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Impacts of heavy groundwater pumping on hydro-geological conditions in Libya: Past and present development and future prognosis on a regional scale

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ABSTRACT:

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Libya, like many other regions with arid climates, suffers from inadequate water resources to cover all the needs of this rapidly developing country. Increasing amounts of water are needed to supply the population, as well as for agricultural irrigation and industrial use. As groundwater is the main water source in the country, it represents a natural resource of the highest economic and social importance. Conceptual and numerical models were implemented on a regional scale to show how the natural situation has changed following heavy groundwater abstraction during the last decades in the northwestern part of the country. The results of the numerical model indicated that the current zones of depression of the piezometric surface could have been caused by smaller withdrawn amounts than previously estimated. The differences in the assessed withdrawn groundwater volumes seem to be quite high and might have a considerable influence on the future possibilities of groundwater use in the study region.

Key words: Libya; Arid countries; Groundwater; Natural flow; Abstractions.

INTRODUCTION

Libya occupies an area of 1.76 million square km. More than 95% of this area is exposed to severe arid climatic conditions and belongs to desert, mostly to the Sahara. Only the northernmost part along the coast of the Mediterranean Sea offers more favourable climate; almost 95% out of the total 6 million Libyan population resides there. The remainder live in several widely scattered oases in the remaining part of the country. The coastal strip is separated by the Gulf of Syrt, where the desert extends northward almost as far as the sea, into two more fertile portions. One is the Jifārah Plain in the northwest, the most populated region in the country, where about 60% of all Libyans live and where the capital, Tripoli, is situated (Text-fig. 1a). The second is the Benghazi Plain in the northeastern part of Libya. Almost all the cultivable land of the country occurs in these two fertile zones, representing some 2% of the total Libyan territory (approx. 38,000 sq. km). Even in

the coastal regions, in spite of relatively better climatic conditions compared to the desert, effective agricultural production is entirely dependent on irrigation. As no perennial water courses occur in Libya, the only feasible water resource is groundwater. Groundwater thus represents a vital natural resource and its economic and social importance for the country is enormous. Groundwater covers almost all the public, agricultural and industrial water demands.

Due to considerable water requirements groundwater has been intensively withdrawn. Consequently, groundwater levels have been lowered dramatically in many areas. This has resulted in various negative impacts. Groundwater now occurs deeper, has become less available and its resources might be considered more and more depleted. Its quality has deteriorated, especially in the coastal regions where heavy pumping has caused sea-water intrusion. All

these problems have been taken very seriously and numerous relevant investigations have have been carried out in the last decades. Many of these were focused on the most important region of the whole country – the Jifārah Plain.

The present study summarises the results previously achieved in this region and, based on available data, assesses on a regional scale quantitative and qualitative environmental and water related impacts of past and present-day heavy groundwater pumping, and provides different options for future development.

NATURAL CONDITIONS IMPORTANT FOR HYDROGEOLOGIC CONSIDERATIONS

The Jifārah Plain is a triangle-shaped region with its eastern apex close to the city of Al-Khums. It is
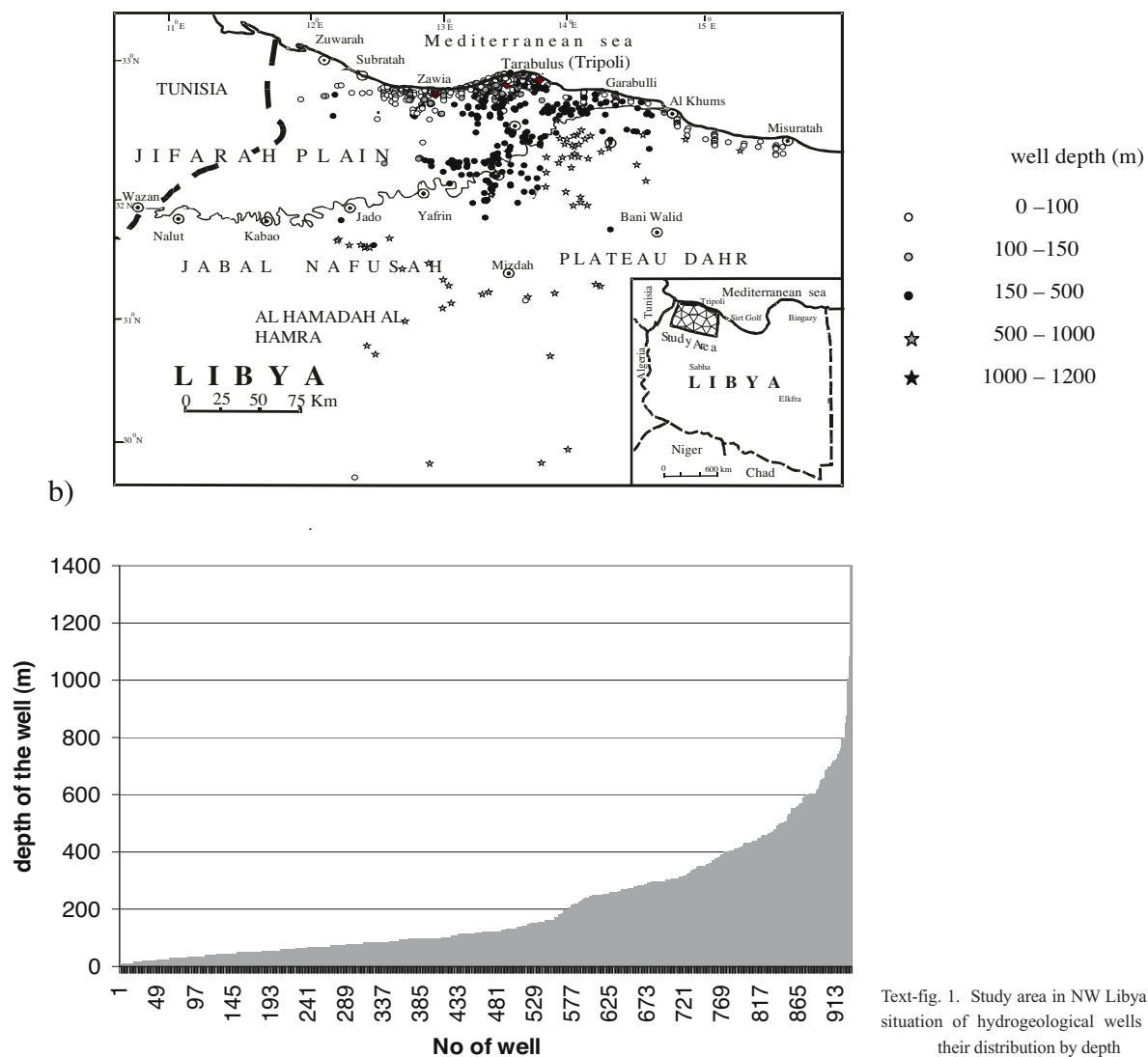
Text-fig. 1. Study area in NW Libya and situation of hydrogeological wells and their distribution by depth

bounded to the north by the Mediterranean coast and the scarp of the Jabal Nafusah forms its southeastern and southern boundary. To the west, it extends to the territory of Tunisia (Text-fig. 1a). Its length between Al Khums and the Tunisian border is more than 250 km; its maximum width reaches some 150 km in the west, and its total area is approximately 17,000 square km.

