Charles University Prague, Faculty of Science
Institute of Hydrogeology, Engineering Geology and Applied Geophysics

Future groundwater development in the Jifarah Plain, Libya, and possible environmental impacts: regional approach

The Thesis Submitted as the Basis for the Award of the Doctor Degree

Yousef Mohamed Elgzeli

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YOUSEF MOHAMED ELGZELI

Supervisor: Dr. Jiří Krásný
Consulting Supervisor: Dr. Jiří Mls

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DECLARATION

I declare that all the results, which are used and published in this Thesis, have been obtained by my own research work and that all the ideas taken from work of others, are properly referred in the text and the literature survey.

I also declare that the Thesis has not been submitted and/or defended at any other place.

Prague, 2010 (Yousef Mohamed Elgzeli)

Dedication

I dedicate this thesis to my father´s innocent spirit, to my mother, my wife, my children, Mohamed, Amani, Abdelrawf, Abdelmoin, Ahmed, Abdelmalk, my brothers, and my sisters whose patience and understanding helped me to complete this thesis.

Yousef Mohamed Elgzeli
2010

Acknowledgement

I am most thankful to Almighty Allah for giving me the patience and making it possible for me to produce this work.

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Abstract

Libya as many other regions under arid climates suffer from inadequate water resources to cover all the needs of this rapidly developing country. Increasing water amounts for population supply, agricultural irrigation and use for industry are needed. 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 in a regional scale to show how the natural situation has been changed after heavy groundwater abstraction having occurred in the last decades in the northwestern part of Libya. Results of the numerical model indicated that the current zones of depression in piezometric surface could have been caused by smaller withdrawn amounts than previously estimated. Indicated differences in assessed withdrawn groundwater volumes seem to be quite high and might influence considerably the future possibilities of groundwater use in the study region.

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1. Introduction

Libya, situated in the northern Africa, occupies extended area of 1.76 million square km. More than 95 per cent of this area is exposed to severe arid climatic conditions and belongs to desert, mostly to Sahara. Only the northernmost part along the coast of the Mediterranean Sea offers more favourable climate where almost 95 per cent out of the total 6 million Libyan populations reside. The rest lives in several oases widely scattered in the remaining part of the country. The coastal strip is separated by the Gulf of Sirt, where the desert reaches northward almost to 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 also the capital of Libya – Tripoli is situated (Fig.3.1). The second is the northeastern part of Libya – the Benghazi Plain. In these two zones almost all the cultivable land of the country occurs, representing some 2% of the total Libyan territory (approx. 38,000 sq. km). Even in coastal regions, in spite of relatively better climatic conditions compared to desert, effective agricultural production decisively depends on irrigation. As no perennial watercourses occur in Libya the only feasible water resource is groundwater. Thus groundwater 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 occurs deeper, has become less available and its resources might be considered consecutively depleted. Its quality has been deteriorated, especially in coastal regions where heavy pumping has caused sea-water intrusion. All these problems have been perceived very seriously and a lot of respective studies have been carried out in the last decades. Many of them were focused on the most important region of the whole country – the Jifārah plain.

The presented Thesis was prepared during my PhD studies at the Charles University Prague, Faculty of Science, Institute of Hydrogeolology, Engineering Geology and Applied Geophysics in the years 2005-2007. It is focused on the most important groundwater and environmental issues of the Jifārah Plain and surrounding units. Based on previous available data and results previously achieved in this region, it summarises and analyses natural conditions of groundwater flow and assesses in a regional scale quantitative and qualitative environmental and water related impacts of past and present-day heavy groundwater pumping. Conceptual and numerical models were implemented, variants of human impacts and future possibilities of groundwater development in the Jifarah Plain were considered.

2. Methods of study

The study was based on detailed analysis of available data received from previously published papers and from many unpublished reports and materials in this extended region. The used publications are quoted in the list of references at the end of the thesis. Most of the unpublished data were provided by the Libyan Authorities as General Water Authority, General Environmental Authority, Agricultural Research Centre, Industrial Research Centre, Elfateh University Libraries, Library of high study Academic, Mad Man River Authority and Libyan Meteorological Department.

At the same time, together with the analysis of available papers and reports inventory of available hydrogeologic data from boreholes has been carried out. This resulted in implementation of the two extended databases, the first one containing mostly quantitative hydrogeologic data and the second one focused especially on water quality data.

During interpretation of available data the main attention was focused on definition of different types of hydrogeologic environment occurring in the study area and determination of geometry and anatomy of particular hydrogeologic bodies. These considerations have involved also detailed analyses of natural conditions of groundwater flow and regional quantitative and qualitative environmental and water related impacts of past and present-day heavy groundwater pumping. Finally, conceptual and numerical models were implemented to consider variants of human impacts and future possibilities of groundwater development in the Jifarah Plain.

Methods used during the study are described in detail in chapter 5 and following chapters.

3. General information on Libya

3.1 Location and population of Libya

Libya occupies a part of northern Africa approximately extended between the 20 and 34 degrees of the northern latitude and between the 10 and 25 degrees of the eastern longitude Fig.3.1. It is bounded in the east by Egypt (the total lengths of the common frontier is 1150 km), in the west by Tunisia (459 km), and Algeria (982 km), by the Mediterranean Sea in the north, and by Sudan (383 km), Chad (1055 km), and Niger (354 km) in the south (CIA, 2004). It has an important physical asset by its strategic location at the midpoint of Africa's northern rim.

The total area of Libya is about 1.76 million km^2. By its extension it ranks forth among all countries of Africa and fifteenth among all countries on earth (McMorris, 1979: 62). More than 95% of Libya is desert, which is a part of Sahara that is the most extensive area of severe aridity. Aridity of the central and eastern Sahara is due to its domination by continental tropical air all the year, which is continually descending from the upper levels of the atmosphere where, in these latitudes, anticyclone conditions are permanent.

The cultivable areas are estimated at 3.8 mill. ha, i.e. slightly over 2% of the total area of the country. These are extended mostly in the northern part of the country along the Mediterranean sea. The extension of the irrigation areas in all Libya was estimated at 400,000 ha (Ben-Mahmoud, ET al. 2000: 2).

The coastal strip is separated by the Gulf of Sirt, where the desert reaches northward almost to the Mediterranean 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 also the capital of Libya – Tripoli is situated with the total population more than one million people. The second is the northeastern part of Libya – the Benghazi Plain. Fig. 3.1.

The fertile lands of Jifarah Plain in northwest, Jabal Alakhdar in the northeast and the coastal plain east of Sirt receive usually sufficient precipitation to support agriculture.

Within the rest of the country widely scattered oases in middle and southern Libya occur.

Libya's total population was 5.67 million in 2006 including more than 350,000 non-nationals. In 2007, population estimate was at 5.77 million with a growth rate of 1.8 (National information Authority of Libya, 2006). Almost 90% of the population live in the coastal region in the north concentrated in the two centres, i.e. in the north-western Jifarah Plain and in the north-eastern Ben-Ghazi Plain. The main reasons for this concentration are fertile soils and seasonable, moderate climatic conditions (Census 2006).

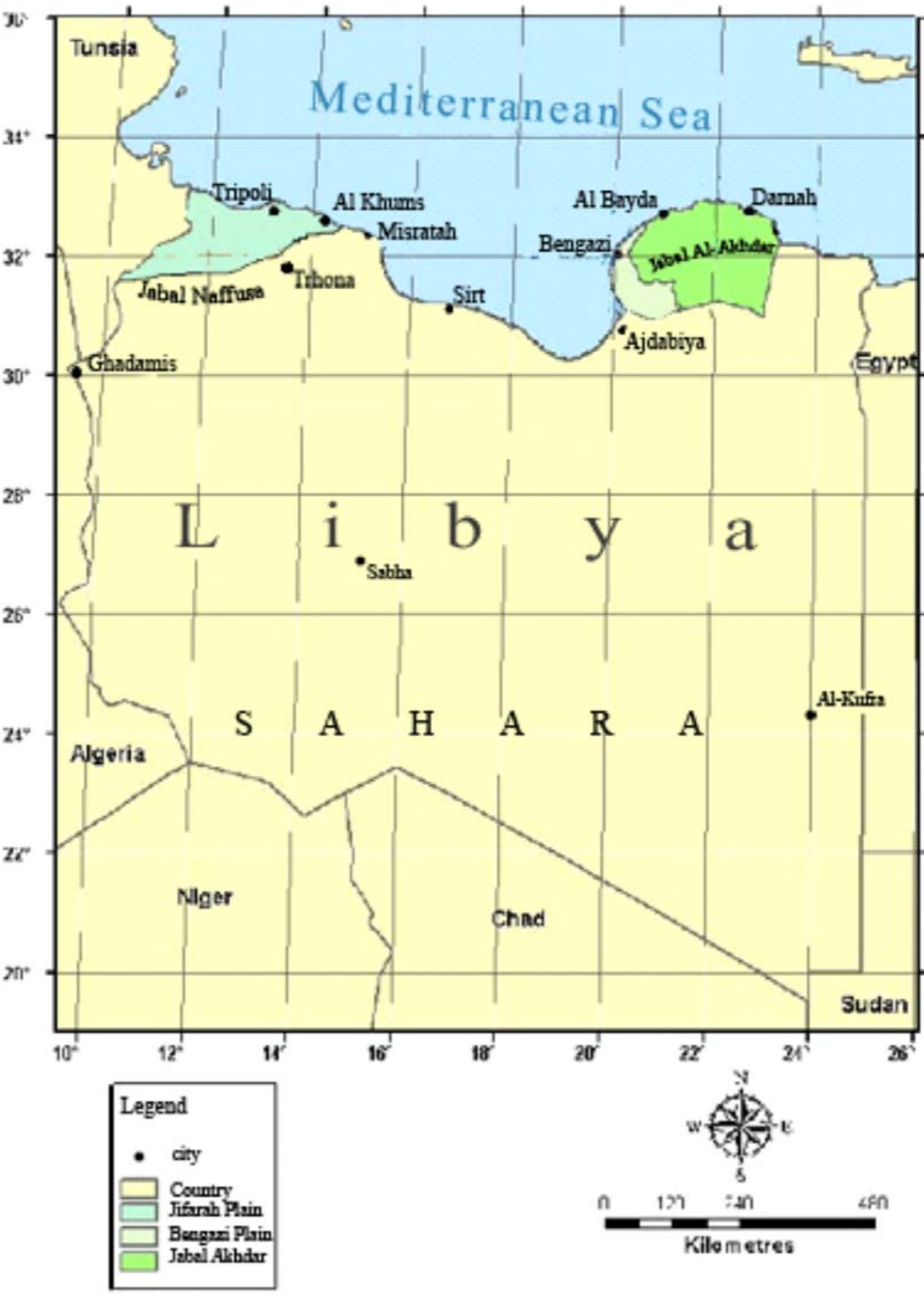


Fig. 3.1 Location of Libya

3.2 Geomorphology

The main geomorphologic features of Libya can be identified as follow:

In northern Libya, coastal plain includes coastal lowlands (Jifarah Plain, Sirt Plain and Ben-Ghazi Plain) as well as Sebkhas, lagoons, salty marshes, swamps and coastal sand dunes. Coastal lowlands are separated from each other by pre-desert zone and backed by plateaus with steep, north-facing scarps. In the west, along the coast of Tripoli, more than 300-km coastal oases alternate with sandy areas and lagoons. In the eastern part fewer coastal oases and the Marj Plain extends inland at a maximum of 50 km along the coast. The cliffs of an arid plateau reach to the Mediterranean Sea in northeastern Libya.

Behind the Marj Plain the terrain rises abruptly to form Jabal El-Aakhdar (Green Mountain; Mc Morris, 1979: 63). The highlands run in the vicinity of the coastal plain including Jabal Naffusah (981 m) in northwestern Libya, which is hilly limestone massif prior to Upper Cretaceous and Jabal Al-Akhdar (875 m) in northeastern Libya composed of Paleogene limestone. Both mountain ranges are divided by a line of fractures and tilt towards the north, such as Jifarah Plain which rises slowly from sea level along the coast to 200 m at the foot slops of Jabal Naffusah (Pallas, 1980: 566). Jabal Naffusah grades southwards to an extensive plateau with stone deserts (El-Hamada El-Hamraa) which persist at heights of about 500 m. The same elevation prevails further to the east by shallow gradation of the Sirt gulf hinterland. The volcanoes rise to 800 m above sea level in the El-Sawda Mountain and up to 1,200 m in the Haruj Es Sawda (Kanter, 1967: 76).

From Jabal Al-Akhdar, a barren grazing belt gives way to the Sahara desert and extends southward where elevation is generally below 200 m. Here the extensive gravel areas of the Serir desert and the sands of the Libyan deserts advance close to 300 km from the coast (Kanter, 1967: 77).

In southern Libya, the prominent and very rugged slopes of the Tadrart Mountain dip gently north and north-eastward. The board valley extends northward from the oases of Ghat and the great sand seas of Murzuk and Ubari, which are separated from the Serir Tibesti by the Nubian-Post-Tassilian outcrops of Jabal Ben-Ghnema and Jabal El-Gussa (PESCE, 1968: 24). Only on arrival in the vicinity of El-Kufra, low hill ranges rise to some 700 m with small oases. Near the southern border Jabal Uwainat attains 1,934 m (Kanter, 1967: 77).

3.3 Climate

Classified as a dry desert climate particularly in the central and southern region, it is characterized by wide variations in temperature between summer and winter seasons along with scarcity and irregularity of rainfall.

The northern coastal strip is situated under a semi-Mediterranean climate and receives winter rainfalls ranging from 200-400 mm/y with moderate temperatures and high relative humidity.

3.3.1 Temperature

The spatial pattern of annual, winter, and summer temperatures over the whole Libyan territory mainly depends on latitude and elevation. Selected data on temperature are presented in the Tab. 3.1

3.3.2 Precipitation

Rainfall is the main feature of atmospheric precipitation in Libya, but snow can also fall exceptionally along the Mediterranean coast as e.g. in Feb. 1949 when a 1-m-thick layer of snow persisted for three days at Jabal El –Akhdar (MARTYN, 1992: 222). Tab.3.2 represents annual climatological data from selected stations in Libya (Libyan Meteorological Department, Tripoli) showing prevailing features parallel to the coastal configuration except for high plateaus of Jabal Al-Akhdar in the northeast and Jabal Naffusah in the northwestern Libya. It can also be observed that mean annual precipitation varies from 0 mm in the south of Libya to 600 mm on the coast. In the northern part of the country it increases from over 300 mm in the northwest (338 mm at Tripoli city) to almost 600 mm (572.6 mm at Shahat) on Jabal Al-Akhdar in the north-eastern Libya .Tab.3.2.

Tab. 3.1 Latitude and elevations of stations under study in Libya and their annual, winter and summer temperatures, 1946-2000

station	Latitude	Elevation (m)	Annual(c)	Winter (Dec-Feb)	Summer (Jun-Aug)
El-Kufra	24.13	436	23.3	14.2	30.8
Sebha	27.01	432	23.4	12.8	30.6
Jalo	29.02	60	22.4	14.1	29.8
Jaghboub	29.45	-1	21.3	12.9	28.8
Ghadames	30.08	357	21.9	11.8	31.4
Agedabia	30.43	7	20.5	13.5	26.5
Sirt	31.12	13	20.5	13.4	25.5
Nalut	31.52	621	19.1	10.5	27.2
Benina	32.19	129	20.1	13.4	26.1
Misurata	32.19	32	20.4	14.1	26.2
Tripoli airport	32.40	81	20.4	12.8	27.6
Derna	32.47	26	20.0	14.8	25.1
Shahat	32.49	621	16.5	10.1	22.8
Zuara	32.53	3	19.8	13.3	25.8
Tripoli city	32.54	25	20.2	14.0	26.4

Data source: Libyan Meteorological Department, Tripoli; Jaghboub and Jalo, 1950-2000

3.3.4 Evaporation

Typically high annual evaporation in the desert stations as Ghadamis, Sabha, Hun, Tazirbu, Jalu, Al Kufra and Jaghbub range from 3182 to 6119 mm (piche), and in the coastal stations Zuwarah, Tripoli, Misratah, Sirt, Binghazi, Shahhat range from 1400 to 2414 mm (piche).

3.3.5 Relative humidity

Relative humidity is generally low throughout the year owing to minimal evaporation and paucity of water vapour. Mean annual relative humidity falls from 65-75 % in the coastal region to less than 35 % in the desert.

Highest water vapour only occurs in coastal region by the Mediterranean Sea effects. In winter relative humidity decreases southwards. It ranges between 70 % at Shahat and 73% at Zwara in the costal zone and 30% at Al Kufra and 34% at Sabha in the Sahara tab. 3.2.

