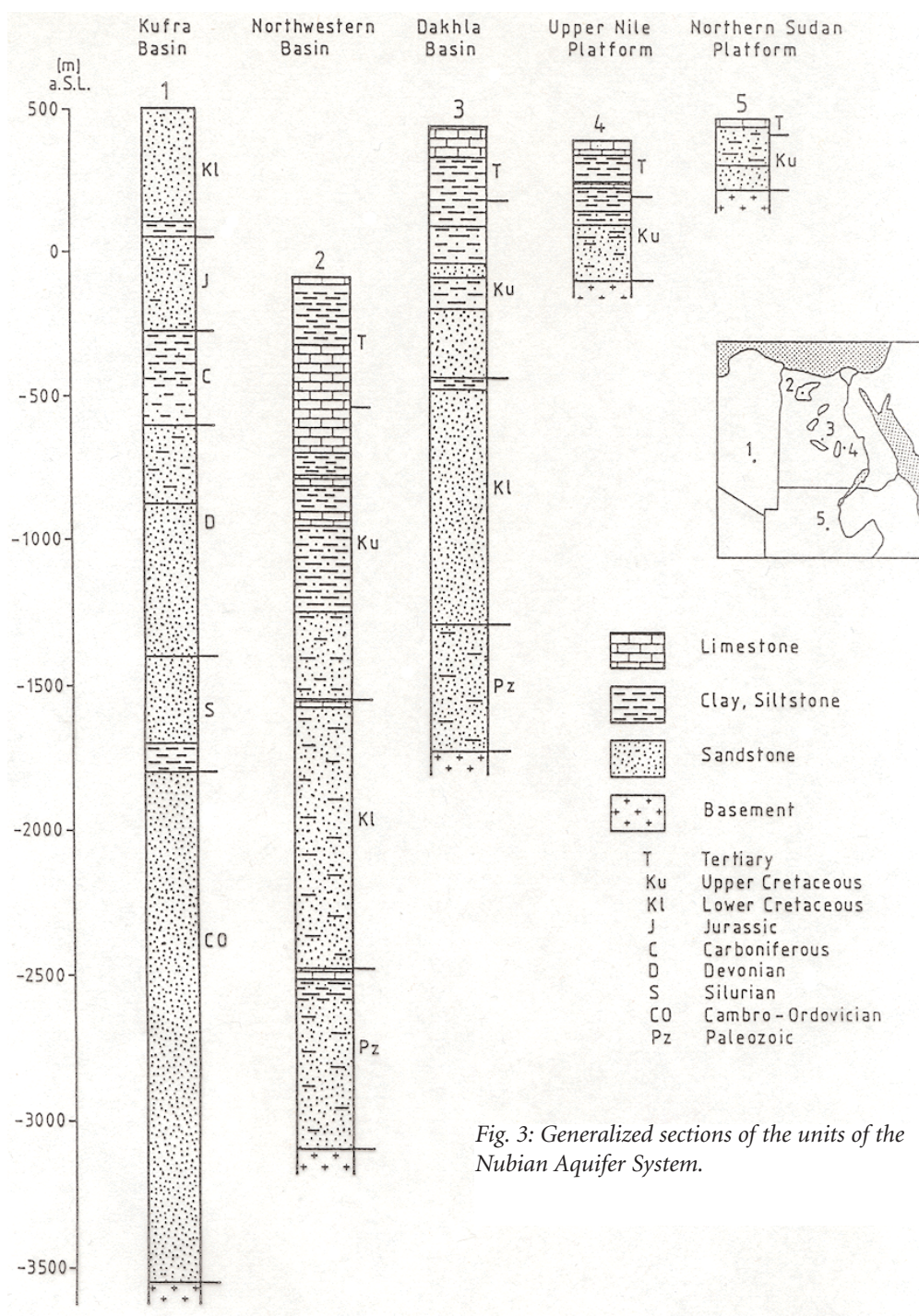
The Nubian Aquifer System is subdivided by uplifts (Fig. 1): The Cairo-Bahariya Arch separates the Northwestern Basin of Egypt from the Dakhla Basin. The Kharga Uplift forms the eastern margin of the Dakhla Basin. The Uweinat-Bir Safsaf-Aswan Uplift separates the Dakhla Basin and the Aswan Platform from the North Sudan Platform. The Howar-Uweinat Uplift forms the eastern border of the Kufra Basin. A separation of the Kufra Basin from the Dakhla Basin caused by an uplift is not evident. At least since the Mesozoic, the transition area (more or less along the Libyan-Egyptian border) was a common sedimentation area. Figure 2 shows the Cretaceous outcrops of the Nubian Aquifer System (green colour).

Fig. 3: Generalized sections of the units of the Nubian Aquifer System.

3 Hydrogeology of the Nubian Aquifer System

The sediments of the Nubian Aquifer System were deposited in predominantly continental environments. Meandering rivers and deltas were the usual transport mechanism, which were spatially effective in different times. Due to this environmental history, correlation from one aquifer outcrop to the next is generally difficult since sedimentation at one location occurred probably in the same period when adjacent areas were eroded. Furthermore, the different development history of the sub-units of the Nubian Aquifer System is extremely critical for the hydrogeological interpretation, concerning thickness and extension of lithological units.

3.1 Groundwater Volume

Details about the groundwater resources in the Sahara have been published repeatedly. The best known are from AMBROGGI (1966), who estimated the total groundwater reservoir of the Sahara at 15 000 km³, and
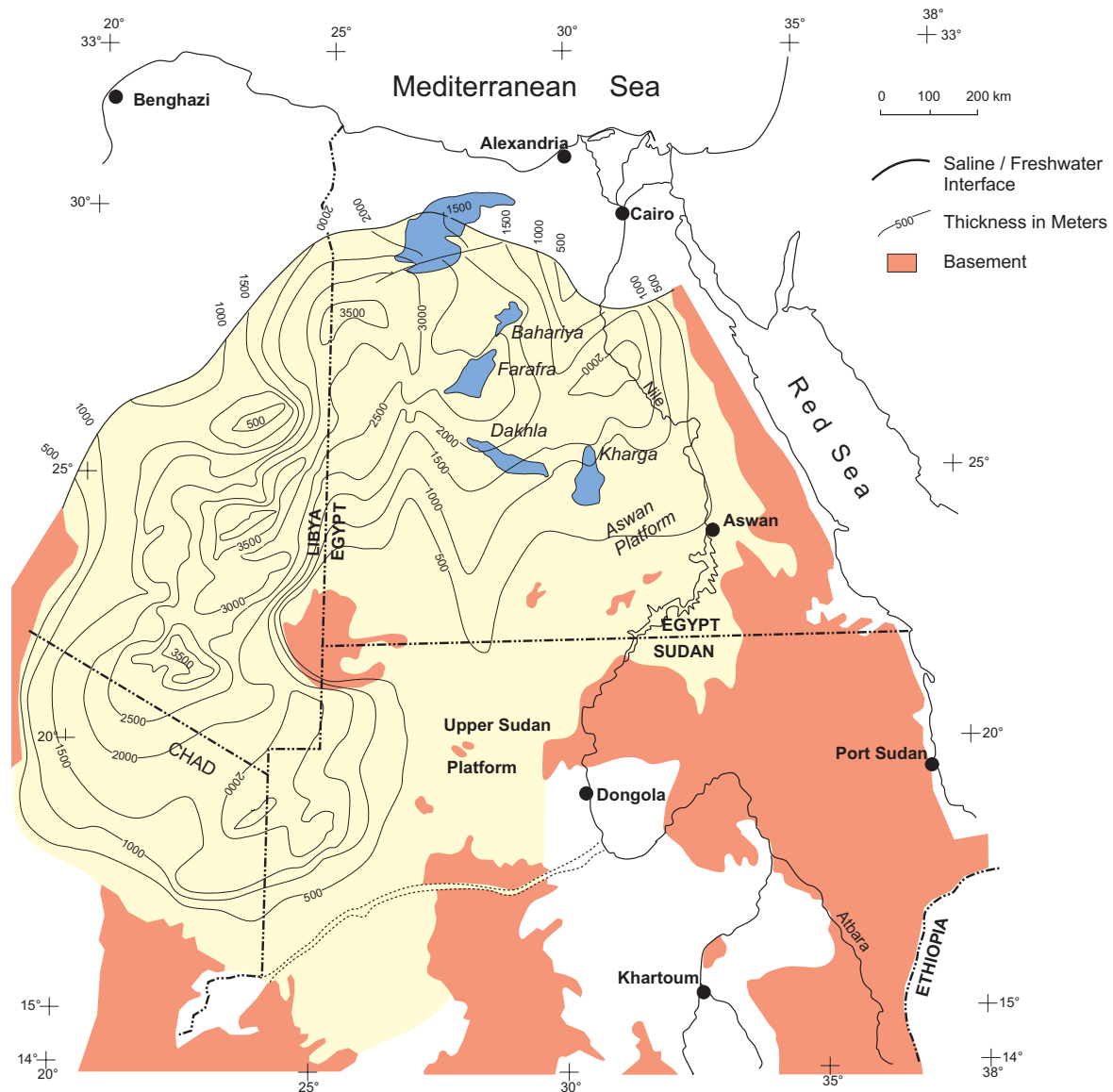