The Jifārah Plain is a low-lying region, with the land surface rising gradually from the Mediterranean coast southward to the foothills of the Jabal Nafusah, where the altitude reaches 200 to 300 m. In this northern part ("Littoral Plain"), Cenozoic deposits cover older formations. No perennial watercourses occur in the Jifārah Plain, but in the piedmont area of the Jabal Nafusah torrential streams have incised deep wadi valleys, leaving steeply sloping outliers of outcropping older rocks ("Outlier Plain") in the southern part of the plain. Farther to the south, behind the steep north-facing scarps of the Jabal Nafusah, the elevated arid plateau ("Dahr") reaches altitudes up to 700 and 800 m a.s.l., with the highest point reaching 981 m a.s.l.

The climate of the Jifārah Plain is influenced by the Mediterranean Sea, which affects temperature and moisture conditions in the north; to the south the climate changes into a typical desert climate. There are considerable differences between mean monthly temperatures in winter (11.0–13.5 °C) and in summer (26.0 to 27.5 °C). In winter minimum temperatures in the Jifārah Plain can sometimes drop to zero but summer temperatures might be extremely high, as proved by the highest ever-recorded world-wide temperature of 57.8°C at Al-Aziziya in September 1922. In addition to seasonal differences, important diurnal temperature changes were observed. The small general decrease in mean temperature at similar latitudes can be caused by different elevations - about 0.64°C/100 m.

Mean long-term annual precipitation decreases in general from more than 300 mm in the Tripoli and Garabulli area to 150–250 mm to the south-west. Higher values are again recorded on Jabal Nafusah, up to 322 mm at Gharian. From there, precipitation decreases to the south towards the desert. The driest part of the Jifārah Plain is located at the Tunisian frontier, where precipitation reaches only 100 mm. The seasonal distribution is significant as most of the rainfall is recorded during the winter between October and March. Sometimes heavy precipitation is concentrated into short intervals so that intermittent surface runoff through wadis can be important. Several dams were constructed in the Jabal Nafusah piedmont zone to retain surface water. Open surface evaporation in the western part of the coast was assessed as 3,700 mm/year.

The geological settings of the two main geomorphologic units, the Jifārah Plain and the Jabal Nafusah, differ considerably (Text-fig. 2). The upper part of the Jifārah Plain is composed of mostly clastic Tertiary and Quaternary deposits that increase in thickness northwards from the foothills of the Jabal Nafusah to up to several hundred metres. The youngest Quaternary deposits, usually up to several metres thick, consist of recent wadi deposits, beach sands, eolian and fluvio-eolian deposits and sabkha sediments. The Cenozoic complex in the eastern portion of the Jifārah Plain is underlain mainly by the Triassic Al Aziziya Formation (mostly limestones) and the lower Kurush Formation (claystones and sandstones), both up to several hundred metres thick. They are overlain by the relatively thin Abu-Shayba Formation (Upper Triassic, mostly sandstones and claystones), which thickens westwards. In the western part of the Jifārah Plain several other formations occur, again covered by the Cenozoic clastic complex. These are the Abu Ghaylan Formation (Upper Triassic limestones) and a sequence of Upper Triassic to Jurassic deposits: in ascending order, the Bir Al Ghanam Formation, with predominant gypsum and anhydrite; the Takbal Formation (mostly limestones); and the Kikla Formation, consisting of three members comprising clastic deposits and limestones. Thin Cretaceous strata occur locally. Relatively thick Cretaceous deposits occur typically in the Jabal Nafusah region, where particular formations can reach up to one hundred metres or more in thickness. The Cretaceous succession comprises, in ascending order, the Sidi Al Sid Formation, consisting of the lower limestone Ain Tobi Member and the upper marly Yafrin Member; and the Nalut and Qasr Tigrinah formations, both predominantly limestones. In the highest part of the plateau, Cretaceous deposits are overlain by Tertiary–Quaternary basalt lava flows with basalt and phonolite intrusions.

The most important structural feature within the Jifārah Plain is the E–W-trending Al Aziziya fault, which divides thick Tertiary–Quaternary sequences to the north from thin Quaternary deposits to the south. Parallel to the Al Aziziya fault and farther to the north, is the Coastal fault. The positions of these two faults are shown in Text-figs 2 and 3 as they form the boundaries between some of the subdomains recognised in this study (for details see chapter 5.2.2). It is possible that the boundary between the Jabal Nafusah and the Jifārah Plain, which is expressed as a conspicuous escarpment, follows a pre-existing fault. Several authors suggest that other faults occur in the Jifārah Plain, mainly of NW–SE strike, but these do not seem to be hydrogeologically important.