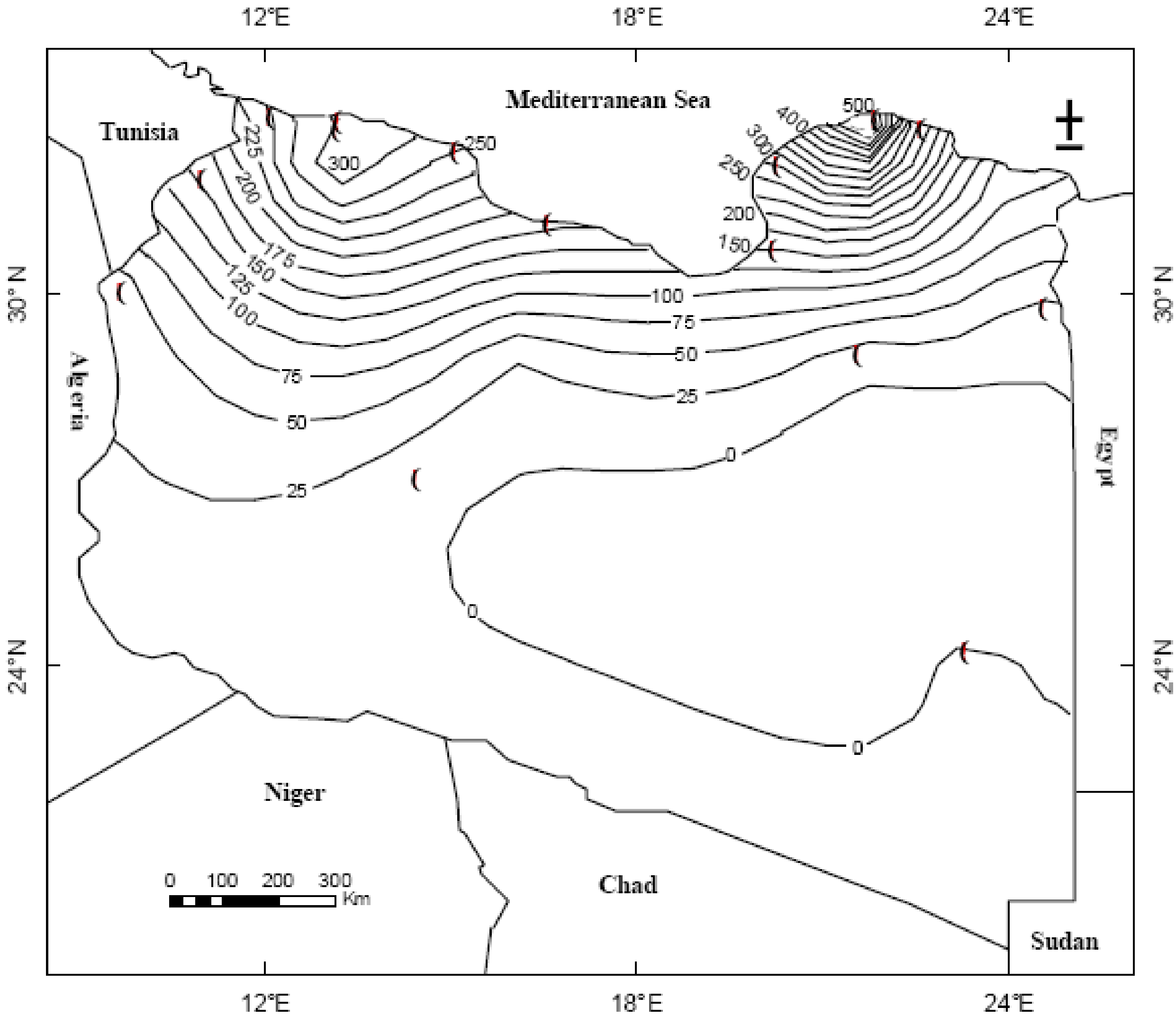


Fig. 3.2 Mean annual rainfall in Libya

Data source: Libyan Meteorological Department, Tripoli

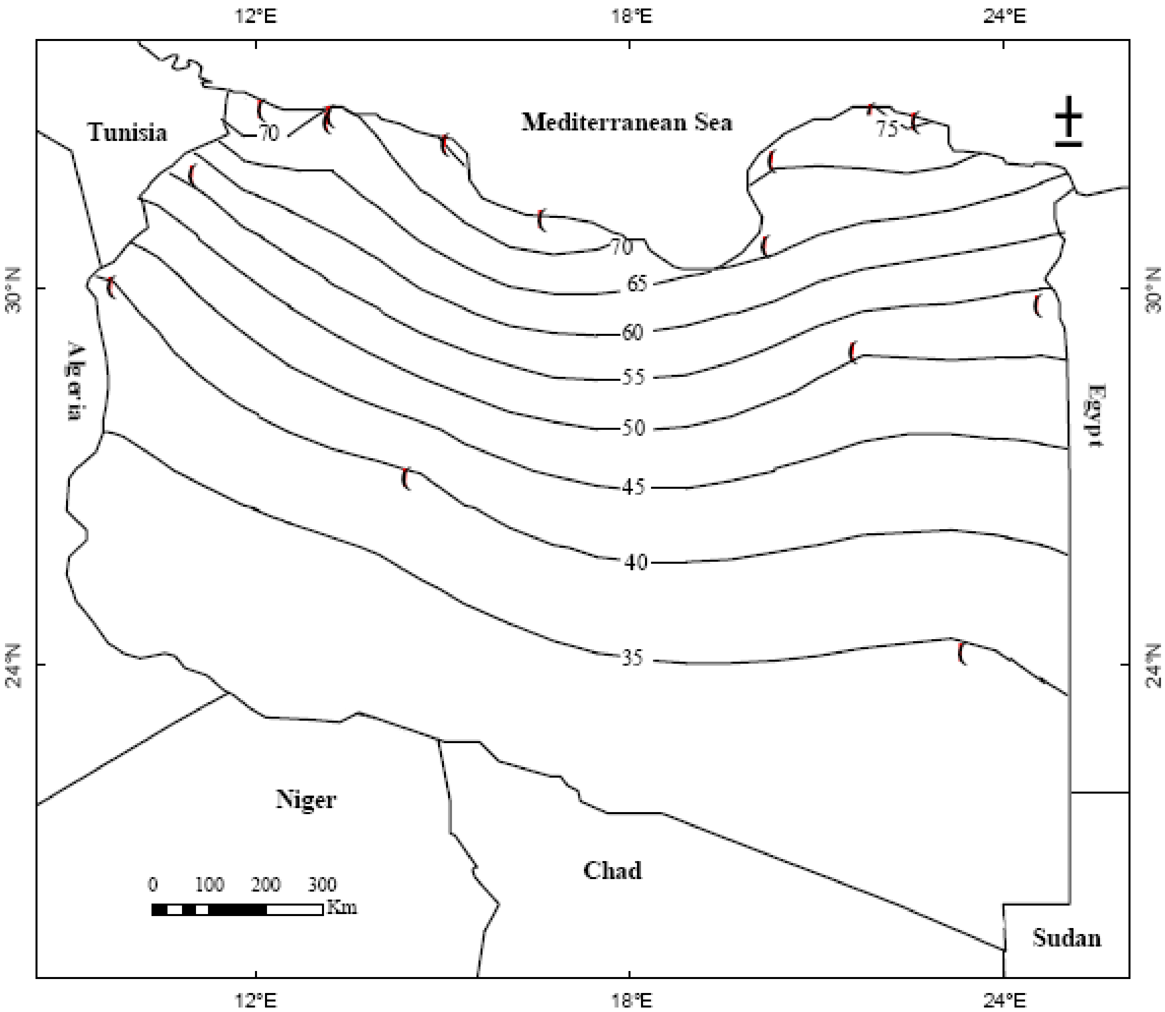


Fig. 3.3 Mean annual relative humidity (%) in Libya, 1946-2000

Tab. 3.2 Average Annual Climatological Data from Selected Stations

Station	Temperature ^{0}C					Relative humidity (%)	Evaporation mm (piche)	Sunshine (hours)	Wind speed (knots)	Rainfall (mm)
	Daily average	Average max	Average min	Abs max	Abs min					
Ghadamis	21.6	29.5	13.6	50.6	-8.0	33	5183	9.4	9.0	33.8
Nalut	18.9	24.3	13.4	44.4	-3.9	49	3182	8.8	8.5	157.2
Zuwarah	19.5	24.3	14.7	48.9	-1.1	73	1722	8.0	7.9	225.1
Gharian	18.1	23.1	13.0	44.8	-6.7	50		8.1		382.2

Tripoli	19.9	24.7	15.0	46.0	-0.6	63	1499	8.2	4.2	338.0
Sabha	22.6	30.1	15.1	46.5	-4.6	34	5668	9.6	9.3	8.8
Misratah	20.3	25.1	15.5	50.6	0.0	71	2090	8.4	6.9	276.7
Hun	20.7	29.1	12.2	47.2	-6.9	48	3921	9.3	7.4	30.3
Sirt	20.3	24.8	15.7	46.7	1.0	71	2244	8.9	8.0	177.7
Ajdabiya	20.3	26.5	14.1	47.4	0.0	62	2517	9.1	5.8	139.6
Tazirbu	22.3	30.1	14.4	47.3	-4.0	36	4341	10.2	5.3	2.7
Baninah (Binghazi)	20.0	25.4	14.6	45.6	0.6	65	2414	8.7	9.8	273.5
Jalu	22.3	29.6	14.9	49.1	-2.8	45	3647	9.5	6.7	9.8
Shahhat	16.3	20.8	11.9	42.0	-1.8	70	1927	9.0	10.1	572.6
Al Kufra	23.0	30.8	15.2	46.2	-3.3	30	6119	10.4	6.9	2.3
Jaghbub	21.3	29.0	13.5	47.5	-2.6	47	3290	9.5	6.7	11.1

Data source: Libyan Meteorological Department, Tripoli

3.4 Geologic setting

The geological map of Libya (1985) shows several main assemblages of basement rocks.

The Archean assemblage includes migmatitic and granitic gneisses with local intercalations of amphibolites and diopside – hornblende gneisses. It is restricted only to the Jabal Oweinat (Jabal Awaynat) area.

The Lower Proterozoic comprises medium to coarse-grained, strongly foliated quartz feldspathic gneisses with interbunded pyroxene gneisses, mica schists, phyllites, amphibolites, basic metavolcanics, graphite schists, quartzites, and conglomerates in the Jabal Oweinat of in the Tibesti Massif.

The Upper Proterozoic encompasses massive metamorphosed greywackes and feldspathic sandstone, with limestone, siltstone, mudstone, shale interbeds and conglomerate bands. This group of rocks is common in the Tibesti area in the southern Libya, in a very restricted area in the northwestern Jabal Oweinat, and in the Hoggar Massif in the southwest corner of Libya.

The older granite/granodiorite units are limited to the Tibesti area. Their age and stratigraphic position are not clear but they are believed to have been formed between 600-500 Ma (Tawadros 2001).

From the point of view of hydrogeology the Proterozoic and Paleozoic rocks represent hydrogeologic massif formed mostly by so called hard rock with strongly prevailing fractured porosity. In large regions, mostly of central and northern Libya, these old rocks are covered by younger sedimentary deposits and partly neovolcanic rocks. These sometimes very thick Triassic, Jurassic, Cretaceous and Cenozoic sequences form extended hydrogeologically important basins many times consisting of extraordinary important aquifers. Geologic conditions of this younger cover are described in detail in the following chapters dealing with groundwater issues of Libya and of the Jifarah Plain specifically (chapters 3.5.2, 4.3).

3.5 Water Resources

There are both surface and groundwater resources in Libya. Yet, due to the fact that no perennial water courses occur in Libya, the most important and feasible water resource is groundwater.

3.5.1 Surface water

Surface water is rather limited as it occurs only in temporary river beds where water flows only after heavy rains. Surface water contribution is assessed to be less than 3 per cent of the total water use for the different activities.

In order to better control these surface water resources, sixteen dams and several reservoirs were constructed for the collection of over 60 million m^3/yr. Natural springs of low to medium discharge provide water for different uses in the Jabal Al Akhdar, Jabal Naffusah and in the central zone.

3.5.2 Groundwater

Libya depends heavily on groundwater, which accounts for more than 97% of the water in use. Groundwater is withdrawn through wells ranging from a few metres to more than 1,000 m in depth.

Groundwater resources are either renewable or non-renewable. The renewable resources are formed by recent groundwater recharge. The respective aquifers belonging to various geologic units from Quaternary to Cretaceous ages are located mostly in the northern zones of Libya where higher precipitation rates occur. Still the estimated annual recharge of less than 650 million m^3 covers only relatively small part of the groundwater demand and use assessed more than 2,400 million m^3/yr. This imbalance has provoked a continuous lowering of groundwater levels accompanied by deterioration in water quality due to sea-water intrusion and invasion of saline water from adjacent aquifers, followed by other adverse features.

To solve the discrepancy between groundwater recharge and water use different measures have been taken to mitigate environmental and hydrogeological impacts of heavy groundwater withdrawals. One of them it the conveyance of non-renewable groundwater resources from the south of the country to the densely populated areas in the north. Some of the extended groundwater basins disposing with large volumes of non-renewable “geologic” resources are mentioned in the chapter 3.5.2.1.

3.5.2.1 Main groundwater units in Libya

The large sedimentary groundwater basins cover extensive areas in the central and southern parts of Libya. Groundwater contributes large quantities of freshwater for local use and agricultural development there.

Starting from the early sixties, groundwater resources can be broadly divided into extended basins or regions as follows: Jifarah Plain, Ghadamis-Hamada Basin, Murzuk Basin, Sarir and Kufra basins and Jabal Al Akhdar System (Fig. 3.4).

3.5.2.1.1 Jifarah Plain

The Jifarah Plain in the NW of Libya is the study area. For its detailed hydrogeologic characterization and analysis of various groundwater issues see chapter 4.4.

3.5.2.1.2 Ghadamis - Hamadah Basin

The Basin includes the northwestern part of Libya except for the Jifarah Plain. It is limited to the north by the Jabal Naffusah from Nalut to Al Khums, then its boundary follows the Mediterranean sea from Al Khums to Bin Jawwad. To the west the Basin passes into Tunisia and Algeria, to the east it borders at 18^{o} E with the Sarir Basin and to the south at 29^{o} N, immediately north of Jabal Hasawnah, with the Murzuk Basin.

The Basin Rainfall receives more significant amount of rainfall, ranging in average from 100 to 300 mm per year, only on the southern and eastern slopes of the Jabal Naffusah. The remaining area as Al Hamadah Al Hamra, western Sirt basin, except for a very narrow strip along the Mediterranean coast, receives less than 50 mm average rainfall per year.

The geology of this area is dominated by a series of heights and depressions. The basement occurs at the height of the Jabal Fazzan in the south where the sediments are reduced to Cambro-Ordovician sandstones and at Tawargha and Jabal Naffusah. Well developed Palaeozoic deposits form a synclinal structure of west direction and the Hun graben which forms a natural division between Al Hamadah Al Hamra and Sirt basins. The Mesozoic transgression penetrated deeply but gradually to the south over the whole area. Shallow marine to continental sedimentation prevailed during the lower Mesozoic, characterized by a series of sandstones and clay with some evaporitic intercalations in the western part of the area. Two peculiarities of the lower Mesozoic sedimentation should be mentioned: the dolomitic Aziziya Formation of the middle Triassic which plays an important hydrogeologic role under Jabal Naffusah and the Jifarah Plain and an abrupt change of facies from sandstone and clay to dolomite north of the latitude of Tawargha. From the Cenomanian up to the top of the Cretaceous the sedimentation becomes definitely marine with alternating limestones, dolomites and marls. The Tertiary deposits are well developed in the Hun graben and in the Sirt basin where evaporitic and carbonate sediments are predominant. In the Misrarah area the Miocene transgression penetrated only a few kilometres inland. Palaeocene sediments as marls and limestones cover Al Hamadah Al Hamra but have not any important function in the groundwater hydrology of the area (Pallas 1980).

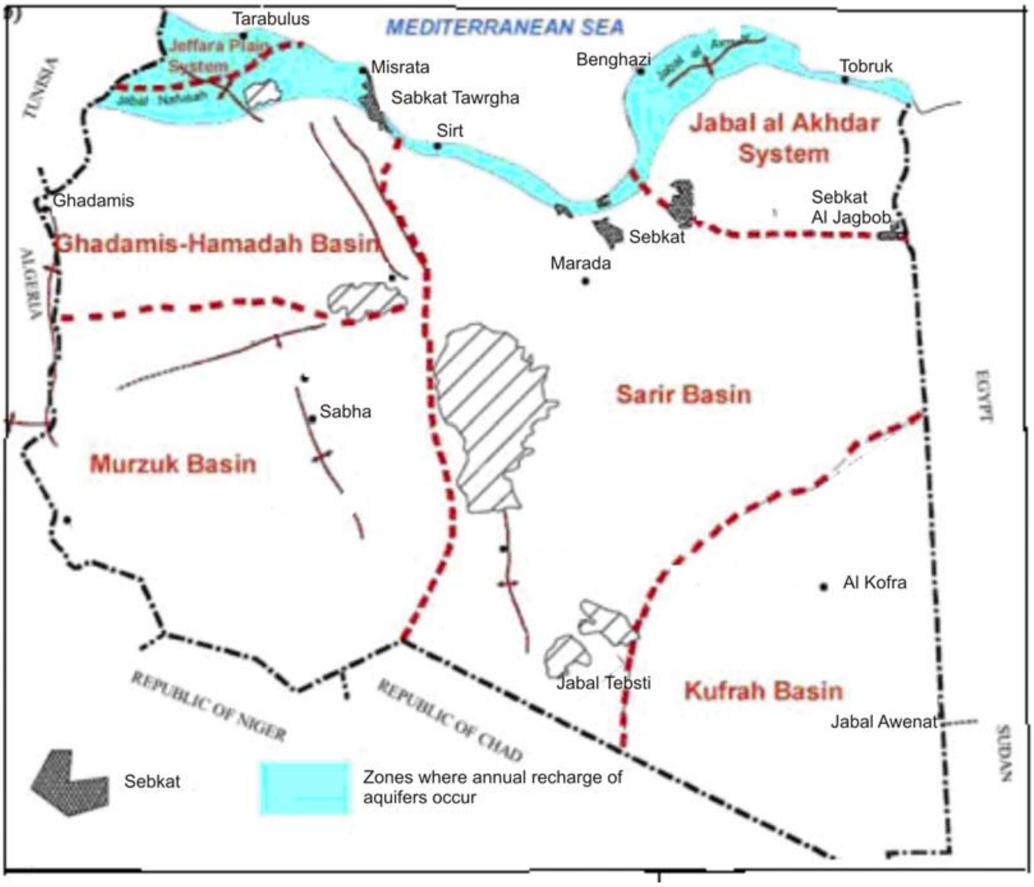


Fig. 3.4 Main groundwater basins (reservoirs) in Libya
Data source: Libyan Meteorological Department, Tripoli

3.5.2.1.3 Murzuk Basin

The Basin extends in the south-western part of Libya. Its northern boundary follows approximately the latitude 28^{o} N, corresponding to Jabal Fazzan –Jabal Hasawna area. To the east, extended Sarir Basin occurs and to the south and southwest the boundary of the Libyan part of the Murzuk basin forms state frontier with Niger and Algeria.