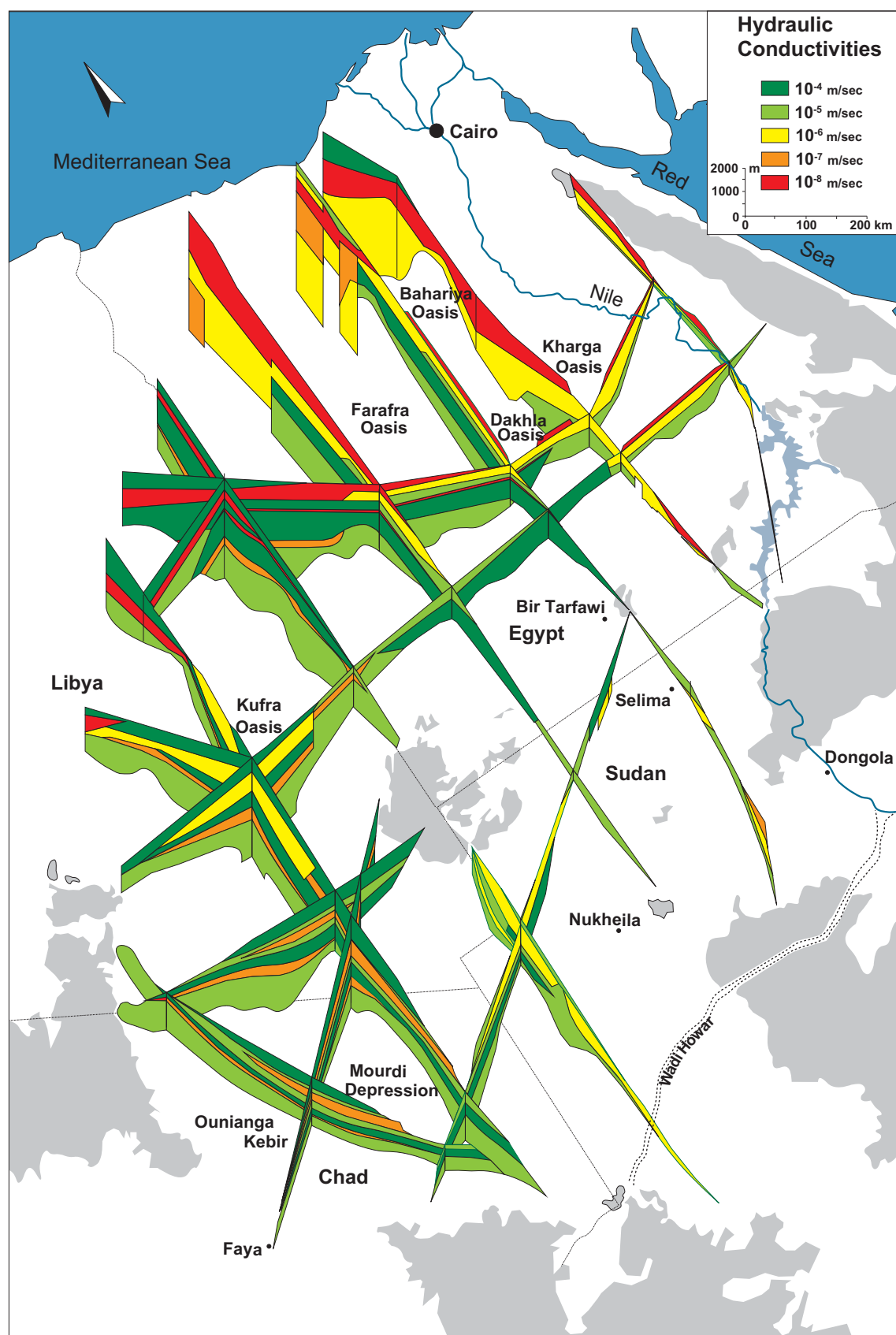*Fig. 4: Thickness of the Nubian Aquifer System.*

Fig. 5: Fence diagram of hydraulic conductivities for the Nubian Aquifer System.

from GISCHLER (1976), who includes at least 60 000 km³. Both could carry out only vague estimates, since at that time the data situation in many areas of the Sahara was still very unreliable. In the Nubian Aquifer System area, imperative geophysical studies on volume calculation were first carried out in the Kufra Basin at the end of the 1960s and in the Dakhla Basin at the end of the 1970s in the course of oil explorations.

Based on updated subsurface data, the Nubian Aquifer System groundwater volume can be calculated at 150 000 km³ (Fig. 4), a very large amount of water largely exceeding previous estimates. This value corresponds to Nile discharge of 1800 years or to a water column of 75 meters over the entire study area of 2 mill. km². Since it is economically unreasonable and infrastructurally impossible to obtain groundwater from great depths over broad areas of the aquifer system, the total volume of the groundwater resources is only of academic interests. For the interpretation of groundwater ages based on radiocarbon analyses, however, it is very important to have an idea of the groundwater's mean residence time, which is dependent on water volume and discharge rate.

3.2 Hydraulic Conductivities

Registering geohydraulic parameters presents a great problem in the study area, since first of all, little to no lateral or vertical hydrogeological data is available in large areas and, second-ly, the measurements do not always reach the desired quality standard or are poorly documented. On the other hand, a reasonable homogenous geology occurs in the study area; in other words, the aquifer system is composed of relatively large units with the same lithology.

In order to model groundwater flow and draw-down in the Nubian Aquifer System it was necessary to evaluate the hydraulic conductivity variability of the entire study area: they depict the hydrogeological input data for the numerical simulations. Hydrogeological data processing must be adequately exact to be able to detect lateral changes in transmissivity for each lithological unit within acceptable errors.

The values for hydraulic conductivities were obtained from pumping tests which have recorded only the Mesozoic sediments in the aquifer system. There are no test records available for the Paleozoic deposits. The hydraulic conductivity for these sediments can only be determined through evident comparison with Mesozoic sediments of similar composition. That holds subjective misinterpretations.

The interpretation of the hydraulic conductivity in the Nubian Aquifer System in a resolution of one order of magnitude is shown as fence diagram in Fig. 5. It shows the hydrogeological interpretation with regard to the transmissivity of individual lithological units in the various hydrogeological provinces. Concerning the transmissivity values, this interpretation is the basis input for the numeric simulation of the groundwater flow.

4 Groundwater Formation

There are three possible ways of groundwater recharge:

1. Seepage of Nile water
2. Regional groundwater influx from areas with modern groundwater recharge
3. Local infiltration through precipitation during wet periods in the past

4.1 Nile Water Seepage

Nile water seepage into the Nubian Aquifer System is possible only when both, geological conditions (permeability) and hydraulic conditions (level of the Nile higher than the groundwater table) are favourable. The geological conditions are provided between Wadi Halfa in northern Sudan and Qena in Egypt as well as between Khartoum and Karma (southern rim of the basement outcrops north of Dongola) in the transition zone to the Blue Nile/Main Nile Rift System. Hydraulic conditions in the area mentioned above are only favorable south of the mouth of the Atbara river, in the Dongola area and artificially along Lake Nasser.

4.2 Groundwater Influx from Areas of present Infiltration

A possible groundwater influx mechanism within the Nubian Aquifer System is the regional groundwater flow from areas with precipitation, sufficient for groundwater recharge. It is certainly very difficult, to obtain a hard and fast formula to determine at which precipitation rate groundwater can be formed. This is highly dependent on precipitation distribution and on the climatic, hydraulic and pedologic conditions.