Important hydrogeological regional and water management studies were carried out by GEFLI (1972), IRC (1975a, b), Kruseman (1977), Kruseman and Floegel (1978), FAO (1981, 1985), Pallas (1978), Krummenacher (1982), Salem (1991), National Consulting Bureau and Mott Mac Donald (1993), The Great
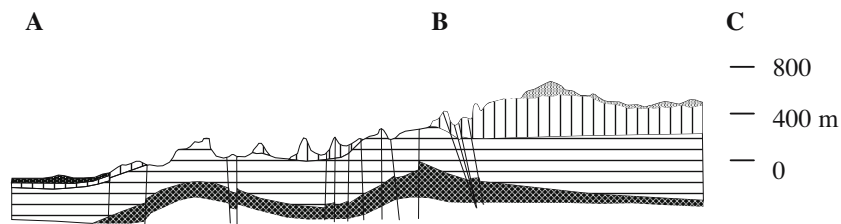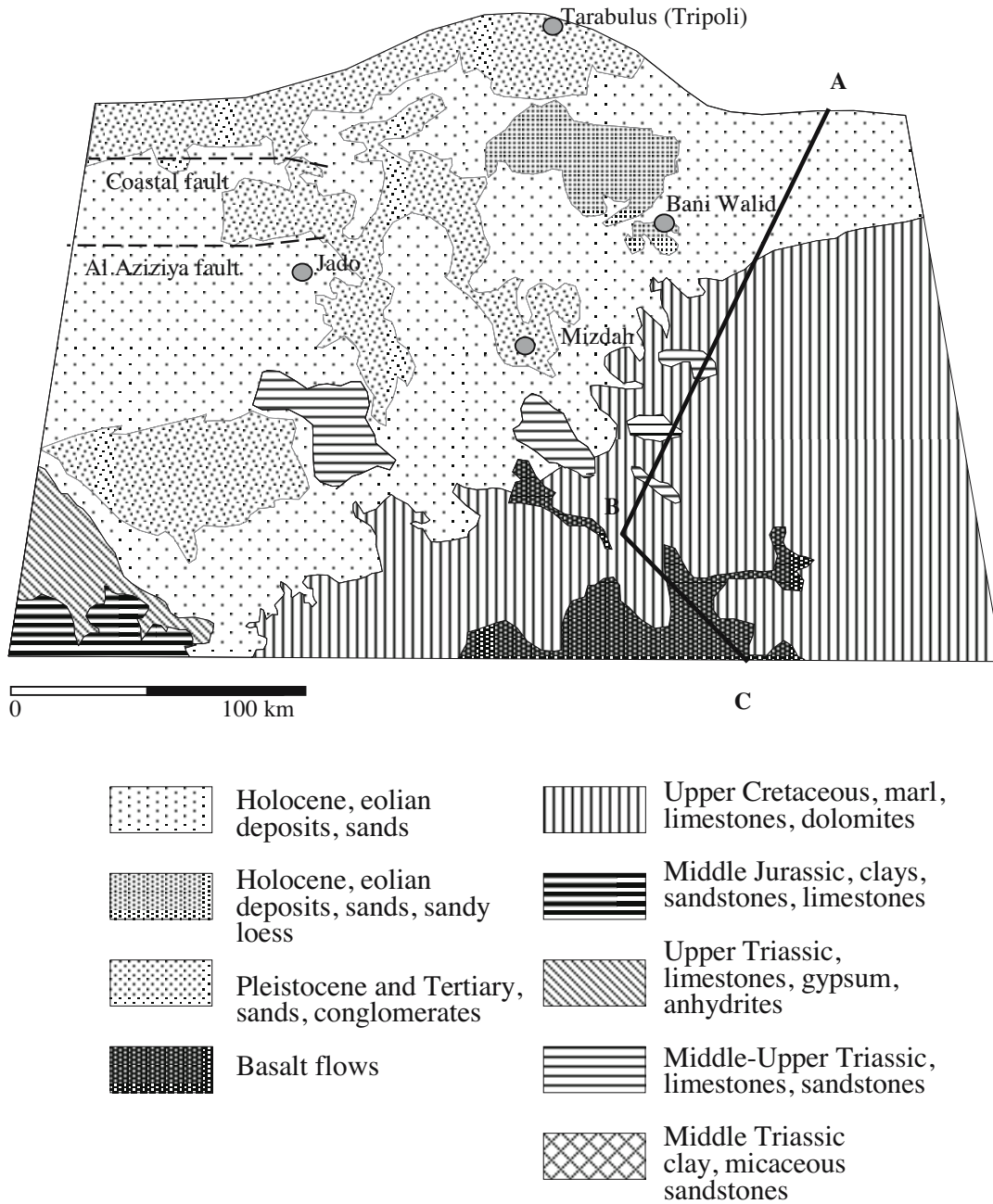
Text-fig. 2. Schematic geological map and N–S cross-section
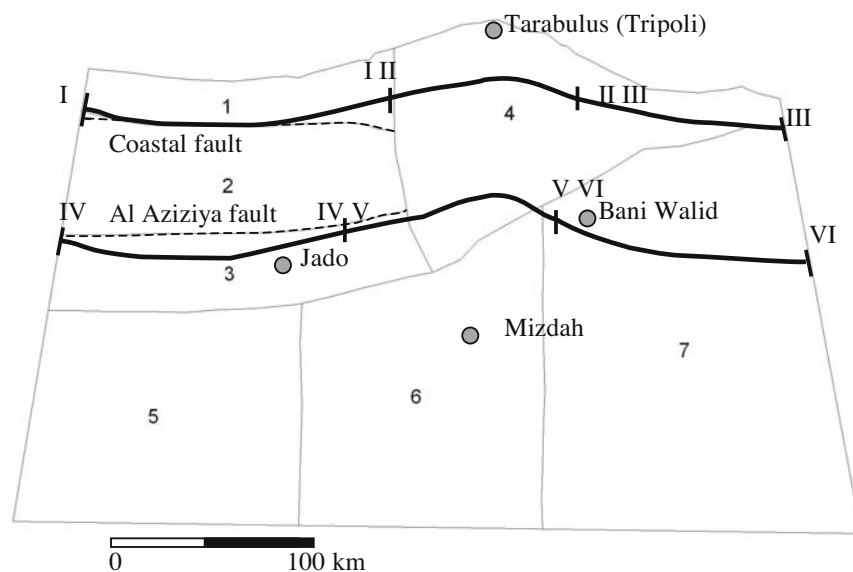
Text-fig. 3. Position and boundaries of model subdomains and their numbering (with Arabic numerals) and position and numbering (with Roman numerals) of sections where total discharge per unit width was assessed

Man-Made River Water Utilization Authority (1996) and Salem and the Libyan Delegation (1998)

MAIN FEATURES OF THE CONCEPTUAL HYDROGEOLOGICAL MODEL UNDER NATURAL CONDITIONS: REGIONAL APPROACH

Previous authors (e.g. Krummenacher 1982; National Consulting Bureau and Mott. Mac Donald 1993; International Centre For Water Resources 1999; Sadeg and Karahanoglu 2001) usually defined groups of important aquifers in the Jifārah Plain and the adjoining Jabal Nafusah with elevated Plateau, based on their stratigraphic position, as follows: 1) Miocene–Quaternary Group; 2) Oligocene–Miocene Group; 3) Cretaceous Group; 4) Jurassic Group; 5) Triassic Group. Within these groups, particular hydrogeological bodies (aquifers and aquitards) can be defined.

The conceptual hydrogeological model as a starting point for numerical modelling, as described below, is based on the following ideas and considerations:

Aquifers are represented mostly by limestones, sandstones and different types of non-indurated clastic deposits. Depending on lithology, their anatomy (internal character, type of porosity) and hydraulic properties differ considerably. The following types of hydrogeological environment can be distinguished:

• Limestones or, more generally, all carbonate rocks are prone to karstification. The hydrogeological environments of double porosity, i.e. combined intergranular and fracture porosity, or even of triple porosity, where limestones are karstified, are prevalent. Permeability might vary extremely. The Al Aziziya Formation and parts of the Takbal and Kikla formations contain important carbonate aquifers in the Jifārah Plain, while the Ain Tobi Member of the Sidi Al Sid Formation, Nalut and Qasr Tigranah formations, consisting mainly of limestones, occur in the Jabal Nafusah. The prevailing transmissivity is reported in hundreds up to thousands of m^2/d.

• Sandstones are characterized by double porosity. The principal representatives of these aquifers are the Abu Shaybah Formation and parts of the Kikla Formation. The reported transmissivity differs in orders of magnitude from units of m^2/d to more than one thousand m^2/d. These differences might be caused by differences in the intensity of fracturing but might also also be due to the presence of less permeable sediments (clayey and silty deposits, shales) within the formation.