In this area negligible total annual rainfall ranging 10-20 mm is common. Rare rainstorms of occasionally high intensity may, however, produce such values in a single hour. These extreme rainfalls were observed in the areas of Brak and Ghat.

Groundwater reservoirs and geology of the Murzuk basin were studied by Pallas (1980) who distinguished two main groundwater reservoirs.

The lower groundwater reservoir is formed by Silurian-Devonian and Cambrian-Ordovician sandstone. Available piezometric data indicate a regional hydraulic gradient from the south to the north. A peculiarity of the lower reservoir is the dome in the piezometric surface corresponding to the Jabal Fazzan –Jabal Hasawna; if still active it might feed aquifers to the north and to the south of it.

The upper groundwater reservoir includes a continental formation of the Triassic, Jurassic and Lower Cretaceous, usually known as the Post-Tassilian and Nubian series. It consists of alternating clay, loose sand and sandstones forming the total saturated thickness of the reservoir more than 1000 m over a large area in the centre of the basin and its north-western part (Wadi Barjuj).

3.5.2.1.4 Sarir and Kufrah Basin

The area corresponds to the extended area of the central, eastern and south-eastern part of Libya. It is limited to the north by the depression marked by several sabkhas close to the Mediterranean coast. It forms part of an extremely large aquifer Megasystem, the Nubian one that along the western slope of Jabal Haruj and the eastern flank of Jabal Ghanimah to the east covers most of the Egyptian territory, the north-western part of Sudan and the north-eastern part of Chad. Respectively by the Egyptian, the Sudanese and the Chadian borders, to the west by long 17 30 E .

The coastal stretch a few kilometres wide receives approximately 100 mm of rainfall per year on average. The area located between Maradah, Jalu and Al Jaghbub receives an average between 15 and 30 mm. South of the 28^{th} parallel rainfall is negligible. Over the Tibisti mountains it is possible that average rainfall reaches values 25 to 40 mm.

South of the parallel of Tazirbu Al Kufrah basin is well delineated on its periphery by Palaeozoic outcrops composed mainly of continental sandstones. The central part of the basin extending more than 250,000 km^2 is occupied by Mesozoic continental sandstone outcrops occasionally covered by sand dunes or alluvial deposits. North of Tazirbu a Cretaceous and Lower Tertiary marine transgression overlies the Mesozoic and Palaeozoic sandstones. After the Eocene a continental environment was established. Post-Eocene deposits consist chiefly of sand, sandstone and clay with some limestone. In the Mesozoic sandstones forming the Nubian aquifers groundwater flows from south (Chad-Sudan) to north (As Sarir) and northeast (Egypt).

3.5.2.1.5 Jabal Al Akhdar System

This area covers the north-eastern part of the country, immediately to the north of the Sarir basin. It includes the Jabal Al Akhdar, its southern flank ending in the depression along latitude 30^{o}N and desert land up to the Egyptian border in the east.

The System reflects the morphological differences of both flanks of the Jabal: to the north, the valleys are short and deeply cut and reach the sea after tens of km; to the south, the valleys are wider and they progressively become large spreading zones at the breaking slope of the Jabal, where water evaporates.

Rainfall in the average ranges from 200 to 600 mm in the mountainous part of the area. To the south the precipitation becomes negligible along the southern limit of the area.

Fractured carbonate rocks of the Eocene and Miocene ages represent the main aquifers in the regional scale. A remarkable hydraulic gradient due to large difference in groundwater levels, reaching more than 400 m over short distances from the axis of the Jabal occurs both in the northern and southern directions. On the other hand, a more relaxed gradient exists at the eastern and western flanks (Pallas and Salem 1978)

3.5.2.2 Groundwater quality

Table 3.3 summarises prevailing groundwater quality, expressed in TDS, occurring in different basins and reservoirs as described in chapter 3.5.2.1.

The best quality in general has been found in the Murzuk basin, where in recently drilled wells and in some areas TDS reaches only a few hundred ppm – up to 250 ppm. On the other hand, groundwater from shallow well might reach even several thousand ppm.

Groundwater quality in the Sarir and Kufrah basins is always excellent as its TDS in the main aquifers usually ranges between 150 and 500 ppm.

Quite good groundwater quality prevails in the Jabal Al Akhdar region where TDS is typically between 500 and 1000 ppm. Groundwater of relatively bad quality usually occurs in the Ghadamis –Hamadah Basin where TDS is sometimes around 5000 ppm.

Tab. 3.3 Quality of groundwater basins / reservoirs of Libya

Basin	**TDS ppm**	**Basin**	**TDS ppm**
Murzuk		Ghadamis - Hamadah	
Lower reservoir		Mio-Pliocene-Quaternary	1000 - 5000
Wadi Ash Shati	300 - 500	Oligo-Miocene	2000 - 4000
Wadi Tanezzuft-Ghat area	150 - 250	Upper Eocene.	2000 - 5000
Upper reservoir		Upper Cretaceous	500 - 5000
Recently drilled wells	100 - 200	Lower Cretaceous,	500 - 3000
Shallow aquifers (dug wells)	1000 - 4000	Triassic and Palaeozoic	
Jabal Al Akhdar	500 - 1000	Sarir-Kufrah	
		Al Kufrah Projects	150 - 250
		Mesozoic Sandstones	< 500

3.5.3 Large-scale water management concept

Recently, several well fields were developed to supply the Great Man-made River Project (GMRP). When completed, the GMRP will supply more than 690 million m^3/day to the agricultural fields and population centres in the north. According to the hydrogeological studies, GMRP water will minimize the water balance deficits in the affected zones.

Non-conventional water resources in the form of desalination cover only a small portion of the domestic and industrial water demand. Treated sewage is still very limited and is mainly used for irrigation purposes.

4. Jifarah Plain

4.1 Location and extension of the Plain

The region of my study – the Jifārah Plain occurs in the north-western part of Libya (Fig. 4.1). It is a triangle-shaped region with its eastern apex close to the Al-Khums city. From this area westwards the northern and southern boundaries of the Plain move away. The Mediterranean coast bound the Plain in the north and the scarp of Jabal Naffusah represents its southeastern and southern boundary. To the west the Plain extends to the Tunisian territory. The length of the Plain between Al Khums and the Tunisian frontier is more than 250 km, its largest width reaches some 150 km in the west and the total area of the Plain is approximately 17,000 square km.

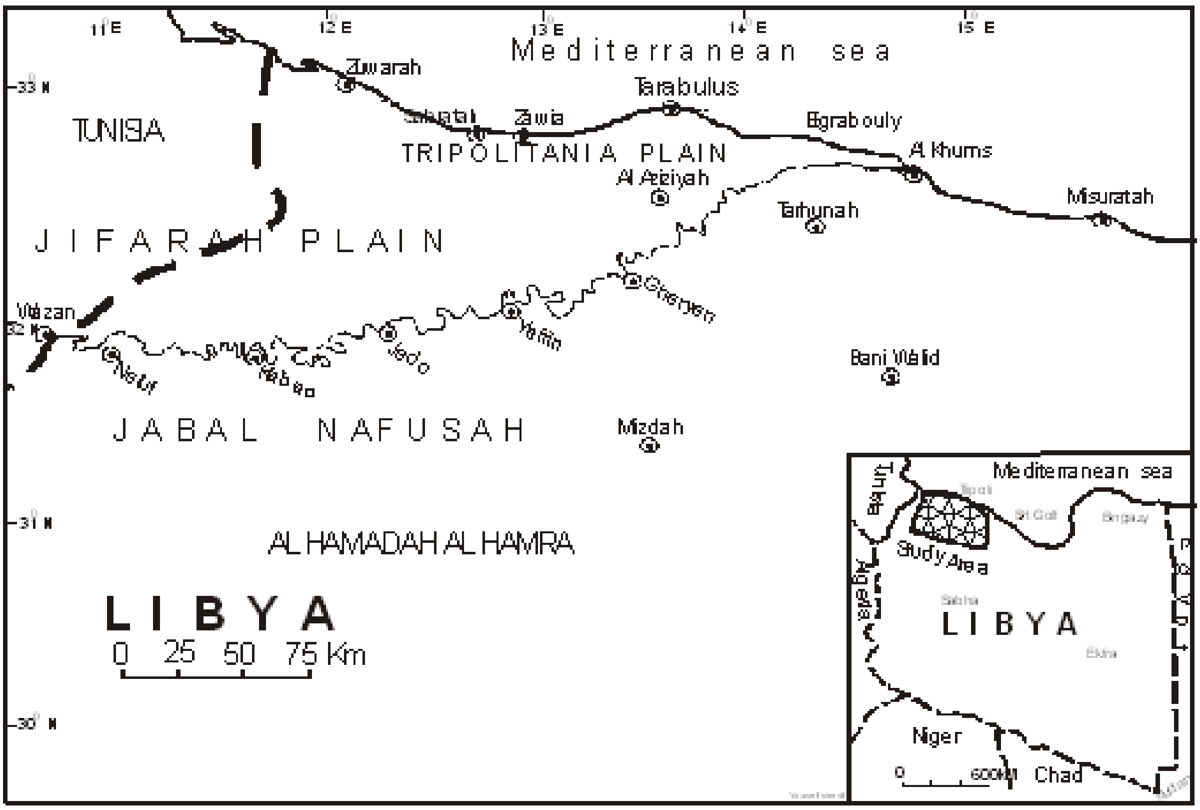


Fig. 4.1 Position of the Jifārah Plain in the NW Libya

4.2. Natural conditions important for hydrogeologic considerations

4.2.1 Geomorphology

The Jifārah Plain is a low-lying region with the land surface gradually rising from the Mediterranean coast southward to the foothills of the Jabal Naffusah where the altitude reaches 200 to 300 m. In this northern part of the Plain ("Littoral Plain") Tertiary and Quaternary deposits cover older formations. No perennial water courses occur in the Jifārah Plain but in the piedmont area of Jabal torrential streams incised deep wadi valleys gullying the surface, leaving in the southern part of the Plain steeply sloping outliers of outcropping older rocks ("Outlier Plain"). More to the south, behind the steep north-facing scarps of Jabal Naffusah, 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.

4.2.2 Climate and main elements of water balance

Climate of the Jifārah Plain is influenced by the Mediterranean Sea, which affects temperature and moisture conditions in the north, but passes into a typical desert climate to the south.

4.2.2.1 Temperature

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 Plain can sometimes drop to zero but summer temperatures might be extremely high as proved by the highest ever-recorded world-wide temperature 57.8 °C at Al-Aziziya in September 1922. In addition to seasonal differences important diurnal temperature changes were observed. Small general decrease in mean temperature at similar latitudes can be caused by different elevations - about 0.64°C/100 m.

4.2.2.2 Precipitation

Mean long-term annual precipitation decreases in general from more than 300 mm in the Tripoli and Garabulli area to the southwest to 150-250 mm. Higher values are once more recorded on Jabal Naffusah, up to 322 mm at Gharian. From there, precipitation once more decreases to the south towards desert (tab. 4.1, fig. 4.2). The driest part of the Plain lies at the Tunisian frontier where precipitation reach only 100 mm. Seasonal distribution is considerable as most of rainfall is recorded during 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 Naffusah piedmont zone to retain surface water. Open surface evaporation in the western part of the coast was assessed as 3,700 mm/year.

Tab. 4.1 Annual rainfall of study area

Station	FAO, 1985 mm/y	Pol-service, 1985 mm/y	MMD 1994 mm/y	From 1956-1985 mm/y	From 1993-2003 mm/y	Average mm/year	m/day $*10^{-4}$
Zuara	277	210	229		226.25	235.6	6.45479
Yifran	281	220	-	-	269.3	256.76	7.03452
Tiji	123	110	119	-	-	117.3	3.2137
Kabaw	147	120	157	-	-	141.33	3.8721
Zintan	209	205	216	-	-	210	3.753
Ber Elgnam	162	160	-	-	-	161	4.4109
Tripoli airport	290	300	288	301.2	243.4	284.52	7.7951
Tripoli city	-	-	-	-	372.34	372.34	10.201
Alaziziya	227	220	229	-	-	225.33	6.1734
Espea	-	-	-	-	339.38	339.38	9.0921
Garabulli	333	325	312	-	-	323.33	8.8583
Gaser Kyar	-	-	-	-	323.32	323.32	8.8583
Tarhunah	276	325	260	-	-	287	7.863
Bani walid	63	100	64	-	-	75.67	2.07315
Zleten	-	-	-	241	-	241	6.60274
Elajelat	-	-	-	221.7	-	221.7	6.0740
Garian	377	300	343	-	307.44	331.86	9.0921
Mizda	-	-	-	-	64.8	64.8	1.7753

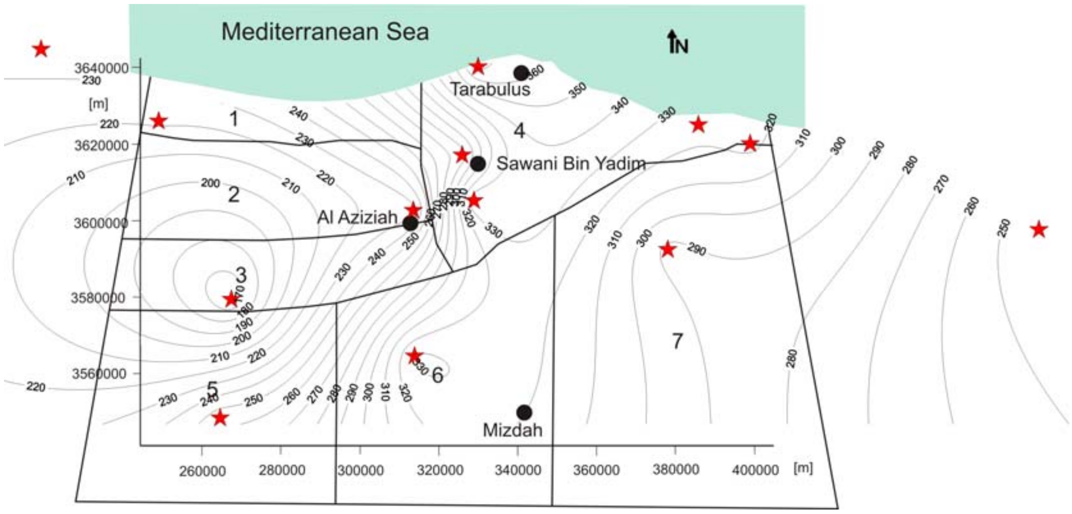


Fig. 4.2 Annual rainfall contour map(mm/y)

Legend: red stars – situation of the meteorological stations

4.2.2.3 Surface runoff

Part of the precipitation falling on the Jabal Naffusah escarpment reaches the Jifarah Plain as surface runoff through many seasonal wadis. Under natural conditions (without dams – tab. 4.2) the runoff water is partly evaporating and partly infiltrating in the spreading zones and this explains why so little water usually reaches the sea. Assuming that 50% of the runoff water can be intercepted this makes an additional resource of 100 Mm^3 /year. In the Jifarah Plain the average annual surface runoff is estimated to be 87.6 Mm^3 /year which represents about 5.2% of total rainfall, recoverable quantity 52 Mm^3 /year.

Tab. 4.2 Data for constructed dams

Names	Catchment area (km^2)	Average annual rainfall (mm)	Total capacity of the dam reservoirs (Mm^3)	Quantity to be retained (Mm^3/yr)
Wadi Al Mejinin	578.9	250	58	10
Wadi Ghan	650	262	30	11
Wadi Zarat	390	275	8.6	4.5
Total			96.6	25.5

Data source : El-Baruni (2000)

4.2.2.4 Evaporation

The average of annual evaporation rates from 1200 to 2100 mm in the coastal area and from 1500 to 3500 mm in the southern area.

4.3 Geologic setting

Main stratigraphic units occurring in the Jifarah Plain and their lithological composition are listed in Table 4.3.

Geologic structure differs considerably in the two main geomorphologic units – the Jifarah Plain and the Jabal Naffusah.

The Plain in its upper part is built up mostly by clastic Tertiary and Quaternary deposits increasing in thickness up to many hundred meters from the Foothills of the Jabal northwards. The youngest Quaternary deposits, usually up to several meters thick, consist of recent wadi deposits, beach sands, eolian and fluvio-eolian deposits and sabkha sediments. Tertiary and Quaternary complex is in the eastern portion of the Plain underlain mainly by Triassic Al Aziziya Formation (mostly limestones) and lower Kurush Formation (claystones and sandstones), both up to several hundred meters thick. Above them relatively thin Abu-Shayba Formation (Upper Triassic, mostly sandstones and claystones) thickens westwards.

Tab. 4.3 Stratigraphic units and their typical lithological composition

Stratigraphic units			Lithology
		Holocen	Recent wadi deposits: gravel, sand and loam; Beach sand: shell fragments, calcareous and silica grains; Eolian deposits: sand dunes and sheets, sandy loess; Fluvio-eolian sediments: silt and fine sand with occasional caliche bands; Sebkha sediments: sand, silt and clay with gypsum and salt
Gargaresh F		Pleistocene	calcarenite with occasional silt lenses
Jiffarah F			silt, sand and conglomerate with occasional gypseous and calcareous crust
Qasr Al Haj F			alluvial cones, proluvial cemented and non-cemented gravels with calcareous crust interbed
Al Assah F		Pliocene-Quaternary	silt, sand and gravel with local occurrence of recrystallized gypsum
Volcanic rocks			basalt flows, cones and dikes, phonotite intrusions
Al Khums F		Miocene	limestone, algal limestone, lumachelle, calcilutit, calcarenit and clay
Qasr Tigranah F		Upper Cretaceous: Cenomanian-Turonian	marl and limestone, partly dolomitic
Nalut F		Upper Cretaceous: Cenomanian	limestone, dolomitic to dolomite with occasional quartzite and quartz sand intercalations
Sidi Al Sid F	Yafrin M		marlstones
	Ain Tobi M		limestone, dolomitic to dolomite with occasional quartzite and quartz sand intercalations
Kikla F	Al Rajban M	Middle-Upper Jurasic: Bathonian-Titonian	sandstone and conglomeratic sandstone with minor clayey interbeds
	Shakshuk M		limestone with clayey and sandy interbeds
	Khasm Al Zarzun M		alternating clay and sandstone
Takbal F		Middle Jurasic: Bathonian	limestone with clayey and marly intercalations
Bir Al Ghanam		Upper Triasic Middle Jurasic: RhaetianBathonian	gypsum and anhydrite with dolomitic limestone bands

Abu Ghaylan F		Upper Triassic: Norian-Rhaetian	limestone, partly dolomitic, with marl and marly limestone interbeds
Abu Shaybah F		Upper Triassic: Carnian	sandstone and clay with minor calcareous intercalations
Al Aziziyah F		Middle-Upper Triassic: Ladinian-Carnian	limestone, dolomitic with chert intercalations, sandstone and phosphatic bands occur near top
Kurush F		Middle Triassic: Ladinian	clay and micaceous sandstone

Notes: F =formation
M=Member

Several other formations, again covered by the Tertiary and Quaternary complex, occur in the western part of the Plain. These are Abu Ghaylan Formation (Upper Triassic limestones) and the sequence of Upper Triasic to Jurassic deposits: from below Bir Al Ghanam Formation with prevailing gypsum and anhydrite, Takbal Formation (mostly limestones) and Kikla Formation consisting of three members formed by clastic deposits and limestones. Somewhere thin layers of Cretaceous deposits occur there.