It can be assumed that there is groundwater recharge through infiltrating precipitation on the southern edge of the study area. The flow time of the groundwater from these infiltration areas to the discharge areas in the north can be roughly calculated. Based on rough estimates of the regional hydraulic parameter of the Nubian Aquifer System (groundwater table gradient: $3 \cdot 10\text{-}4$, hydraulic conductivity: $1 \cdot 10\text{-}5$ m/sec; effective porosity: 10%) with the simple application of Darcy's Law, one arrives at a field velocity of about 1 m/year. Using these figures, this means that the groundwater from the southern edge of the Nubian Aquifer System to the Qattara Depression in the north would need about one million years. During this time many climatic changes including wet periods occurred, which supplied plenty of precipitation to suffice for local groundwater formation.

4.3 Local Infiltration during Wet Periods in the Past

Isotope analyses (radiocarbon age dating in combination with deuterium and oxygen-18) of groundwater have made an important contribution to clarifying the history of groundwater formation and origin during the Late Pleistocene and Holocene.

4.3.1 Stable isotopes D and ^{18}O

The deuterium and oxygen-18 content (δD and $\delta^{18}O$) of the northern Saharan groundwater, the radiocarbon age of which is primarily more than 20 000 years b.p. shows a distinct west-east gradient like in European winter precipitation and groundwater (SONNTAG et al., 1982). This isotope distribution pattern thus indicates that the northern Sahara received winter rains from the western drift before the culmination of the last glacial period, which led to local groundwater recharge. Further south, the groundwater becomes isotopically heavier, which indicates that the southern Sahara always received tropic convective summer rains from humid air masses from the Indian Ocean, the African rain forest or further west from the Gulf of Guinea during past wet periods.
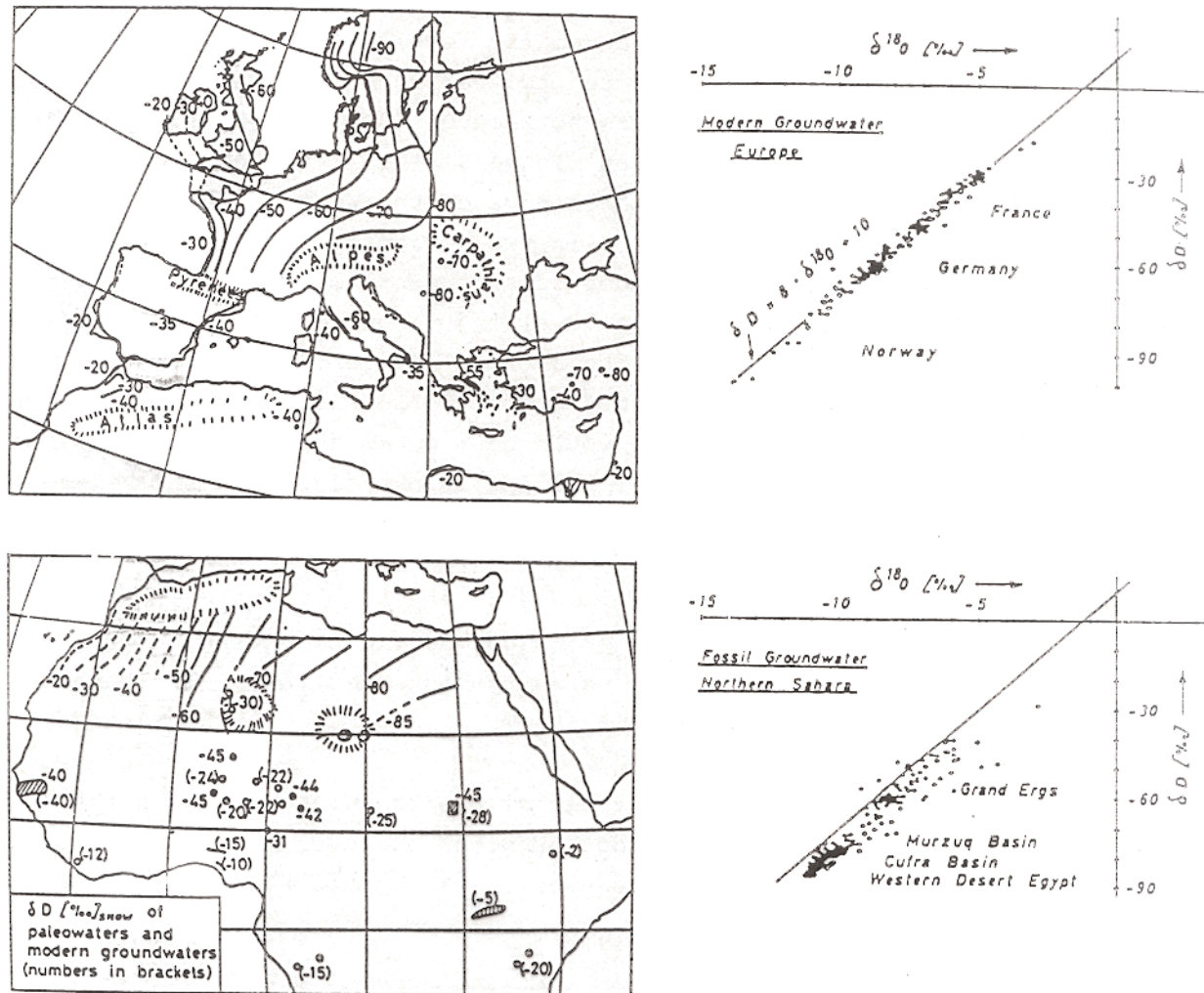
Fig. 6: The stable Isotopes D and ^{18}O show the «continental effect» which proves groundwater formation in the northern Sahara by winter rains of wet atlantic airmasses, transported by western drift, and groundwater formation by tropic convective summer rains in the southern Sahara. This effect is proven by modern groundwaters in Europe (SONNTAG et al., 1982).

If the piezometric data in the Nubian Aquifer System were considered as a cause for a regional groundwater flow as described by BALL (1927), this flow would run in a north and north-east direction and therewith actually more or less along the iso-contours of stable isotopes. For that reason, a possible regional groundwater flow in the eastern Sahara can not be excluded on the basis of stable isotope contents in D and 18O.

4.3.2 Radiocarbon groundwater age

The age distribution of radiocarbon dated groundwater from the Sahara (Fig. 7) shows a long wet period ending approximately 20 000

years ago. Between 20 000 and 14 000 b.p. there was a significant minimum of groundwater recharge representing a semiarid or arid climate period. Later, after 14,000 b.p., numerous radiocarbon datings register a wet period from the beginning of the Holocene, providing groundwater recharge.