• The youngest Cenozoic deposits in the Jifārah Plain are unconsolidated and therefore of predominantly intergranular porosity. Fracturing occurs in zones where the deposits are indurated. Transmissivity typically varies in hundreds of m^2/d but locally can even reach several thousand m^2/d. Transmissivity variation might be generally less than in other hydrogeological environments, since non-indurated deposits such as sands tend to be hydraulically more homogeneous than fractured rocks.

• No hydrogeological data are available for the Tertiary basalt flows in the Nafusah Plateau. Experience from

other countries has shown, however, that young lava flows can show good permeability at least in some parts and might play a positive role in increasing the possibility of recharge of aquifer systems.

Aquitards are represented by the Yafrin Member of the Sidi Al Sid Formation and especially by the Bir Al Ghanam Formation. The several tens of metres thick marly Yafrin Member with gypsum intercalations covers the lower Ain Tobi aquifer and confines its groundwater in the Jabal Nafusah. The gypsiferous Bir Al Ghanam Formation crops out over a wide area in the southern portion of the western part of the Jifārah Plain, where it reaches thicknesses of up to 300 m. Gypsum also occurs in other units, such as in recent sabkha sediments (often together with salt), as recrystallised gypsum in the Pliocene–Quaternary Al Assah Formation or forming gypseous crusts in the Pleistocene Jifārah Formation. Gypsum occurrences might negatively influence natural groundwater quality.

The geometry of hydrogeological bodies, i.e. their extent and thickness, differs considerably within the study area. From this viewpoint, several zones can be distinguished:

• In the "littoral" (northern) part of the Jifārah Plain between the Al Aziziya fault and the Mediterranean coast, the Tertiary–Quaternary Aquifer Complex, up to several hundred metres thick, is underlain by deep-seated Mesozoic deposits. In some parts, the Tertiary–Quaternary Complex is divided by impermeable plastic clay into the upper Miocene–Quaternary aquifer and the lower Miocene aquifer. In the southern ("outlier") part of the Jifārah Plain, between the Al Aziziya fault and the scarp of the Jabal Nafusah, Mesozoic deposits often crop out, overlain by only thin layers of Quaternary sediments. The generally increasing aridity from the east to the west is important for groundwater balance. The character and extent of the Mesozoic deposits also changes considerably in the same direction, causing dif-

SUBDOMAIN							NUMERICAL LAYER
1	2	3	4	5	6	7	
Q	Q	Q	AQT	YF	YF	AK	1
				AT	AT	NL	2
				KI	KI	YF	3
					BI		4
				AR	AS		5
						AT	6
				AS			7
					AZ	KI	8
				TB		AS	9
				BI			10
							11
				AQT			12
		AZ	Q-M	BI	KU	AZ	13
AQT	AQT			AS			14
							15
	M						16
M			AS				17
							18
							19
AQT			AQT			KU	20
			Q-M	AZ			21
AS	AQT		AS				22
	AS						23
				KU			24
AZ	AZ	AQT (KU)	AZ				25
							26

Table 1. Representation of selected lithostratigraphic / hydrogeological units in subdomains and horizontal layers of the numerical model. Legend: Q – Quaternary undivided, AQT – aquitards without identified lithostratigraphic position, Q–M – Quaternary–Miocene, M - Miocene undivided, AK – Al Khums, NL – Nalut, YF – Yefrin, AT – Ain Tobi, AR – Ar Rajban, KI – Kikla, TB – Takbal, BI – Bir Al Ghanam, AS – Abu Shayba, AZ – Al Aziziya, KU – Kurush

ferences in the hydrogeological conditions:
• In the eastern part of the Jifārah Plain (the triangle-shaped Al Khums-Garabulli-Tarhunah area), the Jabal Nafusah extends very close to the the Mediterranean coast.
• In the middle portion (Tripoli area – between Garabulli–Tarhunah in the east and Subratah–Yafrin in the west), the Tertiary–Quaternary Aquifer Complex is underlain mainly by the limestone Al-Aziziya aquifer and partly by the clastic Abu Shaybah aquifer. This portion is economically the most important of the entire Jifārah Plain. Large quantities of groundwater have been withdrawn there.
• In the western portion (from Subratah–Yafrin westward up to the Tunisian frontier) the areally extensive gypsiferous Bir Al Ghanam Formation, both at outcrop and in the subsurface beneath the Tertiary–Quaternary sequences, considerably influences groundwater quality. Low rainfall makes this situation even worse.
• The Jabal Nafusah and Dahr Plateau is composed mostly of Cretaceous deposits and volcanic rocks.

The distribution of particular hydrogeological bodies in subdomains as defined for the numerical modelling is shown in Table 1.

In spite of the above-mentioned differences in distribution of the principal aquifers, the entire Jifārah Plain with the adjoining Jabal Nafusah and Plateau is to be considered on a regional scale as one single extensive, hydraulically interconnected, and spatially complex aquifer system. This system extends to the south as far as the groundwater divide that separates the aquifer system from the southern desert region, where several endorrheic basins occur. Hydraulic interconnection within this Jifārah-Nafusah aquifer system changes in space and time, depending on both the distribution of the hydrogeological bodies and the groundwater heads.

The main features of groundwater flow can be defined as follows:
• Groundwater bodies in all the outcropping aquifers are unconfined, i.e., open to recharge if such a possibility exists. Aquitards occurring in some parts of the system might cause confinement of groundwater level.
• The piezometric surface in all the aquifers inclines generally to the north under natural conditions. The hydraulic gradient might change markedly in the upper parts of the system, mostly depending on differences in surface elevation. In deeper zones, the hydraulic gradient is generally smoother.

Under natural conditions, recharge took place only from rainfall and from surface runoff occurring in rainy seasons in some wadis. Previous authors assessed direct average recharge from precipitation at between 60

and 125 hm³/a, recharge from wadi runoff at some 40 to 70 hm³/a. As no effluent watercourses occur in the study area, the regional discharge zone follows the Mediterranean coast, where groundwater flows directly into the sea or is discharged by evaporation in some low-lying sabkhas. Sabkhas are usually closed basins in arid regions, often representing groundwater discharge zones. Due to intensive evapotranspiration of water and vertical upward seepage of groundwater, soil and groundwater salinisation with high contents of sodium, chlorides and suphates may occur there.
• Part of the groundwater recharged in the Jabal Nafusah area was discharged by springs issuing mainly from Cretaceous limestone aquifers (Ain Tobi Member, Nalut Formation).
• In general, groundwater flow might be partly influenced by the structural setting, mainly by the Al Aziziya fault. This effect, however, does not seem to be regionally very important: even though the vertical throw along the fault is many hundreds of metres, hydraulic connection between adjoining aquifers has not been interrupted.

The natural groundwater quality in many parts of the Jifārah Plain and the Jabal Nafusah was generally suitable for the population and for agricultural use (small-scale irrigation and livestock) even though TDS (total dissolved solids) locally reach several g/L. Groundwater salinity typically increases in areas with gypsum and anhydride occurrences, where high sulphate and calcium / sodium concentrations are often high. Under extremely arid climatic conditions, soil and water salinisation might occur, as for example in sabkha areas due to long-term processes of water evaporation.