Relatively thick Cretaceous formations, however, typically occur in the ***Jabal Naffusah region*** where particular formations can reach up to one hundred meters or even more. The Cretaceous is represented from below by the Sidi Al Sid Formation, consisting from lower Limestone Ain Tobi Member and upper marly Yafrin Member, and Nalut and Qasr Tigrinah Formations, both with prevailing limestones. In 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 Plain is Al Aziziya west-east trending fault that divides thick Tertiary-Quaternary sequences to the north of it and only thin Quaternary deposits to the south. Parallel to Al Aziziya fault Coastal fault occurs more to the north. Possibly also the boundary between the Jabal Naffusah and the Plain, expressed as a conspicuous escarpment, has been pre-disposed by a fault. Several authors suggest that other faults occur in the Plain, mainly of NW-SE strike, but these do not seem to be hydrogeologically important (IRC 1975, Pallas, 1978, 1980)

4.4 Hydrogeology

4.4.1 Review of previous hydrogeologic studies in the Jifarah Plain

The previous studies (Cederstrom and Bertiola 1960) carried out in the north-west of Libya (Jifarah Plain) reported some metres drawdown of groundwater level and small changes in groundwater quality. During the interval 1930-1960 drawdown near the Mediterranean coast has reached 2 m. In the Ben Gashir region it was 13 m with approximate 1 m drawdown during the last four years in the mentioned period (1930-1960). TDS of groundwater from shallow “surface” wells reaches between 200 and 1000 ppm, from deeper “piezometric” wells 2000-4000) ppm. The study identified a pollution of the surface groundwater reservoir in various regions along the coastal strip of the Tripoli region.

The groundwater study in the Zahra – Nasria-Aamaria region (Bertiola 1961) identified a 5.5 m drawdown in groundwater level during 1930-1961 period and TDS contents 456 ppm in the Aziziya region and 2010 ppm in the Aamaria region.

In the Surman region the drawdown of about 5 m and in Reito about 2m/year caused sea-water intrusion in the shallow wells (Oilli, Vorhis and Russo 1962).

Similar situation was reported in different coastal areas where saline groundwater pollution was caused by groundwater withdrawals and consequent sea-water intrusion as e.g. in the Mayia region with groundwater drawdown 0.3-0.5 m/year (Ogibee, Novarro, Dghies 1962), in the Zawya region with drawdown 0.2-0.4 m/year (Ogillbee, Vorhis and Tarhuni 1962) and in other regions in the vicinity of the sea coast as in Musrata, Zleten, Alkoms, Tripoli and Suprata (Novarro 1975).

The studies of FAO (Floejel 1979) focused on water management of the Jifarah Plain identified sea-water intrusion in coastal areas, too. The drawdown in groundwater levels was determined about 0.5-3 m/year during 1975-1990 in the Tripoli region (Fatice 1992). Decline in groundwater levels 0.5-8 m/year was reported also in the Abusheba deep groundwater reservoir of the Tripoli region, with TDS 800-3000 ppm (Elfatice, Elmajarab 1992).

Radioisotope injection tests were carried out during 1971-1972 in the regions of Bengasher, Tajoura and Zawa. Tests in 8 selected wells out of 23 wells were interpreted as represented in Table 4.4. It shows varied productivity range from 0.06 m^3/m^2 in Joudaim region to 0.32 m^3/m^2 in Beralgnamm, storage coefficient between 0.0001 in Joudaim to 0.03 in Beralganm. Transmissivity varied from 1.07 m^2/hr in Joudaim to 41.63 m^2/hr in Ben Gasher and TDS in groundwater between 413 in Ben Gasher to 2275 ppm in Beralgnam region (Hzaa, Talha, Eskinji, El Amari and Soulem 1972).

Tab. 4.4 Conclusions of radioisotope injection tests in the coastal region (after Hzaa, Talha, Eskinji, El Amari and Soulem 1972)

No.	Position of the well	productivity m^3/m^2 land	storage coefficient	transmissivity m^2/hr	TDS ppm.	Tritium (tritium unit)	speed of flow
1	Tajura	0.03	0.001	17.01	434	229 + 12	
2	Elmalaha	0.10	0.0001	3.54	273	235+12	
3	Joudaim	0.06	0.0001	1.07	805	296+13	
4	Beralganmm	0.32	0.03	26.98	2275	259+ 12	
5	South Elass area	0.12	0.002	17.98	1260	238+ 12	Speed =1. 25 m/d
6	Bengasher	0.03	0.001	41.63	413	236 + 12	

In the Elhadpa area about 8 km to the south of the Tripoli city a project tested possibilities of waste water use after its treatment. The study, carried out in 8 wells of the project area identified increased contents of salt in the waste water of Tripoli city due to sea-water intrusion that reached TDS up to 18,000 ppm, with the yield between 15 and 20 m^3/hr and water level between 30 and 45 m below the land surface (Elgadiem, Elryani 1992).

In the Ben Gasheer region situated some 32 km to the south of the Tripoli city the study of Elbarouny, Elfatissi and Elmajarap (1993) reported that the shallow aquifer, used by drilled wells since 1957 had been dried up in the first of 80-ties. Later the second deeper Miocene aquifer, used by farmers of the region, was studied with the intention to use its groundwater for a bottle plant. Chemical composition before and after treatment is compared in Table 4.5. It was found out, however, that the drawdown of groundwater level of this Miocene aquifer reaches 4 –6 m/y, so that the TDS. of the groundwater would increase and in the future this aquifer might be dried up.

Drawdown of the groundwater level and consequent impacts for the groundwater resources in the Tripoli area has been observed in monitoring wells tapping particular groundwater reservoirs and reaching to different depths from 30 to 750 m. In the shallow reservoir groundwater level decline in range 0.5 - 3.5 m/year, the process that has been usually increased during time.

Tab. 4.5 Hydrochemical analyses before and after the treatment of groundwater from the Miocene aquifer (after Elbarouny, Elfatissi and Elmajarap (1993)

Concentration of salt mg/l	Before the treatment (1990)	Before the treatment (1993)	After the treatment (1990)	After the treatment (1993)
TDS	624	794	177	244
Sodium	80	108	17	24
Potassium	4	6	1.5	3
Magnesium	43	49	7.9	24
Calcium	65	69	8	31
Solvate	130	166	18	77
Bicarbonate	213	253	30	91
Chloride	140	159	35	53

Very high drawdown in groundwater level more than 2 m/year is evident in the shallow reservoir in the regions Ayn Zara, Bengasher and Elswany. Yet, some of the wells, which occur along the coast, have shown increase in water level in some years, evidently due to the effect of sea-water intrusion.

There are few wells in general having monitored continuously deeper aquifers. Observed groundwater level decline was between 1.0 and 3.5 m/y, and it has usually increased due to the groundwater overdraft (Elfatisy 1993).

Important hydrogeological study was carried out in the Elswany region situated about 6 km to the south of the Tripoli city (Elbarony, Hhensher 1993). Elswany well field, supplying Tripoli city, consists of 52 wells, 42 of them drilled during 1975 – 1978 and 10 wells later during 1989 – 1990. All of the wells penetrate the shallow groundwater reservoir reaching the depth between 58 and 147 m.

Groundwater level decline more than 0.5 m/year in the well field and even larger declines observed in various areas of the shallow reservoir in the Jifarah Plain, reaching up to 2-6 m/year, have caused intensive sea-water intrusion toward the south. Consequently, contents of most of the components in groundwater increased dramatically so that the water from the

Elswany field does not comply with the drinking water standards. As can be seen from tables 4.6 and 4.7, comparing chemical analyses from the period 1976 – 1977 and from the year 1993, contents of sodium increased during the 16 years from some 50-80 mg/l up to 3,300 mg/l and of chlorides from 50-100 mg/l even up to 6,000 mg/l in some wells. Increase had been proved also in concentrations of other components as calcium, magnesium and potassium. Small decrease is, on the other hand, evident as to the bicarbonates.

Tab. 4.6 Chemical analyses of groundwater in the Elswany well field from the years 1976-1977 (after Elbarony, Hhensher 1993)

well No	pH	EC mS/cm	TDS mg/l	calcium mg/l	magne-sium mg/l	sodium mg/l	potas-sium mg/l	bicar-bonate mg/l	solvate mg/l	chlorate mg/l
56	6.9	578	340	43	4	58	3	165	72	74
52	8.2	604	390	42	21	73	-	173	40	106
58	7.7	489	300	35	6	48	2	171	57	50
2A	7.0	574	415	60	15	65	-	175	78	85
4A	7.6	777	467	48	26	78	-	179	96	52
3B	8.0	819	594	49	29	118	-	185	124	138
7A	7.2	-	380	56	15	67	-	189	-	77
13A	7.0	539	330	41	6	57	3	183	82	53
75	7.8	785	540	57	34	-	-	194	-	107
77	6.8	867	520	51	10	80	3	204	105	11

Tab. 4.7 Chemical analyses of groundwater in the Elswany well field from the year 1993 (after Elbarony, Hhensher 1993)

well No	pH	EC mS/cm	TDS mg/l	calcium mg/l	magne-sium mg/l	sodium mg/l	potas-sium mg/l	bicar-bonate mg/l	solvate mg/l	chlorate mg/l
56	7.4	9530	5848	272	214	1750	21	146	427	3400
52	7. 3	16350	11042	384	408	3300	40	140	1234	6000
58	7.8	1104	612	32	41	105	4	146	52	218
2A	7. 6	8980	5546	272	194	1550	20	142	240	3200
4A	7.6	3940	2393	200	101	510	9	138	250	1160
3B	7. 5	9360	5980	256	194	1750	23	142	412	3400
7A	7.5	962	583	72	27	94	3	152	163	142
13A	7.3	16150	10788	416	370	3200	72	148	993	6000
75	7.9	4980	3142	166	124	820	9	136	278	1600
77	8. 2	3960	2421	128	49	660	10	154	89	1240

Because of the continuous decline of groundwater levels in the shallow reservoir in the regions Alwady Elshargy, Ber Elousta Milad and others and of drying up some wells, deeper wells, usually having reached 200-250 m, had been driven with the aim to tap groundwater in the Miocene reservoir. Consequently, groundwater levels of the Aboshayba aquifer have been lowered in these regions for more than 8 m (Elftisse, Gambrlou, Elalagy 1997).

Several studies have been focused directly on the sea-water intrusion issues in the North West of Libya, based on hydrogeologic data inventory, field reconnaissance, laboratory analyses of water samples to know time and space variability in groundwater TDS and chemical composition and on model implementation. The main results of these studies can be summarized in the following way:

1) In the Zawia region. Sea-water intrusion was identified about 3 km from the sea coast to the south in the Elharsha and Jouddaum region. In the regions Elajelat, Suprata, Surman it was difficult to limit the intrusion due to the occurrence of saline deposits in many areas. The intrusion about 3 km to the south in Elajelat region was estimated.
2) In the Tripoli region sea-water intrusion extended into the shallow groundwater reservoir differently in particular areas: it reached about 8 km in the northern part of Gargarsh region, where from the Elswani well field water is delivered to the Tripoli city, some 7 km in the eastern part of the Tripoli region, 6 km in the Tajura region and 2 km in the Maya region.
3) In the Elkums and Zaliten region: A – in the western part of the region no sea-water intrusion was identified in the Elalous section but could be in the Garaboli section. B – in the eastern part of the region in sections Soug Elkamis, Zaliten, Zawit Elmahajop shallow aquifer consists of fractured limestone. Some fractures of high hydraulic conductivity can enable rapid groundwater flow and thus intensive sea-water intrusion for long distances. This results in large variability of groundwater quality and salt distribution differing from one water-well to others. A modulus in modeling of contaminant with variable density was used in three sections - Gargarsh, Elmaya and Tajwra. This modulus can be used to assess the distribution of salt in the future and to help control sea-water intrusion. The modulus was used by Sadek, Rasharash and Eshawsh (2002) to make a prognosis for the year 2025 in the three mentioned sections according to the present conditions.

The model was constructed to solve the groundwater flow and salt diffusion equations assuming a dispersive type of equilibrium between saltwater and freshwater. The two-dimensional version of the SUTRA model was used in the study. Numerical assessment of the problem has been accomplished by the sequential use of 2-D first; an areal depth integrated 2-D flow model was applied to calculate the head distribution in the region under steady-state conditions. In the second stage, these results were used as input data in a density-dependent cross sectional finite element model to simulate the coupled mechanism of seawater intrusion.

At Ayn Zara, in the Tripoli coastal aquifer, modelling of underground oil fuel leakage was carried out by Ghazali, Sadeg and Sheikh Ali (2001). A mathematical model using the three dimensional Heat and Solute Transport code (HST3D) was developed to simulate an underground oil fuel leakage at Ayn Zara, the suburb east of Tripoli on the Mediterranean coast. The oil leakage probably started approximately in 1973 and continued up to 1995.

The model was used to solve the issues of groundwater flow, contaminant transport and sea-water intrusion. It was calibrated for steady-state conditions in 1957 and for transient conditions in 1972 and 1994 for both flow and salinity concentration. The model was further used to simulate the ground flow, salinity and contaminant transport up to year 2010 based on present conditions and using pump-treat-and-inject remedial action plan. Simulation results revealed the extent of sea-water encroachment and the oil plume spread up to 1995 and predictions up year 2010 for both existing conditions and remedial action plan.

Assessment of sea-water intrusion in the Tripoli region by numerical modelling was made by Sadeg and Karahanoolu (2001). The study area is located in the northern coastal part of the Jifarah plain and forms an almost rectangular area between the Mediterranean Sea and the cities of Swani and Bin Gashir in the south.

Numerical research was introduced in this study to investigate the problem of sea-water intrusion into coastal aquifer along the Mediterranean coast of Libya. Characteristics of the intrusion mechanism and its spatial and temporal variation, as well as its future behaviour, were thoroughly investigated by means of a two step numerical model.

A proposed simulation algorithm required two steps modelling that could be treated as quasi – three–dimensional approaches. First a vertical integrated flow model was applied to calibrate the physical parameters for definition of the flow mechanism, and the initial conditions for flow were evaluated accordingly. Second, the cross section model was utilized to incorporate the diffusion and hydrodynamic dispersion into the fresh water phases via a transient calibration scheme. Afterwards, the simulation was progressed through time in order to evaluate the aquifers temporal response to the foregoing conditions. This was accomplished utilizing the coupled behaviour of the fresh water flow and the salt transport mechanisms that occur in coastal aquifers.

Steady state calibrations with data reported for the 1950 and the history matching period 1950-1993 were found to successful physical parameters and recharge values were appropriate to be used in modelling the sea-water intrusion in the coastal aquifer of Tripoli. Transient simulation, which started with unpolluted initial conditions, reached a steady-state with respect to well discharge in the 1950s, which could be success fully matched with observed data.

Transient simulation runs have shown that the aquifer in the Tripoli region is over-pumped particularly in the last 20 years, too much groundwater has been extracted, inevitably, this has accelerated future predictions clarify that discharge from the aquifer should be properly managed, as this is the only water resource for the region. Migration rate of the intrusion could be reduced by thorough investigation, and by planning new management policies for optimal use of fresh water in the aquifer.

4.4.2 Main hydrogeologic units, groundwater flow and quality

Previous authors (e.g. Krummenacher 1982, Mott. Mac Donald 1993, Sadeg-Karahanoglu 2001) usually defined groups of important aquifers, occurring in the Jifārah Plain and adjoining Jabal Naffusah with elevated Plateau, based on their stratigraphic position, as follows:

1) Miocene-Quaternary Group,
2) Oligo-Miocene Group,
3) Cretaceous Group,
4) Jurassic Group,
5) Triassic Group.

Within these groups various hydrogeologic bodies, aquifers and aquitards, can be defined. Hydrogeologic properties of these bodies, main features of groundwater flow and delimitation of particular aquifer systems within the Jifarah Plain is discussed in detail in chapter 5 where conditions for implementation of conceptual and numerical models are defined.

As to groundwater quality, its natural properties in many parts of the Jifārah Plain and Jabal Naffusah was suitable for population and agricultural (small-extent irrigation and livestock) uses in general even though somewhere TDS reach several g/L. Groundwater salinity typically increases in areas with gypsum and anhydride occurrences where high sulphate and calcium / sodium concentrations is often high. Under extreme arid climatic conditions soil and water salinisation might occur as e.g. in sabkha areas due to long-term processes of water evaporation.

4.4.3 Changes in groundwater conditions due to anthropogenic impacts

Use of groundwater by human beings as the only available permanent water resource goes back to many hundred or even thousand years. Due to limited technical possibilities only hand dug wells had been used with only reduced groundwater abstractions.