A significant direction of age increase of the groundwater in the study area based on radiocarbon activities could not be proved, which should indicate the presence of groundwater flow. However, there is also no difference in the radiocarbon content between the groundwater in the unconfined and confined parts of the aquifer. This fact proves, that also in the confined part of the aquifer system groundwater recharge must have taken
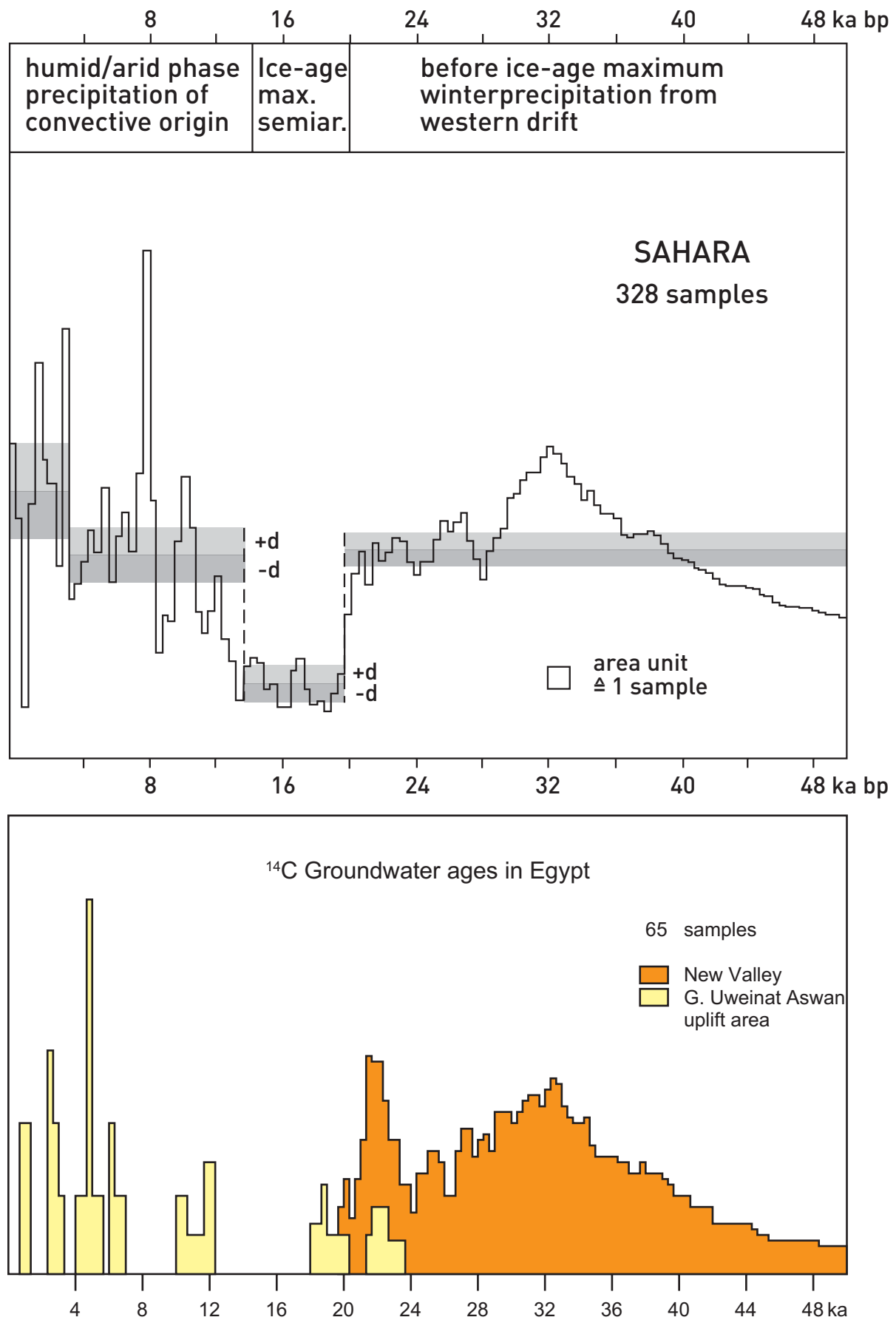
Fig. 7: Frequency distribution of apparent ^{14}C ages of groundwaters of the Sahara (SONNTAG et al. 1982) and in the Egyptian Dakhla Basin of the Nubian Aquifer System (THORWEIHE, 1986).

place through leakage from the confining beds, i.e. infiltration from local precipitation. That stands in superb agreement to the results of the numeric flow model.

The proof of radiocarbon in confined parts allows no quantitative estimate of the groundwater recharge through leakage. The qualitative piece of evidence supports, however, that vertical groundwater transport from the confining beds must be taken into consideration.

4.4 Regional Flow vs. Local Infiltration

The question whether the groundwater encountered today in the Nubian Aquifer System has been formed during former more

humid climatic periods by local infiltration or whether it is still flowing from more humid areas in the south, can also be investigated using the dynamics of groundwater flow.

The more traditional view of regional flow goes back to BALL (1927) and SANDFORD (1935). They found a regular gradient from south-west to north-east, and concluded that groundwater comes by regional flow from some «intake beds» in the south. Although the theory of transient groundwater flow has developed further, BALL's concept was the basis for most of the mathematical flow models, which were set up until today. The considerable transmissivity and the existing gradient support this view. They show clearly that regional flow from south to north exists. But it has been mentioned above, that the
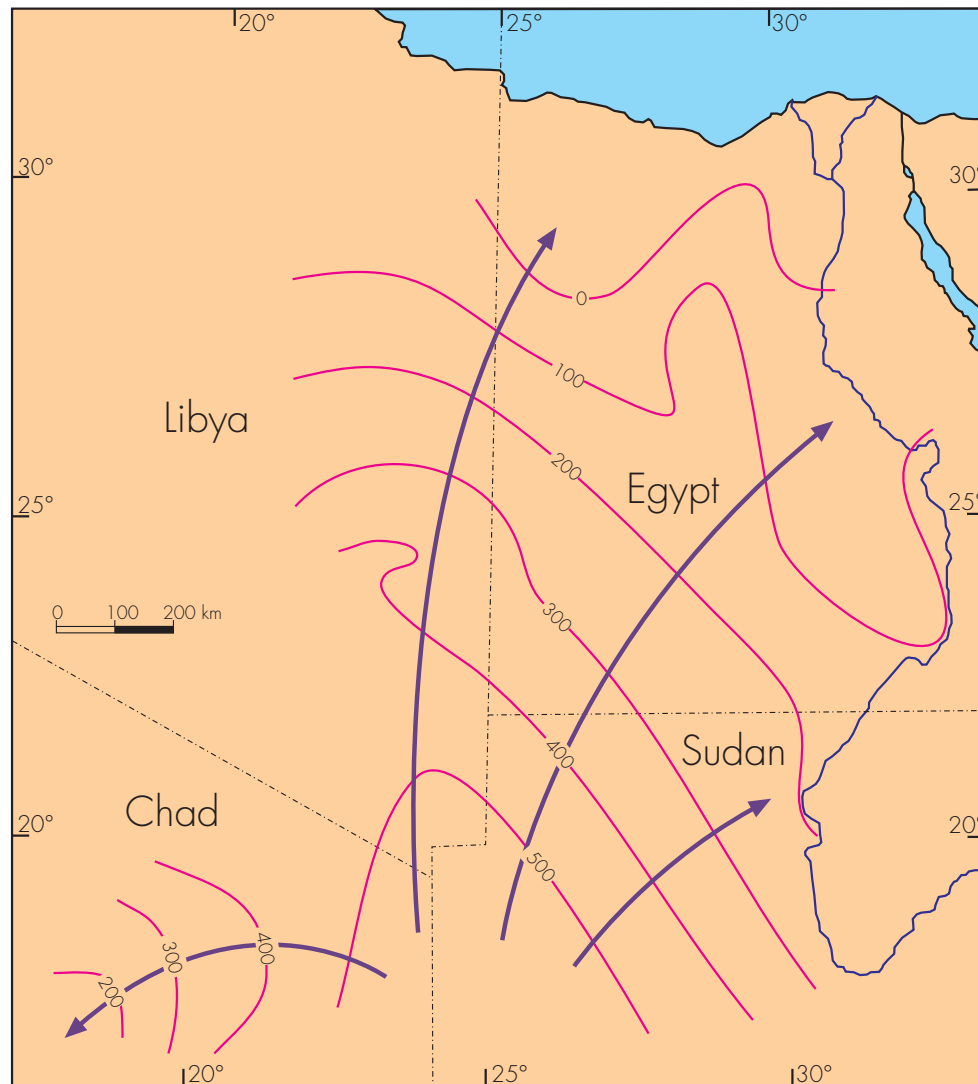

Fig. 8: Interpreted groundwater contours for the Nubian Aquifer System by BALL (1927) and SANDFORD (1935) (modified), which suggest a regional groundwater flow from adjacent areas in the South to major depressions in the system.