CHANGES IN GROUNDWATER CONDITIONS DUE TO ANTHROPOGENIC IMPACTS

Use of groundwater by human beings as the only available permanent water resource goes back many hundreds or even thousands of years. Due to the limited technical possibilities then available, only hand-dug wells were used and only relatively small quantities of groundwater were abstracted.

In the 1950s, improved drilling and pumping technologies resulted in a dramatic increase in the number and depth of water wells and an increase in groundwater withdrawals for municipal and industrial supply as well as for agricultural activities. As proved in many reports (summary e.g. in General Water Authority, Secretary of Agriculture, Great Man-Made River Utilization Authority), such a heavy pumping in excess of recharge has led to a continuous decline of groundwater levels

over wide areas. This situation has continued until now and has caused changes in the hydrogeological conditions. The most important consequences are as follows:

• Groundwater level decline has resulted in an increase in energy consumption and/or the necessity of drilling new deeper water wells or deepening the old ones to reach water level; thus, the possibilities of groundwater abstraction diminish continuously.

• Decrease in piezometric head has changed the natural groundwater flow conditions. In areas of heavy groundwater withdrawals local "cones of depression" have resulted in extended regional piezometric depression. In coastal areas, sea-water intrusion has caused salinisation of groundwater over wide areas. The zones influenced have progressively expanded during the last decades.

• Another consequence of piezometric level decline in upper fresh / non-saline groundwater bodies is uplift of saline groundwater from deep aquifers that under previous natural conditions had flowed more or less horizontally towards the main discharge zone represented by the Mediterranean Sea.

Several measures have been taken to change or at least slow down the adverse relationship between water balance elements (recharge-discharge). The most important of these is the implementation of the Great Man-Made River Project to supply water from remote southern regions to the Jifārah Plain. In addition, increasing agricultural production has intensified the return flow from irrigation. This might be positive from a quantitative point of view but has an adverse impact on groundwater quality: contamination by fertilisers and pesticides appear – an increase in nitrates has been proved in many areas. In addition, leakage from pipelines in urbanised and industrial areas increases artificial recharge; depending on the character of the water losses, however, their effect on groundwater quality can be either positive (mains water-supply) or negative (sewage).

METHODS OF STUDY, CONCEPTUAL AND NUMERICAL MODELS

Available data, their reliability and GIS applications

At the same time as a detailed study of previous reports and publications, an inventory of available hydrogeological data from boreholes was carried out. Most of the data were provided by the Libyan authorities: the General Water Authority, General Environmental Authority, Agricultural Research Centre, Industrial Research Centre, Library of Al-Fatah University, Academic Library of High Study, Great Man-Made River Authority and the Libyan Meteorological Department.

Two databases were created within the GIS Mapinfo during the initial stage of data processing. The first database included technical data from 816 hydrogeological boreholes drilled in the years 1970–2004. The set comprised only boreholes that could be accurately localized by means of their geographic coordinates. The database contains parameters such as the borehole depth, characteristics of the tapped aquifer, borehole open section, as well as data on static and dynamic groundwater level, exploited yields and transmissivity.

The boreholes were relatively evenly distributed over the area of interest and their depths covered more or less all the depth intervals. Half of the boreholes were shallower than 100 metres but more than 200 boreholes were deeper than 250 m. The depths of five boreholes exceeded 1000 metres (Text-fig. 1b).

The second database contained 512 data: these included basic chemical analyses of water, restricted to the content of basic cations and anions, and almost exclusively related to the coastal area. The analyses covered the period 1975–1995 and represented mostly a single sample, whereas repeated analyses were sporadic.

In spite of the great number of technical and chemical data, the reliability of the database information is often questionable. The majority of the hydrogeological wells connect several aquifers, pumping tests are only short term and monitoring data are irregular. In the majority of cases, the monitoring wells are situated in hydraulically affected areas. The technical quality of the monitoring boreholes is another source of inaccuracy. Wells are often corroded or filled in with incrustations.

Based on the available data, different GIS layers were compiled to represent important hydrogeological or hydrochemical features, such as the piezometric surface and the contents of particular components in the groundwater.

Implementation of conceptual and numerical models

Krummenacher (1982) made a steady state three-dimensional groundwater flow model of the western part of the Jifārah Plain (from Tripoli to the Tunisian border). It was based on simplified geology – two aquifers separated by a leakance interface, the upper one unconfined. After calibration, a transient groundwater flow model was developed and several scenarios of future groundwater use were applied to predict their impact on groundwater level in the Jifārah Plain.

Because the predictions differed considerably from in situ measurements in 1990, the model was remade in 1993 so that it included the impact of the Great Man-

Made River. The finite differences method was employed.

Sadeg and Karahanoğlu (2001) made a steady state two-dimensional groundwater flow model of the northern coastal part of the Jifārah Plain around Tripoli. They used the calibrated model parameters for transient two-dimensional, vertical cross-section models of seawater intrusion. The finite element method with quadrangular elements and bilinear functions was employed.

Model of natural conditions

In contrast to previous models, we focused on the regional features of natural groundwater flow, based on spatial identification of all the important hydrogeological bodies as separately defined layers of aquifers and aquitards. The finite element method was used. Changes caused by human activities were then modelled using calibrated natural models with different groundwater withdrawals.

Groundwater flow in the study region has been studied as a three-dimensional problem. The natural conditions of the study region have been considered as a case of steady state flow, with the free groundwater table determined by known geological conditions and average balance data.

The areal extent of the model domain is depicted in Text-figs 1 to 3. The domain reaches from 800 m below sea level up to the land surface. The geological structure of the region is known down to a depth of about 1000 m below sea level from a set of deep boreholes.

The exact shape and position of the boundary were defined according to knowledge of the hydraulic data. The boundary conditions prescribed in order to define the flow problem are of either Neumann or Dirichlet type.

According to the known general groundwater flow direction, boundary conditions of Neumann type were imposed on the western and eastern part of the domain boundary so that the normal component of the flow vector is zero

$$-K\frac{\partial u}{\partial x_i}v_i = 0 \qquad \text{on } \Gamma_N,$$

where K is the hydraulic conductivity, u is the hydraulic head, Γ is the unit outward normal to the boundary and Γ_N denotes the part of the boundary where zero discharge was expected. It was found by means of calibration that Γ_N also contains the southern part of the boundary though some small non-zero inflow from the south can be expected. In fact, it was found by sensitivity analysis that changes of inflow within the range of its possible values did not influence the model result significantly. Zero discharge boundary condition was

also prescribed at the bottom-boundary of the domain, where the vertical component of the water flow was considered to be negligible.

The northern boundary of the modelled region is the seashore. Hence, the Dirichlet boundary condition of zero hydraulic head was prescribed on this part of the boundary.

The phreatic surface marks the upper boundary of the modelled region. The measured values of 18 rainfall stations and assessed infiltration rates in different parts of the region made it possible to estimate spatially dependent inflow. Consequently, the position of the upper boundary was not known, and knowledge of the head and discharge conditions made it possible to define and solve the problem as a free boundary one.