In fifties of the 20th century changes of this ages-lasting situation started. Improved drilling and pumping technologies resulted in dramatic increase in number and depth of water wells and increase in groundwater withdrawals for municipal and industrial supply and agricultural activities. As proved in many reports (summary e.g. in General Water Authority, Secretary of Agriculture, Great Man Mad River Utilization Authority) such a heavy pumping in excess of recharge, i.e. natural groundwater resources formation, has led to continuous decline of groundwater levels in extended areas. This situation has continued until now and has caused changes in hydrogeologic conditions.

The most important consequences are following:

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

Decrease in piezometric head has changed 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 in extended areas. The influenced zones 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 relation between water balance elements (recharge-discharge). The most important is the implementation of the project of Great man-made river that supplies water from remote southern regions to Jifārah plain. In addition, increasing agricultural production has intensified return flow from irrigation. This might be positive from quantitative point of view but with adverse impact as to groundwater quality: contamination by fertilisers and pesticides would appear - increase in nitrates has been proved in many areas. Also leakage from pipelines in urbanised and industrial areas increase artificial recharge; depending on character of water losses, however, their effect on groundwater quality can be either positive (water-supply mains) or negative (sewage).

5 Methods of study, implementation of models

5.1 Available data, their reliability and GIS applications

At the same time with detailed study of previous reports and publications inventory of available hydrogeologic data from boreholes has been carried out. Two databases were created within the GIS MapInfo during the initial stage of data processing (Figs. 5.1, 5.2).

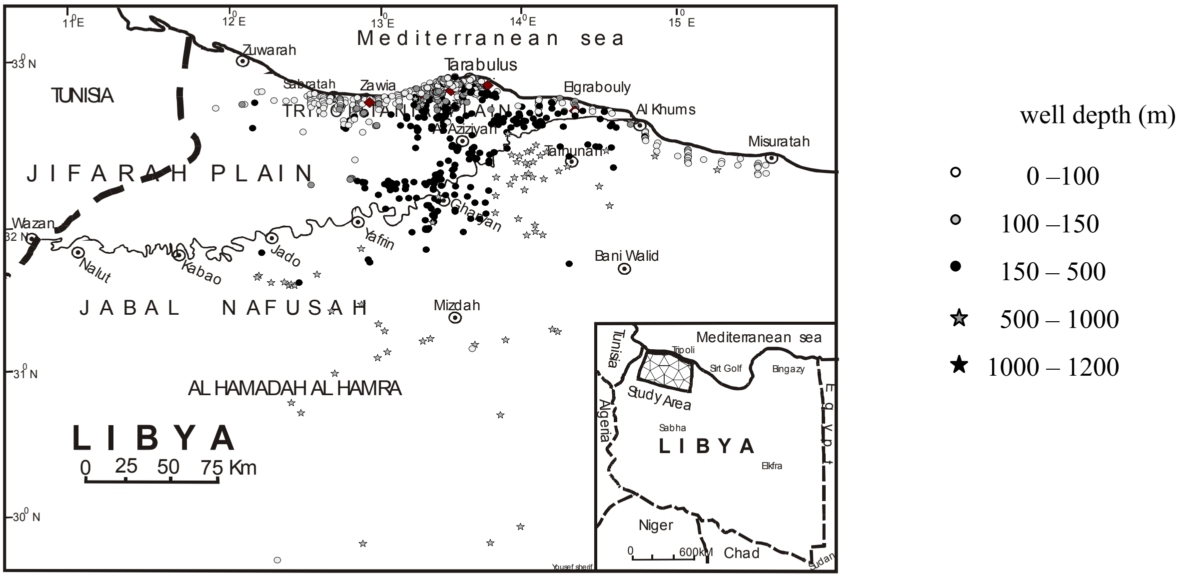
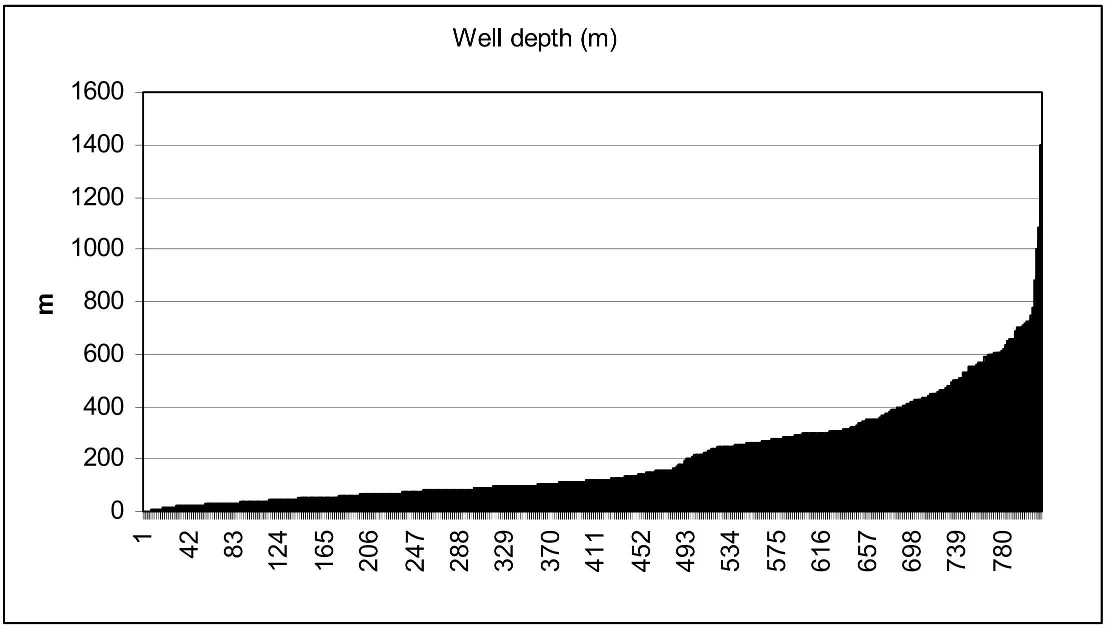


Fig. 5.1 Situation of hydrogeological wells and their distribution after the depths



The ***first database*** included ***technical data from 816 hydrogeologic boreholes*** drilled in the years 1970 - 2004. The set comprised only boreholes that could have been localized according to their geographic coordinates. The database contains parameters such as the borehole depth, characteristics of the tapped aquifer, borehole open section, data on static and dynamic groundwater level, exploited yields and values of transmissivity (fig.5.2).

The ***second database*** containing 512 data included basic ***chemical analyses of water*** (fig. 5.2), which were restricted to the content of basic cations and anions and were almost exclusively related to the coastal area.

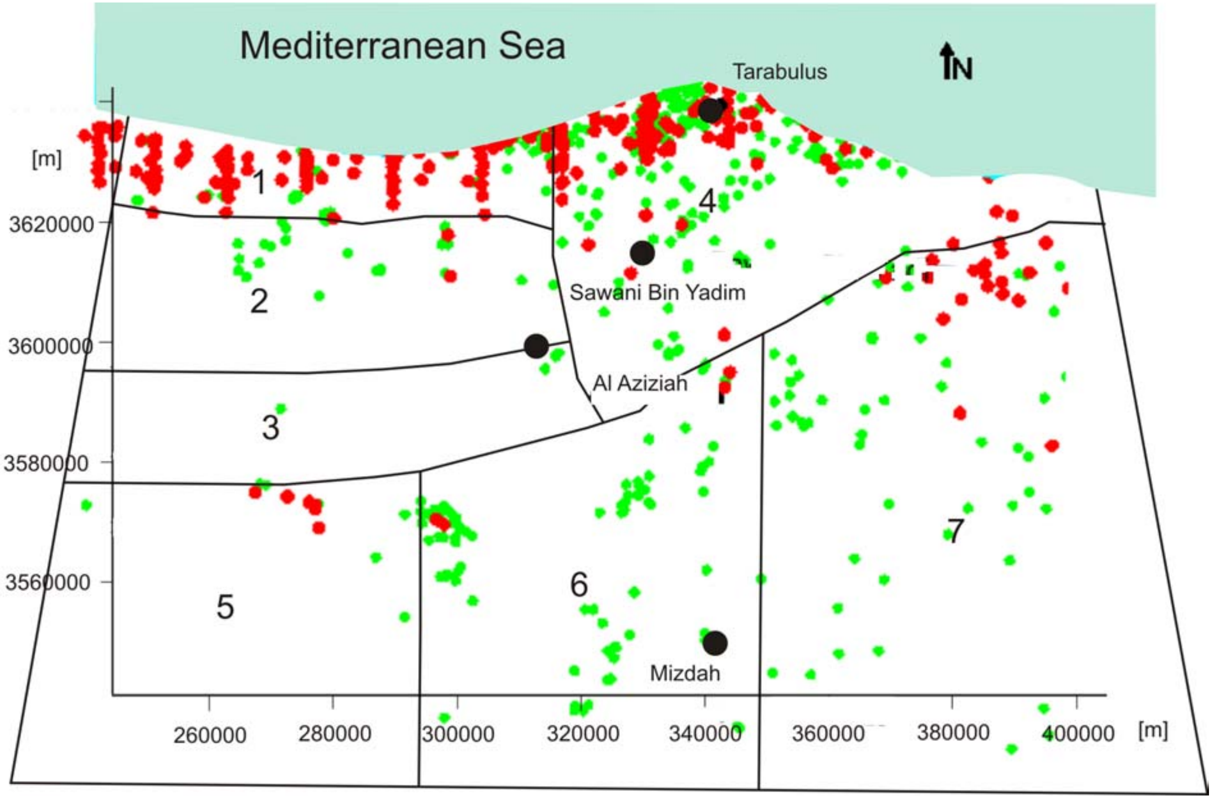


Fig. 5.2 Situation of boreholes differentiated after available data: green points with hydrogeological data and red points with hydrogeochemical data (geologic map as a background)

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 hundred meters but more than 200 boreholes were deeper than 250 m. The depth of five boreholes exceeded 1 000 meters (Fig.5.1).

Appendix E summarizes details on available hydrogeologic and hydrochemical data from boreholes

The analyses covered a period of 1975 – 2006 and represented mostly just one sampling, whereas repeated analyses were sporadic.

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

Based on available data different GIS layers were compiled to represent important hydrogeologic or hydrochemical features as e.g. piezometric surface, contents of particular components in groundwater etc.

In Appendix A1 the contour maps of hydraulic head in particular layers after changes under different terms are enclosed and in Appendix A2 the contour maps of changes in TDS concentrations in various periods.

5.2 Implementation of the conceptual model

On the basis of the available data conceptual and numerical models were implemented.

Conceptual hydrogeologic model as a starting point for numerical modelling, as described in chapter 5.3, is based on following ideas and considerations:

In the sequence of various lithostratigraphic units of different ages from Triassic to Quaternary, occurring in the Jifarah Plain (see Table 4.3), main hydrogeologic bodies – aquifers and aquitard were defined.

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

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

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

The youngest ***Tertiary-Quaternary deposits*** in the Plain are not consolidated and therefore of prevailing intergranular porosity. Fracturing occurs in zones where the deposits are indurated. Transmissivity typically varies in hundreds m^2/d but somewhere can reach even several thousands of m^2/d. Transmissivity variation might be generally less than in other hydrogeologic environments as nonidurated deposits as e.g. sands used to be hydraulically more homogeneous than fractured rocks.

Regarding the Tertiary ***basalt flows*** in the Naffusah Plateau no hydrogeologic data are available. After the experience from other countries, however, young lava flows can be well permeable at least in some parts and might play positive role in increasing recharge possibilities of aquifer systems.

Aquitards are represented by the Yafrin member of Sidi Al Sid Formation and especially by Bir Al Ghanam Formation.

Several ten meters thick marly Yafrin member with gypsum intercalations covers the lower Ain Tobi aquifer and confines its groundwater in the Jabal Naffusah.

Gypsiferous Bir Al Ghanam Formation crops out and is widely extended in the southern portion of the western part of the Jifārah Plain. It reaches thickness up to 300 m there. Gypsum occurs also in other units as in recent sabkha sediments (often together with salt), as recrystallised gypsum in Pliocene-Quaternary Al Assah Formation or forming gypseous crusts in Pleistocene Jifārah Formation. Gypsum occurrences might negatively influence natural groundwater quality.

Geometry of hydrogeologic bodies, i.e. their extension 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 (comp. chapter 4.2.1) between Al Aziziya fault and the Mediterranean coast Tertiary-Quaternary Aquifer Complex up to many hundred meters thick is underlain by deep-seated Mesozoic deposits. In some parts the Tertiary-Quaternary Complex is divided by impermeable plastic clay into upper Miocene-Quaternary aquifer and lower Miocene aquifer. In the southern ("outlier") part of the Plain between Al Aziziya fault and the Scarp of Jabal Naffusah Mesozoic deposits often crop out, overlaid by only thin layers of Quaternary sediments.

Generally increasing aridity from the east to the west is important for groundwater balance. In the east-west direction, also the character and extension of Mesozoic deposits changes considerably, causing differences in hydrogeologic conditions:

In the Eastern portion of the Plain (triangle-shaped area among Al Khums-Garabulli-Tarhunah) Jabal Naffusah considerably approaches to the Mediterranean coast.

In the Middle portion (Tripoli area - between connecting lines Garabulli-Tarhunah in the east and Surman-Bir Al Ghanam in the west) Tertiary-Quaternary Aquifer Complex is underlain mainly by limestone Al-Aziziya aquifer and partly by clastic Abu Shaybah aquifer. This portion is economically the most important of the whole Plain. Large quantities of groundwater have been withdrawn there.

In the Western portion (from the connecting line Surman-Bir Al Ghanam to the west up to the Tunisian frontier) widely extended gypsiferous Bir Al Ghanam Formation, both in outcrops and underlying parts of the Tertiary-Quaternary sequences considerably influences groundwater quality. Low rainfall makes this situation even worse.

Jabal Naffusah and Plateau Dahr are mostly built up by Cretaceous deposits and volcanic rocks.

In spite of the above-mentioned differences in distribution of the principal aquifers all the Jifārah Plain with adjoining Jabal Naffusah and Plateau is to be considered in a regional scale ***one extended hydraulically interconnected spatially complicated aquifer system***. This system reaches to the south up to the groundwater divide that separates the Jifārah-Naffusah aquifer system from the southern desert region (Ghadamis - Hamadah Basin – see chapter 3.5.2.1.2) where several endorrheic basins occur.

Hydraulic interconnection within the Jifārah-Naffusah aquifer system changes in space and time, depending both on distribution of hydrogeologic bodies and groundwater heads. General regional features of groundwater flow of the aquifer system 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.

Piezometric surface under natural conditions in all the aquifers generally inclines to the north. Hydraulic gradient might change considerably in upper parts of the system, mostly depending on differences in surface elevation. In deeper zones, hydraulic gradient is smoother in general.

Under natural conditions recharge took place only from rainfall and from surface runoff occurring in rainy seasons in some wadis. Previous authors assess direct average recharge from precipitation ranging between 60 and 125 hm^3/a, recharge from wadi runoff some 40 to 70 hm^3/a. As no effluent water courses 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. Part of groundwater recharged in Jabal Naffusah 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 structural setting, mainly by 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 meters connection between adjoining aquifers has not been interrupted.

5.3 Implementation of the numerical model

5.3.1 Previous models

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

Because the predictions declined from in situ measurements considerably in 1990, the model was remade in 1993 so that it includes impacts of the great man made river. Finite difference method was employed.

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

5.3.2 Model of natural conditions

In difference to previous models we focused on regional features of natural groundwater flow based on spatial identification of all-important hydrogeologic bodies as separately defining layers of aquifers and aquitards. Finite element method was used. Changes caused by human activities were then modelled using calibrated natural models influenced by different groundwater withdrawals.

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

Areal extent of the model domain is depicted in Figs.5.1 and 5.3. The domain reaches from 800 m below the sea level up to the earth surface. Geological structure of the region is known down to about 1000 m below the sea level from a set of deep boreholes.

The exact shape and position of the boundary were defined according to the 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 western and eastern part of the domain boundary so that the normal component of the flow vector is zero

$$-K\frac{\partial u}{\partial x_i}\upsilon_i = 0 \quad \text{on } \Gamma_N, \boldsymbol{\nu}$$

Where K is the hydraulic conductivity, u is the hydraulic head, $\boldsymbol{\nu}$ 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, contains also the southern part of the boundary though some small non-zero inflow from south can be expected. Actually, it was found that even considerable values of inflow affect hydraulic head values in this domain very little. Zero discharge boundary condition was also prescribed at the bottom-boundary of the domain, where the water flow has been considered negligible.

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

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

The hydrogeologic environment consists of several formations. Concerning the hydraulic conductivity, particular formations had been assumed homogeneous and vertically anisotropic, with ratio $\boldsymbol{K_{horiz.}/K_{vert.}}$ = 5 or 10 depending on formation. This anisotropy might be caused either by differently permeable layers, i.e. aquifers and aquitards, or by distinct vertical and horizontal hydraulic conductivity in particular aquifers.

The domain was divided into seven subdomains due to different geologic settings of western and eastern parts of both Jifarah plain and mountain range, and the presence of three big tectonic zones - the coastal fault, the Aziziya fault and the escarpment, which borders the mountain range. The subdomains 1 to 3 cover the western part of the Jifarah Plain where the two important faults – the coastal and Aziziya ones occur. The narrower eastern part of the Plain up to Al Khums belongs to subdomain 4. The remaining subdomains 5, 6 and 7 occupy the mountainous region to the south of the escarpment; their southern reach coincides with the limit of the study area. According to its geological structure, each subdomain was divided into a set of horizontal layers. The defined subdomains are represented in Fig. 5.3.