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travel velocity is so slow, that climatic changes also have to be considered. In the Nubian Aquifer System the slope of the ground level is in the same direction as the gradient of precipitation, from south to north. This can mislead to the conclusion, that there is continuous recharge. South of the Sahara the conditions are inverse. The climate becomes more humid towards the lower areas, e.g. the Bahr El Arab. Here we find still a very small gradient from the more elevated arid to the more humid southern areas (HEINL & THORWEIHE, 1993). The mathematical groundwater model for the Nubian Aquifer System can help to quantify the ratio of regional and local flow.
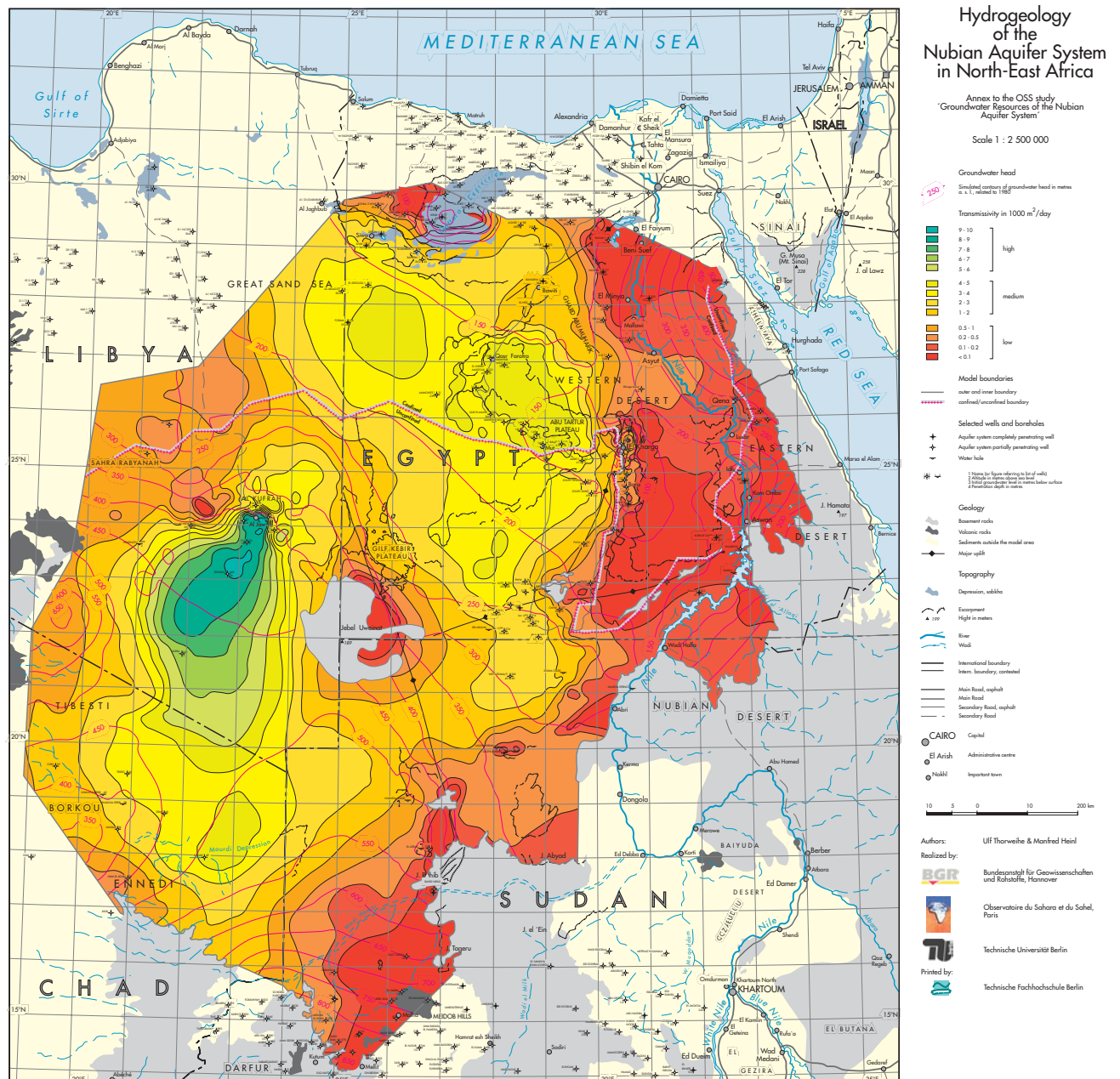

Fig. 9: Scale down of a 1:2.5 million scaled hydrogeological map of the Nubian Aquifer System (THOWEIHE & HEINL, 2000).
The transmissivities are represented in the coloured areas; red to orange: less than 1000 m²/day, yellowish: 1000 to 5000 m²/day, green to cyan: 5000 to 10 000 m²/day.
Furthwermore the map shows the simulated groundwater contours for the year 1980 and data of selected boreholes and wells.

5   Numerical Groundwater Model

A two dimensional horizontal Finite Element Model was chosen as a basic tool for the simulation of the Nubian Aquifer System. The Finite Element grid covered an area of two million square kilometres. Thus, large distance flow from the Chad to the Qattara depression could be modelled as well as the transition from semiarid climate to the present hyper-arid conditions during several thousand years, which is the flow time of the large distance flow.

The model was designed as a closed system. In this way, reliable no-flow boundary conditions could be identified at the outcrops of the basement, i.e. the natural boundaries of the system. All groundwater flow, recharge and discharge occurred within the model area.

The confined part of the system in the north was considered as «leaky aquifer», allowing vertical water exchange between the Nubian aquifer and overlaying sediments: Exfiltration in the large Egyptian depressions like Kharga or Dakhla and also possible infiltration from highlands. Horizontal flow in the post-Nubian sediments was not simulated, because available data are not sufficient.

The basic geological input to the model was the hydraulic conductivity (Fig. 5). In a first step, the horizontal permeabilities of the different Nubian layers were integrated over the entire sediment thickness resulting in the transmissivity distribution along the axes of the cross sections. In geologically homogeneous areas, the transmissivity values then were attributed to the model elements. During the calibration of the model these values have been modified in certain areas, predominantly SW-Egypt. The final transmissivity is represented in the coloured areas in Fig. 9.

5.1   Simulation Results

The simulation consisted of three parts:
1. Steady-state conditions during semiarid climate, 8000 years ago

2. Long-term simulation of the aquifer behaviour, due to climatic change
3. Short-term simulation of the Egyptian New-Valley Project 1960-1980

All three phases were simulated in the same model. Only different time-steps (100 years and 52 days respectively) were used in the long-term and short-term calculations.

5.1.1 Steady-state filled-up conditions

The climatic change in the Sahara resulted in a delayed lowering of the water table. It was intended to simulate the development of groundwater flow from a situation under humid conditions to the current hyper-arid conditions.

Starting point for these calculations was a filled aquifer system that existed at some earlier time (Fig. 10). Filled-up conditions mean that the water-bearing sandstone were saturated up to the surface and that the potential water head was located at surface or slightly below. Such a state is likely to have existed some 8,000 years ago. Even under wetter conditions of a semi-arid climate, the water table could not rise considerably above the present ground because it would have been carried away by surface run-off or evapotranspiration.

The resulting groundwater contour lines are plotted in Fig. 10. It may surprise, that a recharge of a few mm/year is sufficient, to keep the groundwater level near the surface. This is the maximum flow, the system could carry on a regional scale. Higher recharge would induce higher local flow rates with discharge areas nearby.

5.1.2 Long-term decline due to climatic change

The purpose of the long-term simulation was to show the time scale of the aquifer reaction on climatic change. At the same time it pro-

duced initial conditions for short-term simulations of groundwater extraction.