The hydrogeological environment consists of several formations. Concerning the hydraulic conductivity, particular formations were assumed to be homogeneous and vertically anisotropic, with ratio $K_{horiz.}/K_{vert.}$ = 5 or 10, depending on the formation. This anisotropy might be caused either by alternating layers of different permeability, i.e., regionally insignificant aquifers and aquitards, or be due to the microscale structure of the particular regional aquifer.

The domain was divided into seven subdomains based on the different geological settings of the western and eastern parts of the Jifārah Plain and mountain range, and the presence of three major tectonic zones – the Coastal fault, the Al Aziziya fault and the escarpment that borders the mountain range. Subdomains 1 to 3 cover the western part of the Jifārah Plain, where two important faults occur. The Coastal fault forms the boundary between subdomains 1 and 2, and the Al Aziziya fault forms the boundary between subdomains 2 and 3 (see Text-fig. 3). The faults themselves were judged to be of small hydrogeological importance, because no significant difference in hydraulic head has been observed across the faults under the present hydrogeological and hydrological conditions. The model's mesh geometry respects the position and shape of both faults, but neither distinct hydraulic parameters nor special finite elements were applied. The narrower eastern part of the Jifārah Plain up to Al Khums belongs to subdomain 4. The remaining subdomains 5, 6 and 7, which occupy the western, central and eastern parts of the mountainous region respectively (see Text-fig. 3), are bounded by the escarpment to the north. Their southern extent coincides with the boundary of the study area and is considered identical to the main groundwater divide. According to its geological structure, each subdomain was divided into a set of horizontal layers. The extent of subdomains 1 to 7 is represented in Text-fig. 3; the occurrence of particular hydrogeological bodies

Lithostratigraphical / Hydrogeologic unit	Hydraulic conductivity [10^{-4} m/s]
Quaternary	10.1
Yefrin	0.501
aquitard	0.001
Ain Tobi	9.26
Al Khums	0.347
Nalut	0.6
Kikla	0.65
Bir al Ghanam	0.111
Ar Rajban	0.2
Abu Shayba	0.182
Azizia	3.34
Takbal	0.501
Kurrush	0.012 – 4.0

Table 2. Hydraulic conductivities of lithostratigraphic / hydrogeological units obtained by calibration of the model of natural conditions

and the position of horizontal layers in all the subdomains are shown in Table 1.

The numerical modelling software FEFLOW was used to solve the above-formulated problem. The finite element method was utilized.

The differences in the hydrogeological character of particular lithostratigraphic units over the region and in their depths below the land surface required 26 numer-

ical layers of triangular prism elements to be defined. Each layer spans the whole areal extent of the domain, representing part of real geological / hydrogeological environments (Table 1).

The hydraulic parameters of each layer are not constant and vary stepwise with respect to particular subdomains. The values of hydraulic conductivities accepted for the modelling on a regional scale resulted from the model calibration (for example see Table 2). The geometry of the subdomains was chosen so that parts of the subdomain boundaries represent some of the tectonic zones mentioned above. The top and bottom surfaces of the layers were chosen in order to match some stratigraphic interface in at least one subdomain. This has divided the domain into parts that can be considered hydraulically homogeneous.

The top boundary of the domain represents the free groundwater table and is therefore moveable, i.e., its position and shape are not prescribed and result from the problem solution.

Groundwater level data from suitable boreholes that tap the most important aquifers in the study region were used to calibrate the steady-state model. Table 3 summarizes the position of the calibration points, together with the observed and computed hydraulic heads at these points. The median absolute value of head differ-

No.	E	N	m a. s. l.	h obs.	h calib.	Layer no.	Subdomain no.
1	317600	3548400	320	118	122	6	6
2	255500	3577200	96	85	83	11	3
3	325250	3581631	43	78	76	13	6
4	277400	3580700	60	82	74	13	3
5	300743	3575111	48	80	91	13	6
6	512221	3578470	72	77	80	13	6
7	339250	3631300	0	11	17	14	4
8	278544	3616180	27	39	31	14	2
9	328900	3600900	19	57	54	14	4
10	394850	3619100	-22	37	37	16	4
11	333600	3599750	-53	48	55	18	4
12	302900	3568900	-63	108	106	18	6
13	367190	3614550	-48	56	43	18	7
14	329750	3601500	-80	43	53	19	4
15	328750	3608000	-121	41	47	20	4
16	331200	3614600	-131	44	40	20	4
17	356160	3613180	-158	56	44	22	4
18	339800	3626601	-264	39	24	24	4
19	372301	3571400	-36	61	58	17	7
20	363350	3597150	-10	43	53	16	7

Table 3. Comparison of observed hydraulic heads (**h obs.**) and hydraulic heads computed with the model of natural conditions (**h calib.**). Positions of model calibration points by geographic coordinates (**E, N**) and by subdomain and model layer

ence is a little less than 6 m. Regional values of hydraulic head cannot be expected to match individual point measurements better.

Main results of the model of natural conditions

Calibration of the model of natural hydrogeological conditions was based on the agreement of the modelled and real piezometric surface. The results of calibration expressed by differences between observed and calculated heads at calibration points throughout the study region are presented in Table 3.

The highest groundwater levels occur in the southwest of the domain, i.e., in subdomain 5, the western part of subdomain 6 and the southern part of subdomain 3 (Text-fig. 4). From there about 14% of water flows to the east to subdomain 7, represented partly by a closed basin in the Tajoury region. This represents total discharge per unit width of less than 1 m²/d. The major part of the groundwater, however, flows northward, at approximately 3 m²/d, towards the zone of regional groundwater discharge along the Mediterranean coast.

Groundwater leaves the domain only through the coastline. The assessment of regional groundwater flow in the Jifārah Plain was made in transects each consisting of the three sections: the southern transect, comprising sections IV to VI, more or less follows the Al Aziziya fault while the northern one, comprising sections I to III, is situated closer to the coast (Text-fig. 3). The discharge per unit width of aquifer through the coastline is higher than farther from the coast. As can be seen from Tables 4 and 5, the difference is approximately 293 760 m³/d. This might be caused partly by the additional recharge in the region between the two transects but is most probably due to the influence of an ascending deep-seated groundwater flow close to the regional zone of discharge.