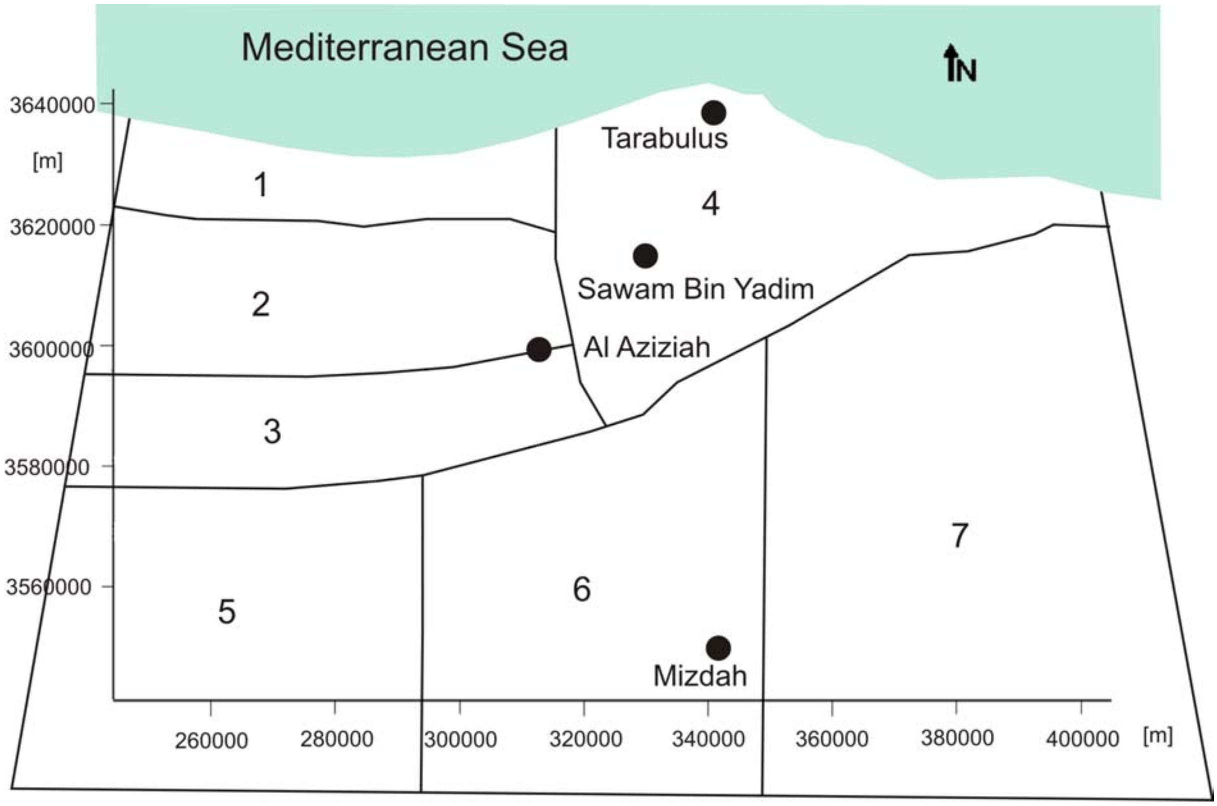


Fig. 5.3 Model domain and position, numbering and boundaries of model subdomains.

5.3.3 Numerical modelling

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

The differences in hydrogeologic character of particular lithostratigraphic units over the region and in their depth below the land surface required defining 26 numerical layers of triangular prism elements. Each layer spans the whole areal extent of the domain, representing part of real geologic / hydrogeologic environments (Table 5.1).

Hydraulic parameters of each layer are not constant and vary depending on subdomain (for examples see Table 5.2). The geometry of the subdomains was chosen so that parts of the subdomain boundaries represent some of the tectonic zones mentioned above. 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.

Table 5.1 Representation of selected lithostratigraphic / hydrogeologic 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 – Yafrin, AT – Ain Tobi, AR – Ar Rajban, KI – Kikla, TB – Takbal, BI – Bir Al Ghanam, AS – Abu Shayba, AZ – Al Aziziya, KU – Kurush.

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

Tab. 5.2 Representative values of hydraulic conductivity of lithostratigraphic / hydrogeologic units obtained by calibration of the model of natural conditions

Lithostratigraphical / Hydrogeologic unit	Hydraulic conductivity [10^{-4} m/s]
Quaternary	10.1
Yafrin	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

The top boundary of the domain represents free groundwater table and therefore is movable. Groundwater level data from suitable boreholes, which tap the most important aquifers in the study region, were used to calibrate the steady-state model.

Total groundwater extraction was estimated and distributed to XY subregions according to data in El Baruni et al. (2004). Due to return flow, inefficient irrigation, etc., the model has been calibrated to match groundwater levels in observation points. Available data on these points are listed in tab.5.3 and their location in fig. 5.4.

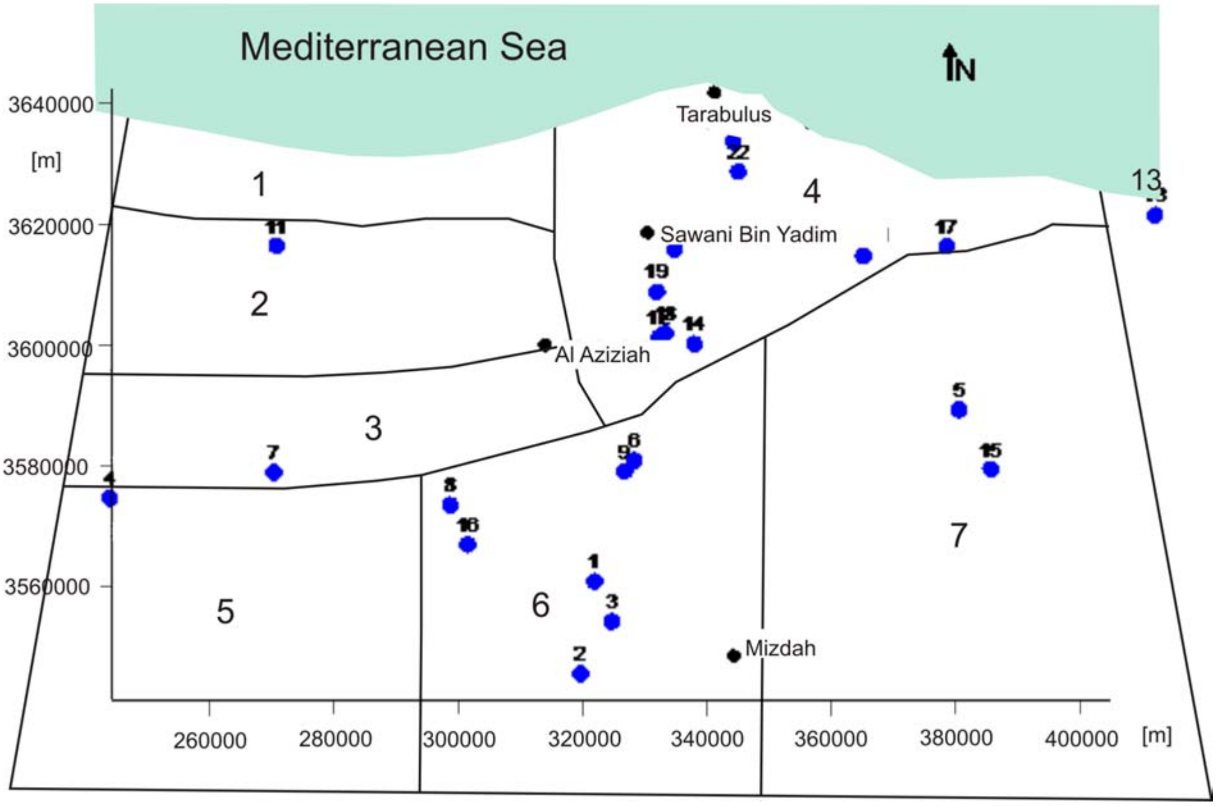


Fig. 5.4 Location of observation points (details of points are given in tab 5.3)

Tab. 5.3. Information on observation points

Point no.	Borehole no.	Open screen altitude [m]	Hydraulic head (observed) [m]	Model layer no.	Subdomain no.
1	T/1/0191/78	293.6	303.52	6	6
2	T/1/0169/76	320	118	6	6
3	T/1/027/80	194	297.55	8	6
4	T/1/0218/93	95.7	84.9	11	3
6	T/1/0118/78	43	77.52	13	6
7	T/1/0245/78	59.5	81.57	13	3
8	T/1/0150/78	48	80.04	13	6
9	T/1B/023/78	72	76	13	6
10	T/1/0210/78	0.1	11.1	14	4
11	T/1/0357/76	27	39	14	2
12	T/1/036/79	19	57.67	14	4
13	T/1/0157/77	-21.5	36.48	16	4
14	T/1/0130/81	-53	47.59	18	4
16	T/1/0145/87	-63	108	18	6

17	F-11	-48	56.4	18	7
18	T/1/0115/81	-80	42.77	19	4
19	T/1/0247/78	-121	41.18	20	4
20	T/1/041/77	-131	44.25	20	4
21	G-17	-158	55.47	22	4
22	T/1B/05/82	-264	39	24	4
23	T/1/041/77	-36	61.42	17	7
26	T/1/0179/77	-10	43.1	16	7

5.2.4 Current groundwater extraction and future water demand

In the Jifarah Plain deficit exists between water demand and water resources ("water supply"). The difference between these two parts of the water balance is expected to increase dramatically in the future (comp. tables 5.4, 5.5 and 5.7). Even after completing the project of the Man Made River, Phase no.2, with water supply from the southern parts of Libya to the Jifarah Plain, the deficit will remain (Table 5.6).

Tab. 5.4 Assessment of water resources (water supply) available in 2007 in the Jifarah Plain (in Mm^3/year)

Groundwater	200
Surface water	52
Unconventional sources	27.5
Man made river at present	109.5
Total	389

Tab. 5.5 Water balance – relation between water demand and water supply under present conditions (2007) and prognosis of its future development (in Mm^3/y)

	2007	2015	2020	2030	2040	2050
Water supply	389	389	389	389	389	389
Total demand	1547	1797	1956	2281	2617	2965
Deficit	1158	1408	1567	1892	2228	2576

Tab. 5.6 Water balance after completing the project of the Man Made River, Phase no.2, which will supply 2.5 Mm³/day to the Jifarah Plain

	2015	2020	2030	2040	2050
Water supply Mm^3/y	1192	1192	1192	1192	1192
Total demand Mm^3/y	1797	1956	2281	2617	2965
Deficit Mm^3/y	605	764	1089	1425	1773

Tab. 5.7 Estimation of groundwater extractions in the Jifarah Plain (Mm^3/year)

Date of estimation	1959-1962	1972	1975	1978	1978	1980	1993	1998	2003	2007
Author	USGS	GEFLI	GEFLI	SDWR	GEFLI	FAO	NCB, MMD	GPC	S.S.O	present study
Agricul-tural use	195	313	475	461	435	483	802	1478.8	1015	1285.7
Domestic and industrial use	15	65	92	94	97	91	200	198.2	245	233
total	210	378	567	555	532	574	1002	1677	1260	1518.7

Explanations:
USGS (United States Geological Survey)
GEFLI (France Company)
SDWR (Secretariat of Dams and Water Resources, now General Water Authority)
FAO (Food and Agriculture Organisation of the United Nations
NCB, MMD (National Consulting Bureau, and Mott. Mac Donald)
S.S.O (Sahara and Sahel Observatory)
Resources of census (Secretariat of Planning. Preliminary results of the general Census (in Arabic). Tripoli, 2006.

Domestic use was assessed according to the latest census conducted in 2006. In the Jifarah plain with the Jabal Naffusah population was 2,927,143 millions, in the study area it was 2,545,957 millions. The rate of population growth in 1995—2006 was 1.8.

Assessment was made assuming the average water consumption 200-300 litters per capita per day in delimited areas (see Table 5.8), as represented in Fig. 5.7.

Estimated groundwater abstraction for agricultural uses was made in the same areas as in the assessment of domestic use (Fig. 5.6). The respective data are listed in Table 5.9.

For estimated total water extraction within particular areas see Table 5.10.

Tab. 5.8 Groundwater abstraction for domestic use in 2007, assessed in delimited areas represented in Fig. 5.7

Area No.	% of abstraction	Mm^3/year
11	1.71	3.9843
12	0.8	1.864
13 ,14	84.89	197.7937
15	0.12	0.2796
18 ,17	1.93	4.4969
19	5.84	13.6072
20	0.45	1.0485
23	0.51	1.1883
22 ,21	0.7	1.631
9	0.26	0.6058
24	0.31	0.7223
2	0.18	0.4194
16	1.13	2.6329

On the basis of available groundwater extraction data it can be possible graphically estimate quite regular rate of groundwater abstraction between 1950 and 2007 (2010).

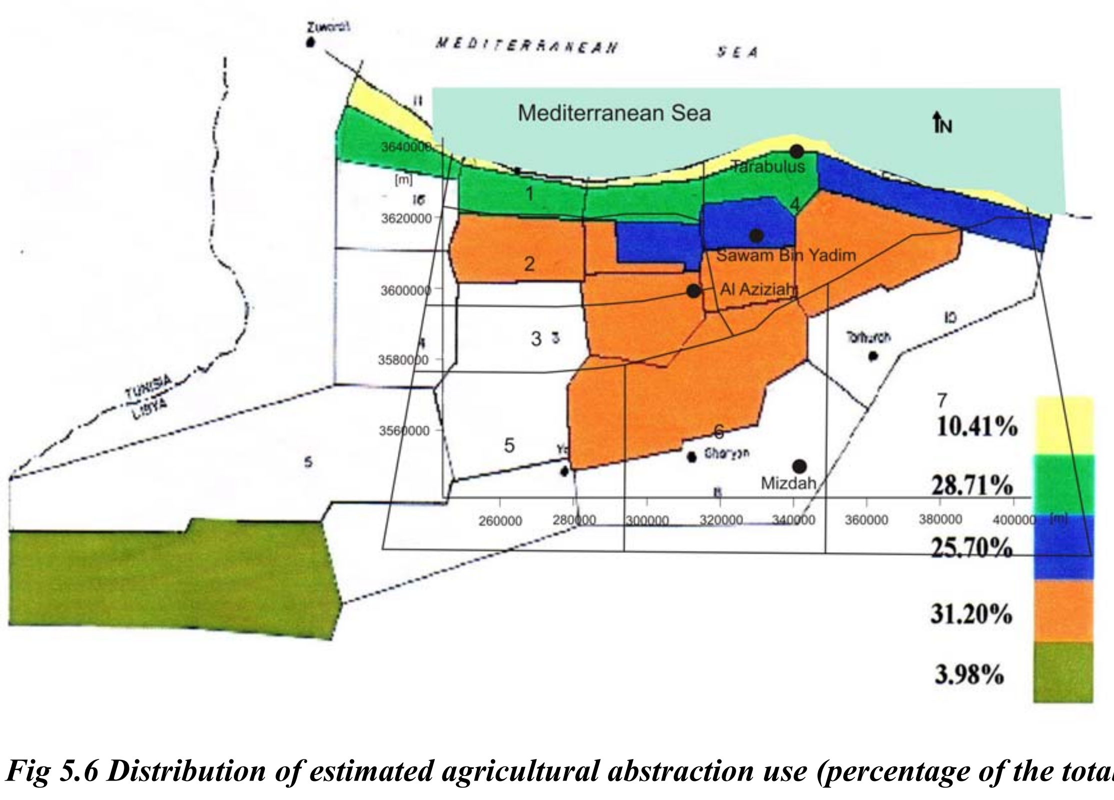


Fig 5.6 Distribution of estimated agricultural abstraction use (percentage of the total use)

(Source Mott Mac Donald,1994, El Baroni, et at ,2000)

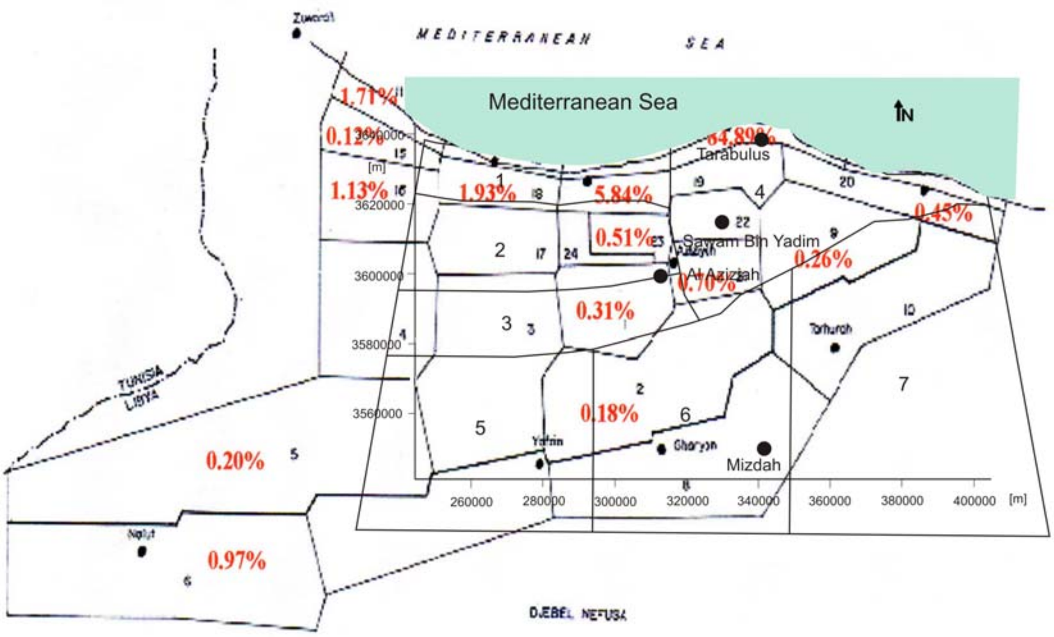


Fig 5.7 Distribution of estimated domestic abstraction use (percentage of the total use)

(Source Mott Mac Donald,1994, El Baroni, et at ,2000).