The simulated draw-down shows a different behaviour of the aquifer in elevated and low areas respectively. After the stop of infiltration, 8000 years ago, the groundwater dropped rapidly in the elevated recharge areas. In the unconfined section, where the initial recharge had been 10 mm/year, groundwater level dropped 60 m in 1000 years in Ennedi and Gilf Kebir. In the Tibesti mountains and the Red Sea Hills it dropped more than 100 m. In the confined part, groundwater level in elevated areas of downward leakage (recharge) dropped as well. On the plateau east of the Kharga Oasis, the draw-down was
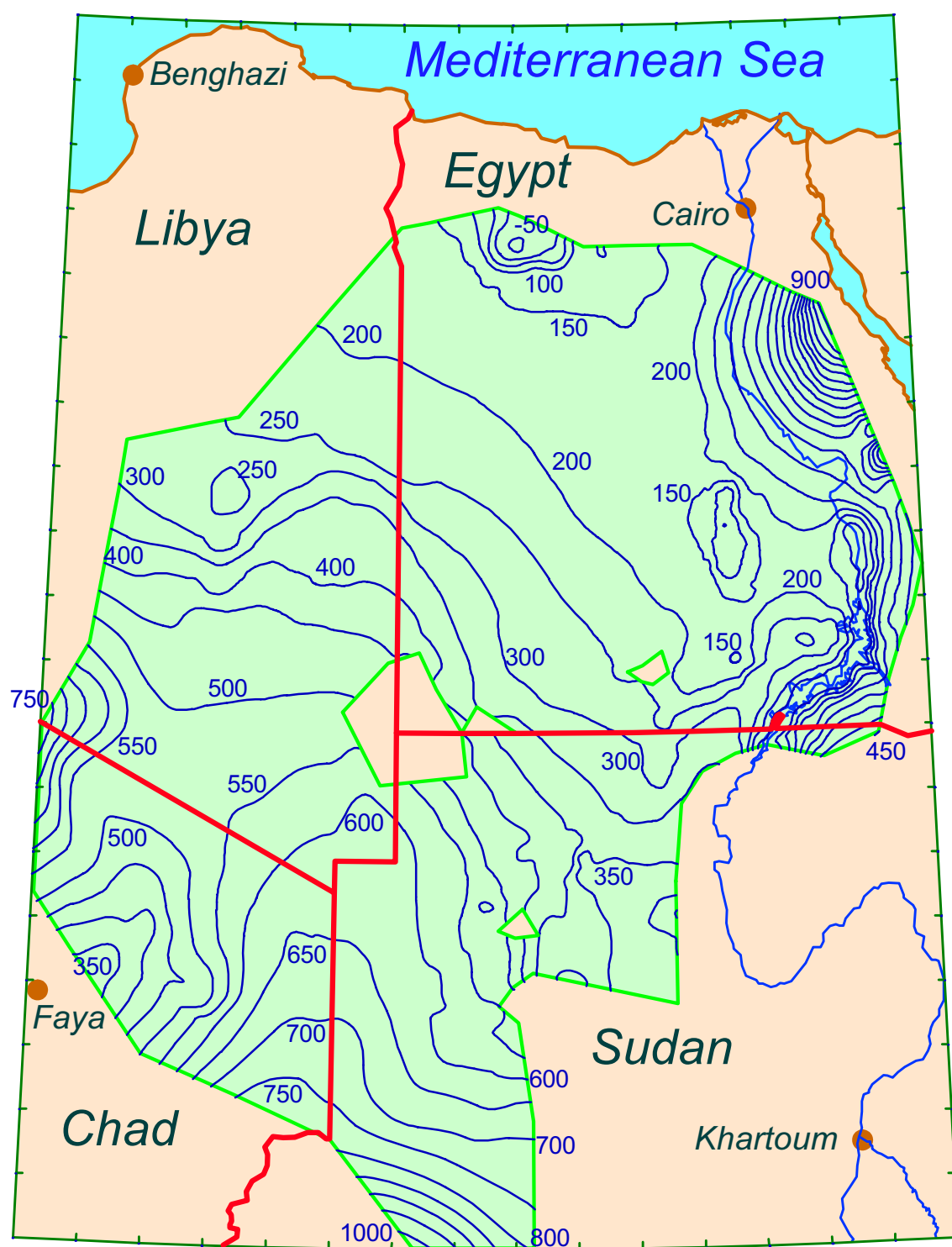

Fig. 10: Simulated groundwater contours, steady-state filled-up conditions.

60 m in 1000 years. During the second millennium, when the climatic conditions remained unchanged, the draw-down was much less. Flow conditions were still clearly transient even after 8000 years.

The steady-state results indicated that even very little recharge can keep the Nubian Aquifer System in equilibrium conditions, but that without recharge in major parts of the system, groundwater would decline.

The transient simulation shows that the Nubian aquifer system already was in an outflow process before the New Valley project and other development projects started. The de-
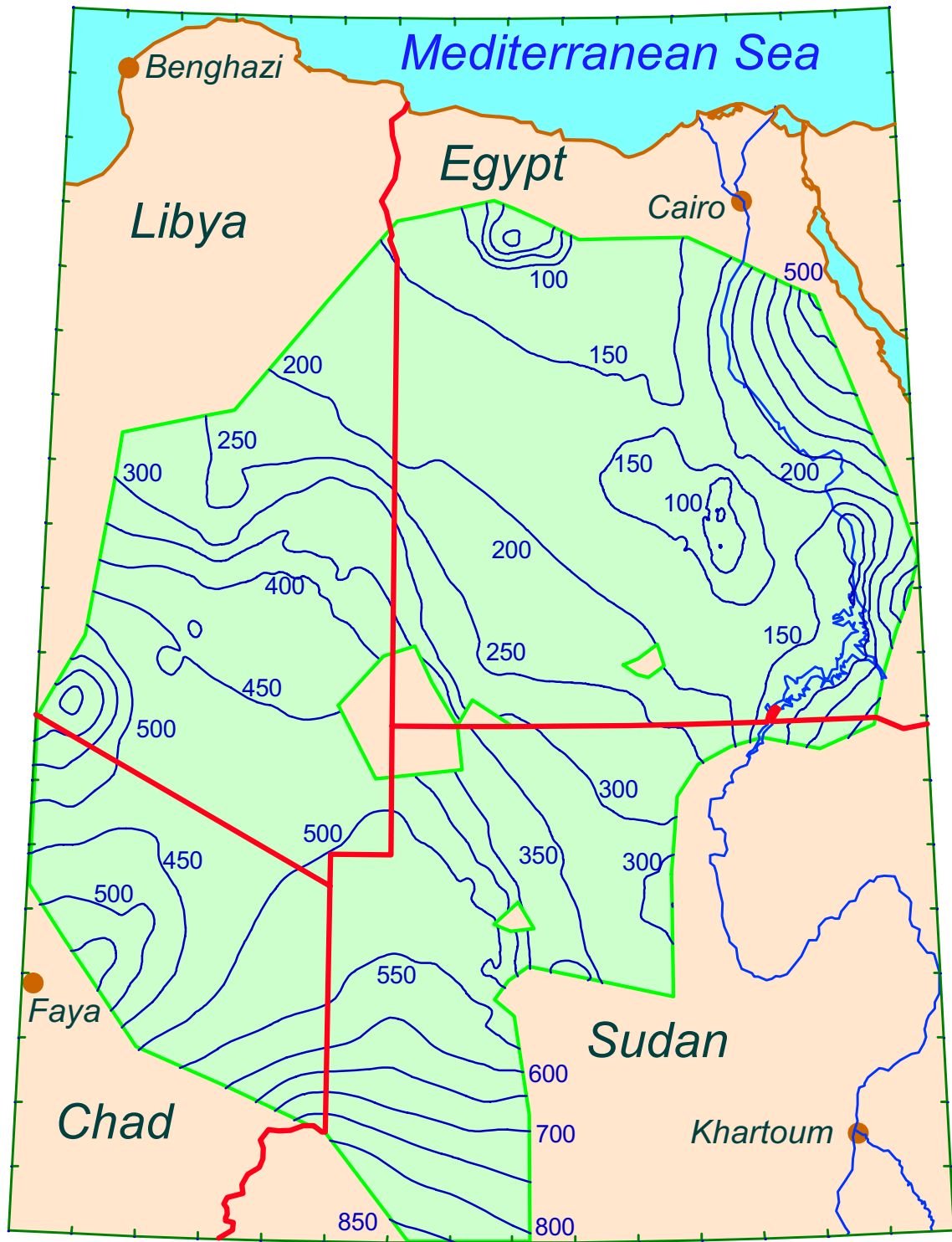