The smallest values of discharge per unit width of aquifer were found on the coast around Tripoli (5 to 6 m²/d). Discharge values per unit width of aquifer in-

Hydraulic head [m]	Section			Total
	4	5	6	m³/d
natural condition	370952.81	150361.2	399385	920699.1
2	151952.72	31440.71	206604.2	389997.7
1.5	150164.72	29474.46	203896.8	383536
1	148354.74	27450.08	201137.8	376942.7
0.5	146532.12	25363	198324	370219.1

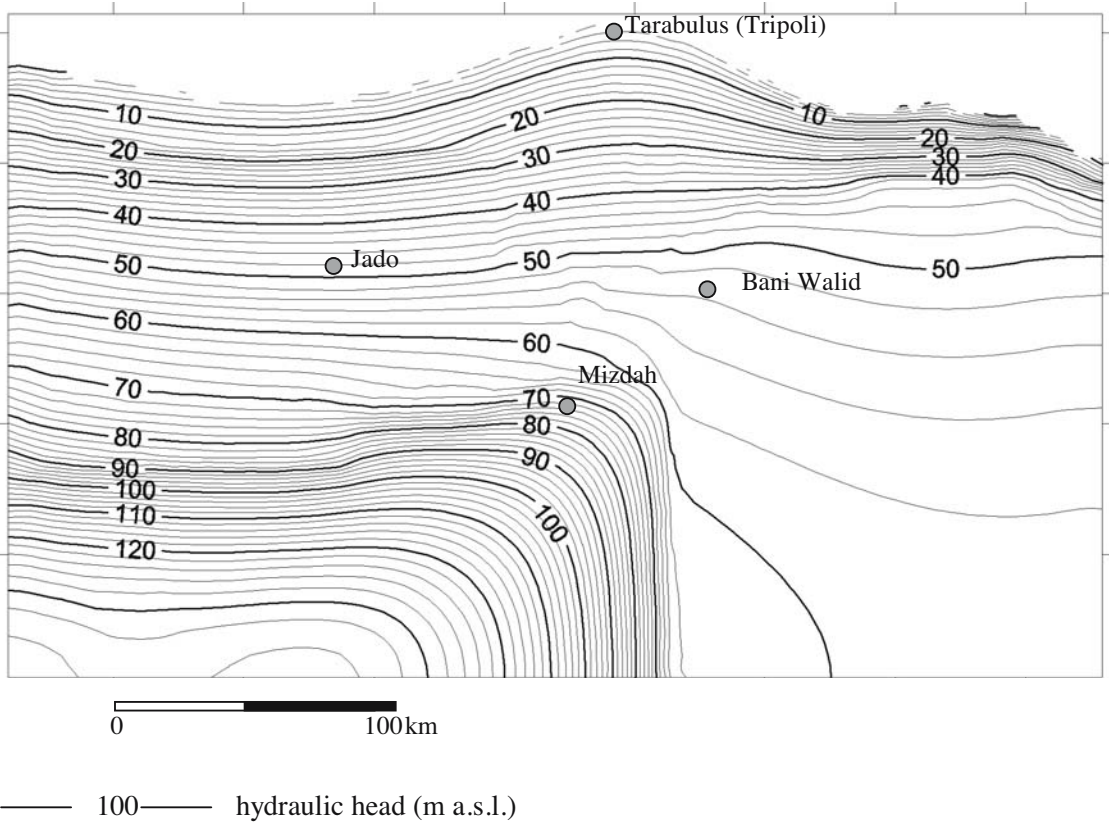Table 5. Fluxes in m³/d through the sections IV to VI (along the Al Aziziya fault)

crease to the west and to the east of Tripoli. The greatest values were found along the eastern part of the coastline (12–13.5 m²/d), while a discharge value per unit width of aquifer of about 10 m²/d can be assessed along the western part of the coastline. The results agree with the prescribed infiltration rate on the top boundary of the domain.

## Main results of the model of current groundwater extraction

According to water-extraction data in the past from El Baruni *et al.* (2004), an estimate of current total water extraction has been calculated. This value has been distributed in the domain according to the water extraction distribution schemes from El-Baruni *et al.* (2004). The resulting groundwater levels show large depression cones around Tripoli and west of Al Aziziya. As a steady state model, it shows the piezometric levels after balance has been achieved.

The model was then calibrated to match the current piezometric levels in the region. The total water extraction in this model is about half the previously estimated value. The distribution of extraction is also different. If we assume the current state in the Jifārah Plain to be steady/stationary/balanced, the result implies that the return flow from irrigation and municipal water losses must be about half the total amount of extracted water. However, a more probable interpretation (i.e., not assuming the current state to be steady) is that the current state is just an immediate value of a function that has a decreasing trend.

The present groundwater extraction creates an irregular cone of depression along the coast, which is deepest around Tripoli (Text-fig. 5). Pumping causes seawater to infiltrate the aquifers. Steady state computations have shown that discharge per unit width of aquifer of seawater is 3–6 m²/d through the western part of the coast and 10.5–12 m²/d through the coast around Tripoli. However, groundwater still discharges (0–5 m²/d) into the sea through the eastern part of the coast.

Hydraulic head [m]	Section			Total
	1	2	3	m³/d
natural condition	462506.4	247201.1	512024.4	1221732.0
2	89964.2	51867.3	66589.8	208421.3
1.5	87553.5	47984.5	60781.9	196319.8
1	85160.0	43933.3	54909.4	184002.7
0.5	82767.0	39713.6	48965.6	171446.2

Table 4. Fluxes in m3/d through transects I to III

Text-fig. 4. Piezometric surface under natural conditions as a result of the numerical modelling of the whole aquifer system
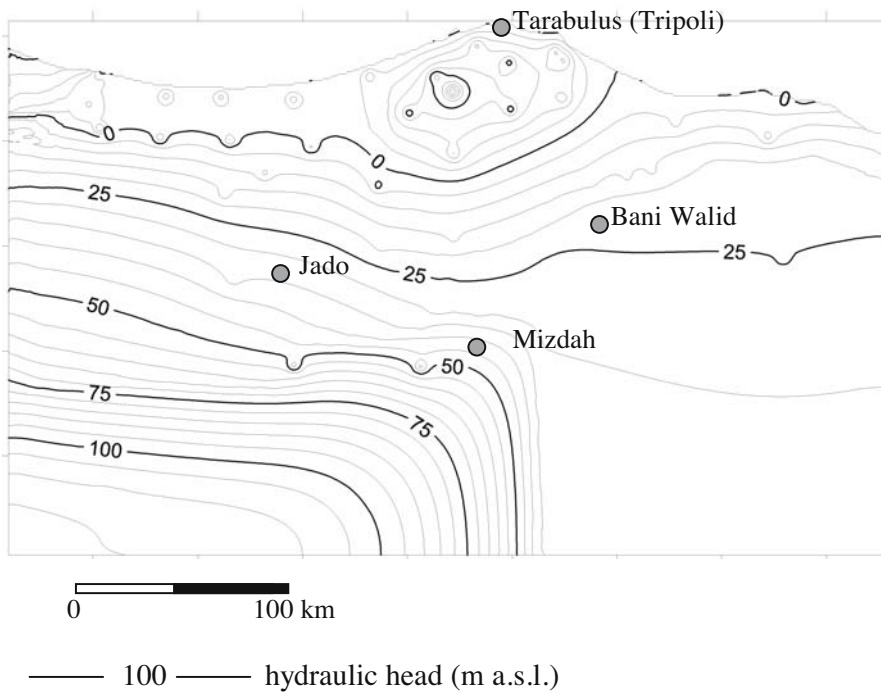
Text-fig. 5. Regional steady-state conditions under anthropogenically changed conditions

Tables 4 and 5 summarize groundwater flow in distinct areas and under different conditions, i.e., under natural conditions and with differently prescribed heads along sections I to VI. For example, Table 4 shows the situation along sections I to III, close to the Mediterranean coast, and Table 5 groundwater flow more to the south, along sections IV to VI, following the Al Aziziya fault. For the positions of these sections see Text-fig. 3.