Tab. 5.9 Groundwater abstraction for irrigation in 2007 (assessed in delimited areas represented in Fig. 5.6 for total water use 1285 Mm^3/year)

Area No.	% of abstraction	Total [Mm^3/year]	Per area [Mm^3/year]
11,12,13,14	10.14	133.84137	33.4603425
15,18,19	28.71	369.12447	123.04149
20,22,23	25.7	330.4249	110.1416333
17,24,21,9,2	31.2	401.1384	80.22768
5,6	3.98	51.17086	25.58543

(Source Mott Mac Donald 1994, El Baroni, et al. 2000)

Tab. 5.10 Total estimated abstraction in delimited areas in 2007

No. of area	Irrigation Mm^3/year	Domestic use Mm^3/year	Total abstraction Mm^3/year	Total abstraction Mm^3/day
11	33.46034	3.9843	37.44464	0.102588
12	33.46034	1.864	35.32434	0.096779
13	33.46034	197.7937	231.25404	0.633573

14	33.46034	197.7937	231.25404	0.633573
15	123.0415	0.2796	123.3211	0.337866
18	123.0415	4.4969	127.5384	0.34942
19	123.0415	13.6072	136.6487	0.37438
20	110.1416	1.0485	111.1901	0.30463
22	110.1416	1.631	111.7726	0.306226
23	110.1416	1.1883	111.3299	0.305013
2	80.22768	0.4194	80.64708	0.220951
9	80.22768	0.6058	80.83348	0.221462
17	80.22768	2.24845	82.47613	0.225962
21	80.22768	0.8155	81.04318	0.222036
24	80.22768	0.7223	80.94998	0.221781

Withdrawals of selected boreholes (Fig. 5.8) indicated amount of groundwater abstraction and demand for domestic, agriculture and industrial use (tab. 5.11).

Tab. 5.11 Basic data about the simulation of groundwater pumping

No.bh	No.	Area	Mm^3/y	Z (altetued) m	Slice No.	estemate m^3 /d	Model m^3 /d
T/1/0403/87	1	13	33.03629	-90	19	90510.39	95000
T/1/0010/77	2	13	33.03629	-50.2	18	90510.39	90510.39
T/1/0061/80	3	13	33.03629	-670	27	90510.39	90510.39
F-11	4	14	77.08468	-130	20	211190.9	32400
T/1/0075/94	5	18	63.7692	-78	19	174710.1	42000
T/1/1146/77	6	11	12.48155	-43	18	34196.02	34796
T/1/0162/77	7	15	123.3211	-61	18	337866	52300
T/1/095/94	8	18	63.7692	-90	19	174710.1	42000
T/1/0133/77	9	12	35.32434	-79	19	96779.01	96779
T/1/0450/92	10	19	27.32974	-149	22	74876	31000
T/1/1046/92	11	19	27.32974	-111	20	74876	91000
T/1B/0005	12	19	27.32974	-444	25	74876	91000
T/1/0045/94	13	19	27.32974	-300	24	74876	91000
G-1	14	14	77.08468	-186	23	211190.9	32400
G-29	15	9	40.41674	-93	19	110730.8	32400
T/1/0220/86	16	21	40.52459	-228.5	24	111018.1	22100
T/1B/002/79	17	21	40.52159	-170	22	111018.1	22100
T/1/0003/80	18	23	55.66495	-267	24	152506.7	36500
T/1/0090/94	19	23	55.66495	-38	17	152506.7	20500
T/1/0148/78	20	2	40.32354	-91	19	110475.5	15000

T/1/0214/81	21	2	40.32354	-90	19	110475.5	15000
T/1/0080/89	22	9	40.41674	-157	22	110730.8	32500
T/1/1059/96	23	20	55.59505	-321	25	152315.2	180000
T/1/0156/77	24	20	55.59505	-175	22	152315.2	76400
T/1/0051/74	25	24	80.94998	6.8	14	221780.8	22000
T/1/0299/76	26	13	33.03629	-63.5	18	90510.39	90510.387
Z22	27	11	12.48155	-21	16	34196.02	34196
T/1/0442/92	28	13	33.03629	-66	18	90510.39	90510.4
T/1/1079/95	29	11	12.48155	-92.5	19	34196.02	34796
Z304	30	13	33.03629	-21	16	90510.39	90510
T/1/0549/91	31	13	33.03629	-62	18	90510.39	90510.39
T/1/0677/97	32	14	77.08468	-121	20	211190.9	43700
T/1/0081/77	33	22	111.7726	-100	19	306226.3	175000
T/1/0134/83	34	19	27.32974	-422	25	74876	91000
T/1/0207/89	35	17	82.47613	25	13	225962	34300
Total						4556240	2162228.957

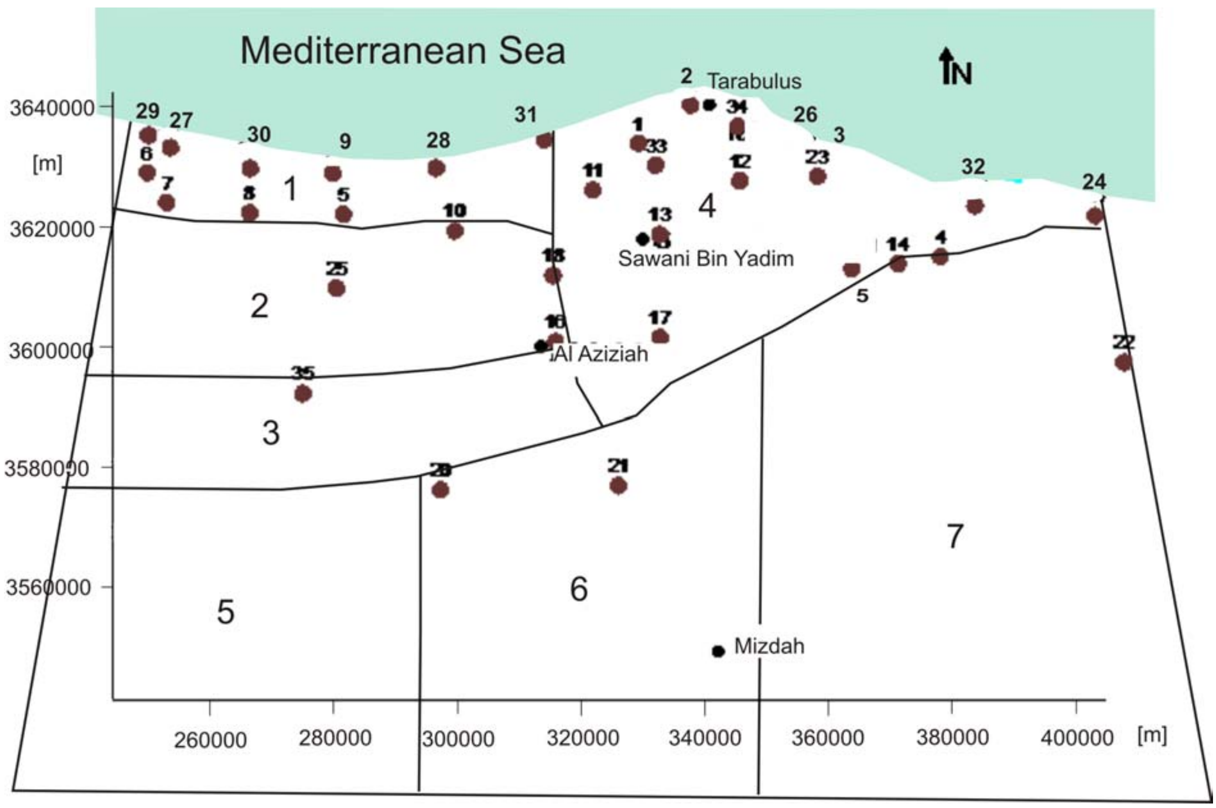


Fig. 5.8 Location of boreholes used for the simulation of groundwater pumping (geologic map as a background), (details of points are given in tab 5.10)

6. Main results

6.1 Main results of the model of natural conditions

The calibration of the model of natural hydrogeologic conditions was based on agreement of modelled and real piezometric surface. The highest groundwater levels occur in the south-west of the domain, i.e. in the subdomain 5, western part of subdomain 6 and southern part of subdomain 3 (comp. Figs. 5.3, 6.1). From there about 14% of water flows to the east to subdomain 7, partly represented by a closed basin in the Tajoura region. This represents groundwater flow through a vertical section less than 1 m^2/d. Major part of the groundwater, however, flows to the north with roughly 3 m^2/d towards the zone of regional groundwater discharge along the Mediterranean coast.

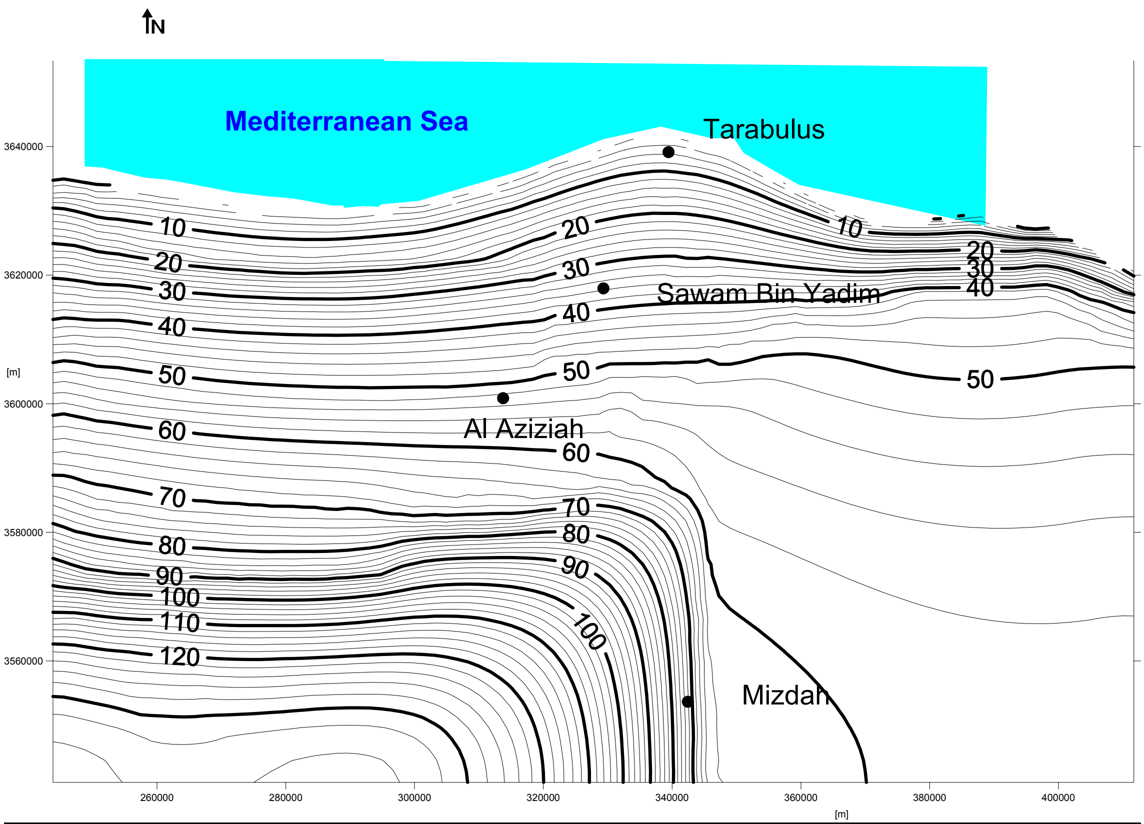


Fig. 6.1 Piezometric surface (m a. s. l.) under natural conditions as a result of the numerical modelling of the whole aquifer system

Groundwater leaves the domain through the coastline only. The assessment of regional groundwater flow in the Jifarah Plain was made in the two cross section each consisting of the three portions: the southern cross-section 4-5-6 follows the Al Aziziya fault and the northern one (1-2-3) is situated closer to the coast (Fig. 6.2). The specific discharge through the coastline is higher than further from the coast. As can be seen from Tables 6.1, 6.2 the difference is approximately 3.4 m^3/s. This might be partly caused by the additional recharge in the region between the two lines but the most probably due to the influence of an ascending deep-seated groundwater flow close to the regional zone of discharge.

The smallest values of specific discharge were found on the coast around Tripoli (5-6 m^2/d). The specific discharge increases to the west and to the east of Tripoli. The greatest values were found on the east of the coastline (12 – 13.5 m^2/d); while the specific discharge about 10 m^2/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.

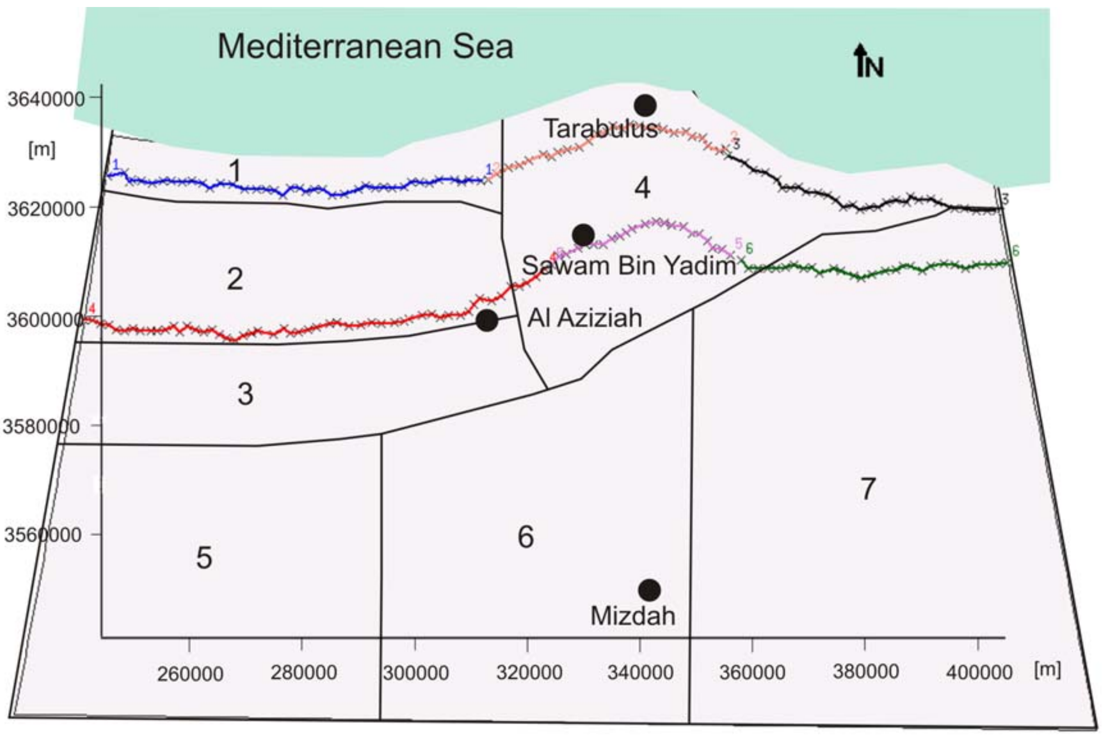


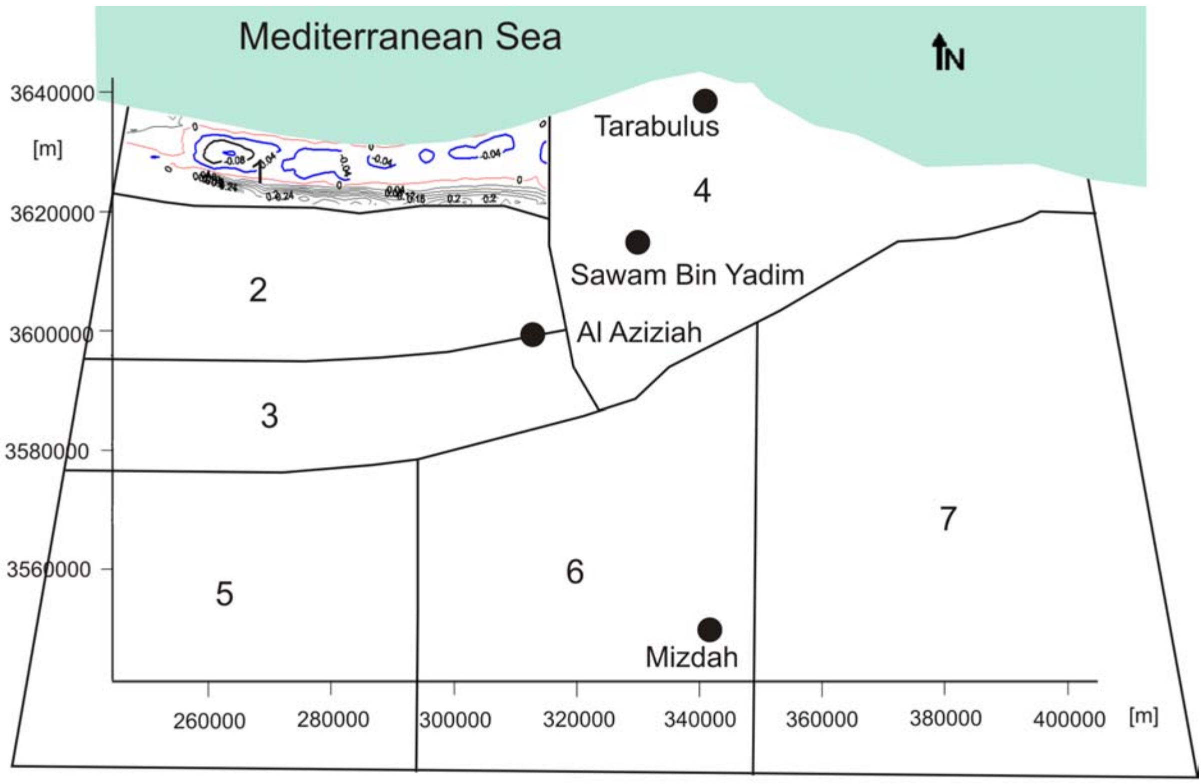
Fig. 6.2 Seawater intrusion protection. Lines indicate two scenarios of specific discharge computation points. Specific discharge assessment lines of the model of natural conditions.

During the modelling of both natural and influenced - current groundwater conditions a set of various contour maps was prepared expressing different hydraulic head between top and bottom of particular aquifers, maps of groundwater velocities and maps of amount and directions of horizontal flux for defined layers, in each subdomain. Selected examples of these maps and schemes follow, the complete set is attached in Apendices.