Fig. 11: Simulated groundwater contours for the year 1960, initialize of major groundwater exploitation programs in the Kufra Basin, Libya, and the New Valley, Egypt.
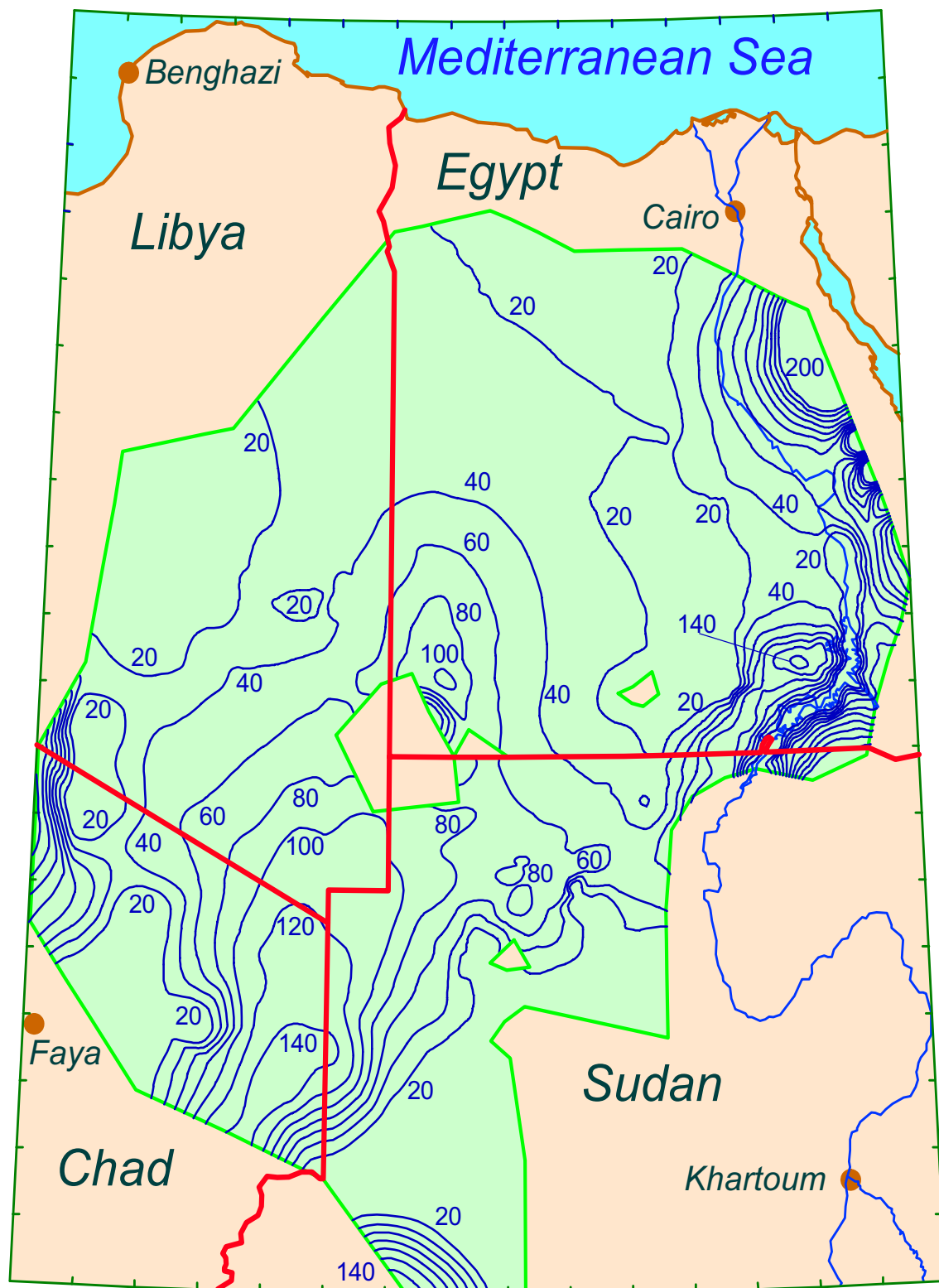
Fig. 12: Simulated draw-down during 8000 years after climatic change to arid conditions.

cline of the groundwater surface started about 8000 years ago, but it was slowed down or interrupted by local infiltrations occurring in the central highlands and other parts of the system. Steady-state and transient simulations both indicate that the pre-development situation cannot be considered as equilibrium condition. The long-term transient simulation gives the (transient) initial condition for the simulation of the subsequent extraction .

5.1.3 Short-term Simulation of the New-Valley Project, Egypt, 1960-1980

In order to get more reliable transient results, the model was calibrated in a limited area and time interval. For this purpose data of the New-Valley extraction and draw-down from the period 1960-1980 were used. The trans-missivity distribution resulting from the calibration was already shown in Fig. 9. The main change compared to the values presented in the final report is a reduction of permeability of the Six-Hills formation by 30%. The leakage coefficients have been reduced considerably. Storativity was reduced in a transition area south of Dakhla and west of Kharga.
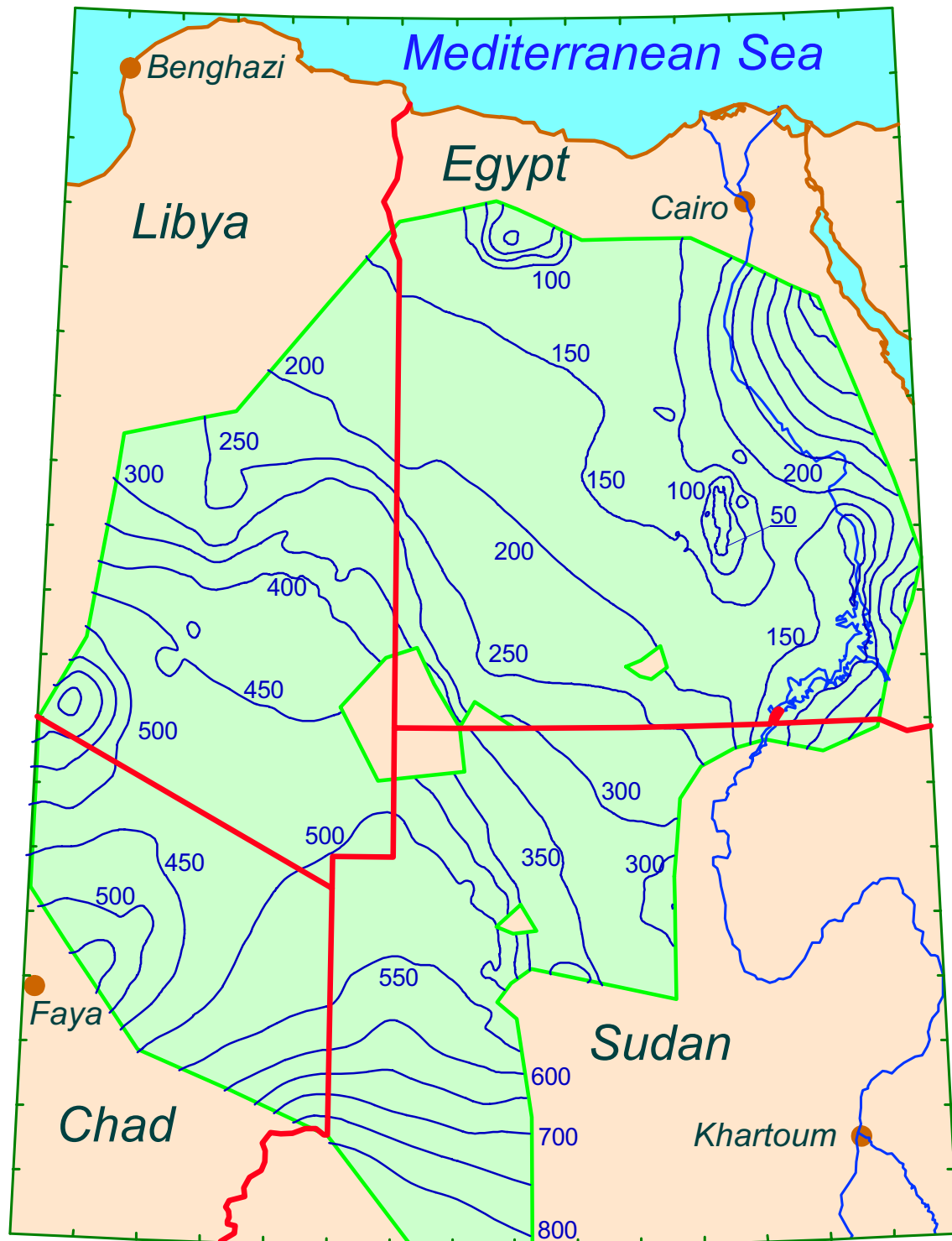

Fig. 13: Groundwater contour lines at the end of the short-term simulation (in the year 1980).

The calculated contour lines for 1980, at the end of the short term simulation, are shown in Fig. 13.

5.2 Groundwater Balance for the Transient Development

A more general picture of the behaviour of the aquifer system can be obtained by integrating the different flow components of the entire system. Thus, the rather complex picture of groundwater level change, recharge and discharge for each element can be simplified into one diagram.

Fig. 14 shows the different flow components, and, in the lower part an integrated volume curve. The total change of storage as well as extraction is shown in a different time scale for long-term and short-term changes (before and after 1960).