Discussion of sensitivity

The model is primarily sensitive to changes in infiltration. Increasing it by 5% causes the hydraulic head in calibration wells/points to rise by 1 to 5 metres (median 2.5 m), depending on the position and depth of a particular point.

The model is quite insensitive to hydraulic conductivity. The significance of various aquifers depends on their position and thickness.

The hydraulic conductivity of aquifers near the coast (i.e., aquifers of subdomains 1 and 4) has the greatest influence on the hydraulic head. This is caused by both the Dirichlet boundary condition prescribed on the northern part of the boundary and the fact that most water infiltrates the domain south of these aquifers. For example, a 20% increase in the hydraulic conductivity of the Abu Shayba aquifer in subdomains 1 and 4 causes a drop in hydraulic head of less than 2.5 m, while a 20% increase in the hydraulic conductivity of the Quaternary–Miocene aquifer in subdomain 4 causes a 0.5 m to 5.5 m (median 4 m) drop in hydraulic head.

The model is almost insensitive to the values of flux density imposed by Neumann boundary condition in the southern part of the domain, even for considerable values of flux. From a hydrogeological point of view, we can expect only very small values of flux density in the southern part of the boundary, which make no significant difference in the calculated hydraulic head.

The values of flux density prescribed by Neumann boundary condition at the western and eastern parts of the boundary do not affect hydraulic heads in the calibration points because of the generally N–S direction of groundwater flow.

The Dirichlet boundary condition at the northern part of the boundary has not been the subject of calibration.

CONCLUSIONS AND SUGGESTIONS

Based on available data, a conceptual model of hydrogeological conditions in the north-western part of Libya – in the Jifārah Plain and its surroundings – was implemented. The lithostratigraphic units were characterized hydrogeologically and their geometry and anatomy assessed. This enabled the groundwater situation to be modelled on a regional scale and a comparison of the past natural situation with man-made changes that have occurred in the last decades. The main results of the study are as follows:

• Under natural conditions, groundwater flows northward from the southernmost part of the study region to the regional discharge zone represented by the Mediterranean Sea. Part of the groundwater, however, also flows to the east.

• It has been estimated that, in addition to the water recharged in the remote southern part, some water might also be recharged in the Jifārah Plain itself, possibly at a rate of around 100 000 m^3/d.

• Thus, the total amount of water discharged under natural groundwater conditions along the Mediterranean coast can be assessed as high as 1 278 720 m^3/d.

• There are some important differences between particular parts of the coast. The highest discharge per unit width of aquifer (12–13 m^2/d) occurs along the coast east of Tripoli, while the lowest occurs around Tripoli (5–6 m^2/d). The discharge per unit width of aquifer is about 10 m^2/d along the western part of the coast.

• Under man-made conditions, regional groundwater flow has changed considerably. Groundwater flows to the areas with heavy groundwater abstraction, not only from former (natural) recharge areas, but also from the sea-coast. Due to the decrease in piezometric head, the upward vertical component of groundwater flow has certainly increased. In addition, artificial contamination occurs in irrigated, industrial and urban areas. All this results in a deterioration in groundwater quality over wide areas.

• A very important practical result of the numerical model might be an assessment of the abstraction rate in the current zones of depression. Calibrated to present available data on the piezometric surface, the amount of water abstraction should have been smaller than previously estimated values: according to the model it could be about 518 000 m^3/d in total compared to the previously mentioned assessments by Krummenacher (1982), Sadeg and Karahanoglu (2001) and the National Consulting Bureau and Mott Mac Donald (1994).

• The reason for this difference could be either the fact that the real withdrawn groundwater is less than the recorded amounts or that return flow and/or artificial recharge is so high that they do not permit for the extention of the depression to an extent predicted by the model. This conclusion highlights the importance of input data for groundwater balance. The differences indicated in the assessed withdrawn groundwater vol-

umes seem to be quite high and might considerably influence the future possibilities of groundwater use in the study region.

Acknowledgement

REFERENCES

El-Baruni, S.S., Futasi, R.H.,Taloua, H.M. and El-Ghadi, M. 2004. Hydrogeology of the Libyan Jifārah Plain (unpublished report).

FAO 1981. The Gefara plain water management plan. FAO, LIB/005.

FAO 1985. Water supply alternatives in the Gefara Plain. Rome.

GEFLI 1972. Soil and water resources survey for hydro-agricultural development, Western Zone. Unpublished Report, Ground Water Authority, Tripoli.

Krummenacher, R. 1982. Report on groundwater resources of Gefara plain. SARLD Report, Tripoli.

Kruseman, G.P. 1977. Evaluation of water resources of the Gefara plain. SDWR, unpublished report, Tripoli.

Kruseman, G.P. and Floegel, H. 1978. Hydrogeology of the Gefara plain, NW Libya. 2nd Symposium Geology of Libya, Tripoli.

International Center For Water Resources 1999. Groundwater quality in some wells in northwestern Libya, El-Ajilat, Libya.

IRC 1975a. Geological map of Libya 1:250,000 sheet. Tarabulus, explanatory booklet. Industrial Research Center, Tripoli.

IRC 1975b. Geological map of Libya, 1:250,000 sheet. Elkums, explanatory booklet. Industrial Research Center, Tripoli.

National Consulting Bureau and Mott Mac Donald 1993. Water management plan. Great Man Made River Water Utilization Authority by the National Consulting Bureau of GSPLAJ with Mott MacDonald of the UK, Tripoli.

National Consulting Bureau and Mott Mac Donald. 1994. General plan for the utilization of the Great Man-made River waters, phase 2. GMRWUA. Tripoli-Libya.

Pallas, P. 1978. Water resources of the SPLAJ. SDWR, Tripoli.

Sadeg, S. and Karahanoğlu, N. 2001. Numerical assessment of seawater intrusion in the Tripoli region, Libya, Environmental Geology. 40, no 9: 1151–1168, Aug. 2001, Springer Verlag.

The Great Man-Made River Water Utilization Authority 1996. The Great Man-Made River General Authority (second phase), Eljamahireiah Press, Tripoli, Libya.

Salem, O. 1991. The Great Man-Made River Project: A partial solution to Libya's future water supply. Planning for groundwater development in arid and semi arid regions. Edited by RIGW/WACO, Cairo-Rotterdam.

Salem, O. and the Libyan Delegation 1998. Management of Water Scarcity in Libya for sustainable development. Memorandum submitted to the 100th inter-parliamentary conference Moscow, September 1998.