In general, the natural discharge does not directly depend on climatic conditions. For a given set of transmissivities it depends on the
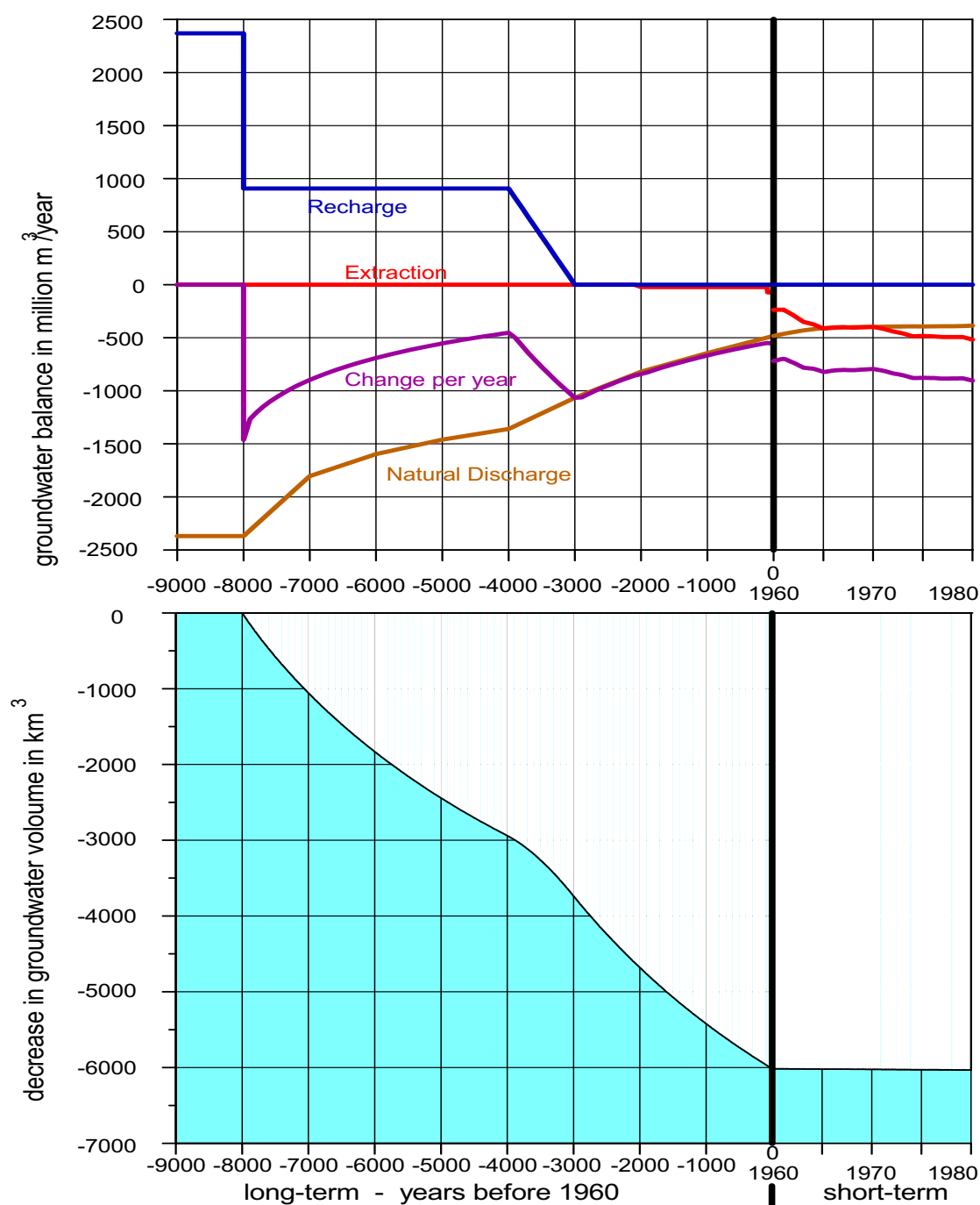

Fig. 14: balance for the Nubian Aquifer System.

distribution of potential heads, i.e. the groundwater surface. Since this does not change all of a sudden after transition to arid conditions 8,000 years b.p., discharge continues in the first instant at the same level. The lacking groundwater is replaced from the storage. Only after decline of the groundwater level, discharge starts to diminish and slowly approximates the actual recharge.

In the long-term simulation recharge is reduced 8000 years b.p. by 1463 mill. m³/a from 2369 to 906 mill. m³/a (in the Ennedi mountains). Thus, 1463 mill. m³/a is taken immediately from storage after the change. After 1000 years the change in storage is reduced to 906 mill. m³/a. Therefore, groundwater discharge has been reduced to 700 mill. m³/a. The first part of the storage curve has an exponential shape. After 4000 years, when recharge in the Ennedi mountains stops, the change in storage suddenly increases to 1300 mill. m³/a. At the end of the long-term simulation it has diminished to 550 mill. m³/a only.

6 Assessment of Groundwater Resources in the Nubien Aquifer System

Before evaluating the groundwater resources in the Nubian Aquifer System, the results of the numerical simulation are reviewed. The model revealed some general dynamics of the Nubian Aquifer system:

Based on paleoclimatic evidence (PACHUR et al., 1987) it is assumed, that there has always been a change between humid and arid phases, each lasting for several thousand years. After an arid depletion of the aquifer system, the groundwater is quickly replenished over large areas in the entire unconfined part as soon as humid climatic conditions set in. This filling process ends when recharge and discharge balance each other, i.e. in a humid or semi-arid steady-state. Such state probably existed 8000 years ago.

It may be maintained with as little as 10 mm/year recharge in the highlands. No recharge does then occur in depressions and plains. Recharge and large scale flow are limited by relatively small gradients. Most of the recharged water flows to discharge areas nearby; only a minor part reaches more distant areas at a lower level. The Nubian Aquifer is a continuous system. However, the regional flow across the system is very small compared to the flow within sub-regions of the system.

The water balance for steady and transient conditions shows a deficit in the confined part, which is compensated by regional flow from south to north because of the higher average elevation of the unconfined part. Under arid conditions, water comes mainly from unconfined storage.

Infiltration, supporting equilibrium conditions, stopped some 8000 years ago, but continued on a minor scale in different areas and time intervals. Possible subrecent groundwater recharge in central or southern highlands are small and difficult to assess. Present recharge in Wadi Howar or the Tibesti mountains is only relevant for natural flow conditions in geological time scales. For artificial extraction it is negligible. The river Nile acting as a drainage channel does not recharge the system.

The natural system with a timescale of thousands of years is under unsteady conditions. For artificial extraction in timescale of tens of years these may be regarded as quasi steady initial conditions. However, in any case artificial extraction leads to a highly unsteady situation with almost the entire extracted water taken from storage.

Sophisticated small scale extraction schemes require detailed modeling. Boundary and initial conditions for such models may be determined by the regional model. They have to account for the non-equilibrium of the pre-development state. When calculating the arti-

ficial draw-down, the «natural» decline of the groundwater level may be neglected. A steady-state calculation of initial conditions, however, will result in transmissivities too high, if it is based on extraction figures. Still, any prediction of draw-downs for high extraction rates over 100 years will be biased since only small extraction rates or none have been measured over a short period of time.

It has been shown that recent groundwater recharge is negligible, and that extraction from the Nubian Aquifer System is mining of an non-renewable resource. Nevertheless, the large amount of groundwater allows for reasonable exploitation.

In general, the extraction has to be very much restricted to limited areas. Although the groundwater reserves under the Sahara are immense, they are not sufficient for irrigation of large areas. The available groundwater volume corresponds to an average water cover of about 75 m. This has to be compared to the water consumption of green vegetation which is about 1.5 m/year. Even if all the groundwater could be extracted, this would be a very limited supply. Therefore, the extraction has to be limited to a few pumping centres.

These pumping centres form extraction cones. Groundwater from the surrounding 100 or 200 kilometres flows into these cones. The water which had been recharged in the surrounding areas thousands of years ago is consumed within a much shorter period in the centre of such cones (e.g. New-Valley or Kufra). The disposable water for such a project is not the whole groundwater body, but only the amount of water stored in the extraction cone.

For a feasibility study of a certain project a more detailed groundwater model is needed. The regional model helps to supply boundary conditions for such a detailed model. The predictions of the impact of planned extractions give an idea of the draw-down to be expected. With the results of a detailed model, pumping costs and feasibility can be evaluated.

Acknowledgement

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