Maps of different hydraulic head represent differences of hydraulic head between the bottom and top of a layer – the case of natural conditions

Fig. 6.3 expresses an exemple from the Abusheyba aquifer in subdomain 1: the model shows the different range in hydraulic heads (0.04 to –0.08 m).

Appendix C1 represents different hydraulic head between top and bottom of aquifers and aquitards in each subdomain - natural model.



Detail:

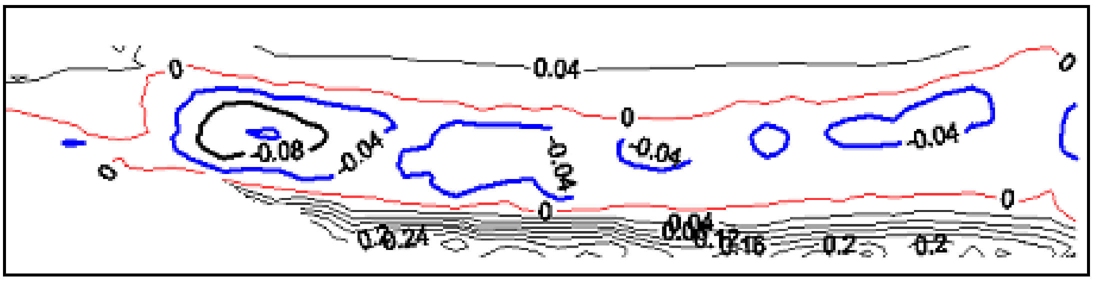
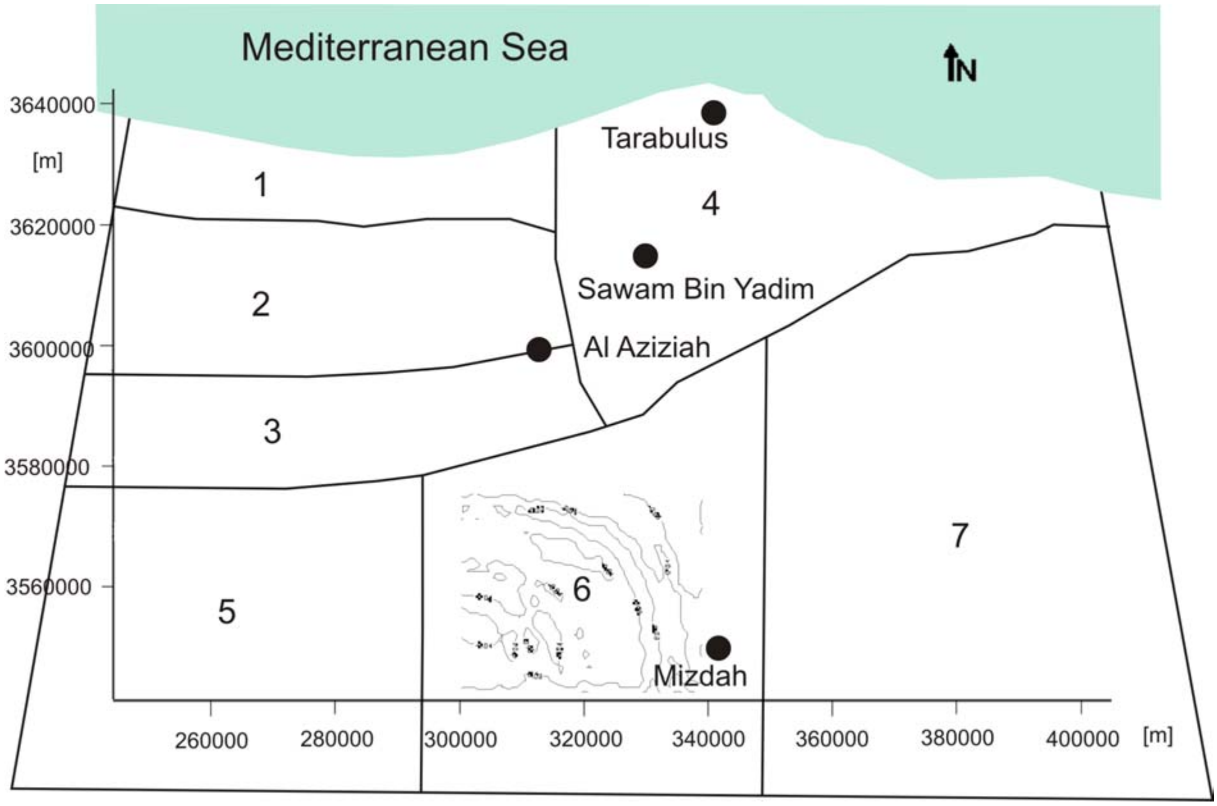


Fig. 6.3 Difference of hydraulic head between top and bottom of the Abusheyba aquifer in the subdomain 1 – model of natural conditions. Figure documents negligible values of vertical groundwater flow (if –Q=0 , than not indicated in the map).

Maps of different hydraulic head under current conditions:

According to maps of different hydraulic head between top and bottom of the Aziziya aquifer under current conditions differences can be seen among subdomains – see for example subdomain 6 (fig. 6.4) ranging from –0.025 to –0.06m.

Appendix C2 represents different hydraulic head between top and bottom of aquifers and aquitards in more subdomains – model of simulated pumping.



Detail:

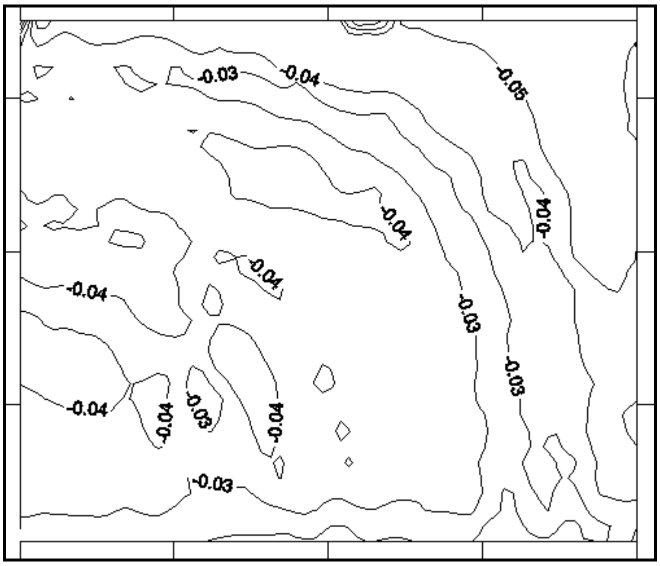


Fig. 6.4 Different hydraulic head between bottom and top of the Aziziya Formation, subdomain 6, model of simulated pumping

Maps of the velocity of groundwater flow, expressed as $-k (H_2-H_1) /(Z_2-Z_1)$,

where k = hydraulic conductivity in m/s,

H_2 = hydraulic head at the bottom of the aquifer in m,

H_1 =hydraulic head at the top of the aquifer in m,

$(Z_2 - Z_1)$ = thickness of the aquifer in m

show for the Ar Rajban aquifer under natural conditions velocities in subdomain 5 from

$-1*10^{-8}$ to $-5*10^{-8}$ m/d .

In the Appendix B1 the set of respective maps is included.

As an example of contour maps of groundwater flow velocity under current conditions in the **Quaternary** and **Quaternary-Miocene aquifers** can be followed in two regions**.** Velocity ranging from $1*10^{-6}$ to $5*10^{-7}$ m/d was modelled to the south of the coastal fault and velocity about $-1*10^{-6}$ to $-5*10^{-7}$ m in the north of the subdomain 1; flow velocity in the Quaternary-Miocene aquifer of subdomain 4 ranges from $-5*10^{-8}$ to 0 m/d.

The Appendix B2 express counter maps of velocity of aquifers and aquitared in subdomain current model.

Horizontal flux in particular layers

Horizontal flux in m^3/d was assessed for all the determined layers both under natural and current conditions in 17 selected sections, as represented in Figs. 6.5 and 6.6. All the sections were oriented more or less perpendicularly to the prevailing groundwater flow, i.e. approximately between the west-east and the SW-NE direction. Sections 1, 2, 3 are situated in the southern part of the study area, sections 4, 5, 6 follow the Jabal Naffusa escarpment in its close vicinity and further to the north, almost parallel to them run sections 7, 8, 9. Sections 10, 11 are situated before - to the south of the Aziziya fault in subdomains 3 and 4, and section 12 to the north of the Aziziya fault. Sections 13, 14 are before the Coastal fault and section 15 behind it. Sections 16 and 17 nearly follow the Mediterranean coastal line.

Fig. 6.5 represents the horizontal flux for all layers under natural conditions, the sign +Q expressing flux to the north and -Q flux to the south. Section 17 following the coastal line shows the total flux about 783,641 m^3 /d to the north. The northern direction of groundwater flow occurs almost in all the aquifers under natural conditions. The only exception is the section 2 where in several aquifers the flow to the south was identified, totalling some 1,790 m^3/d (Table 6.1).

In contrast with natural conditions the current model (fig. 6.6) assessed the amount of flux in the section 17 paralleling the coastal line (in subdomain 4) from the sea to the inland, i.e. to the south, about 203,400 m^3/d and in the section 16 (subdomain 1) the flux in the same direction of about 144,300 m^3/d (Table 6.2), thus in both sections confirming sea water intrusion.

When considering horizontal flux in particular layers, in Miocene aquifer the total flux to the south in section 16 is 3199 m^3/d and in section 17 even 6236 m^3/d, while in other sections in the northern part of the Jifarah Plain the direction of horizontal flux remains under the anthropologically changed conditions to the north as under the natural conditions.
Horizontal flux to the south in the Quaternary aquifer at the seaside (section 16) indicates extremely high sea-water intrusion, the highest one compared with all the other studied cases, of about 112,290 m^3/d.

Important sea-water intrusion occurs in sections 16 and 17 in the Abusheba aquifer, the horizontal flux being some 31,443 m^3/d to the south in the section 16 and about 5,915 m^3/d in the section 17 and in the Aziziya aquifer: some 9,120 m^3/d and 1,260 m^3/d in sections 16 and 17, resp. (Table 6.2).

Appendix D expresses detailed extended data on horizontal flux for some particular layers from models both under natural and current conditions.

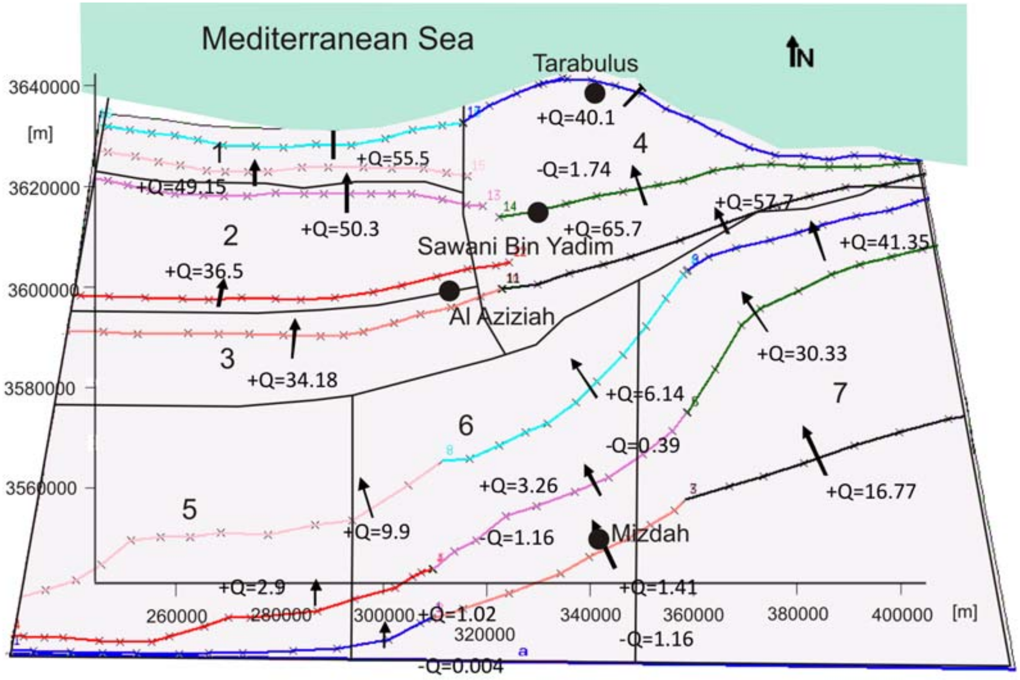


Fig. 6.5 Horizontal flux (in 10^4 m^3/d) for all layers for natural conditions model. The "+Q" value indicates flux in general northward direction, "-Q" flux in general southward direction, (if –Q=0 , than not indicated in the map).

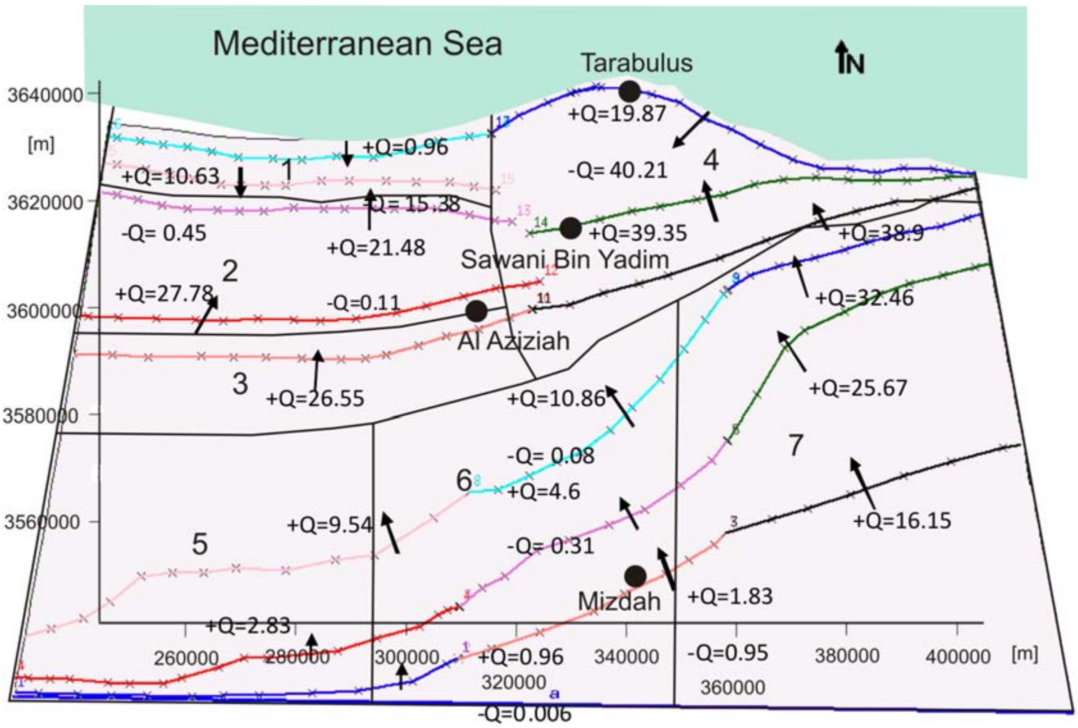


Fig. 6.6 Horizontal flux (in 10^4 m^3/d) for all layers for model of simulated pumping. The "+Q" value designates flux in general northward direction, "-Q" designates flux in general southward direction. TQ designates total flux (positive in northward direction), (if –Q=0 , than not indicated in the valio), (if –Q=0 , than not indicated in the map).

Tab. 6.1 Horizontal flux related to aquifers and sections corresponding to Fig. 6.5 – natural condition model. Positive value indicates groundwater flow from south to north, negative value indicates the reverse.

Horizontal flux for aquifers natural condition model - total flux m^3/d									
Layer	section1	2	3	4	5	6	7	8	9
Yefrin	841.685	-322.073	394.964	2254.074	21.056	717.746	0	0	0
Ain Topi	602.167	-627.262	1281.749	1744.992	116.46	2320.864	0	0	0
Ar Rajban	458.805	0	0	1731.528	0	0	0	0	0
Nalut	0	0	538.179	0	0	973.847	0	0	0
Kikla	454.732	-391.482	506.672	1321.707	313.438	917.016	0	0	0
Takbal	111.308	0	0	332.846	0	0	0	0	0
Al Khums	0	0	384.628	0	0	517.359	0	0	0
Miocien	0	0	0	0	0	0	0	0	94963.67
Quaternary	0	0	0	0	0	0	28293.35	0	0
Bir al Ghanam	566.607	-213.873	0	1866.486	321.411	0	0	0	0
Abu Shayba	2434.334	374.323	13169.98	7176.844	350.553	23834.38	0	23698.38	127467.6
Aziziya	1083.203	-235.326	14146.86	3225.517	1719.805	25598.2	48843.77	4750.173	61370.39
Kurrush	3125.236	7545.147	98625.63	8113.426	17041.3	178141.2	0	0	0
all layers	10172.08	2409.753	167788.6	29368.6	28284.79	303364.4	99309.72	57547.82	413580.8

Horizontal flux for aquifers natural condition model – total flux m^3/d								
Layer	10	11	12	13	14	15	16	17
Yefren	0	0	0	0	0	0	0	0
Ain topi	0	0	0	0	0	0	0	0
Arajban	0	0	0	0	0	0	0	0
Nalut	0	0	0	0	0	0	0	0
Kikla	0	0	0	0	0	0	0	0
Takbal	0	0	0	0	0	0	0	0
Alkums	0	0	0	0	0	0	0	0
Miocien	0	89296.15	23345.37	40920.76	89296.15	8919.785	9517.03	203612.7
Quaternary	166371.5	0	258003.9	290844	0	331702.2	413256.5	0
Birelgnam	0	0	0	0	0	0	0	0
Aboushеba	0	53258.12	20030.55	37649.63	49997.26	48956.67	52650.31	65489.31
Aziziya	172874.7	6488.275	50233.13	108824.8	2918.89	69322.74	68661.59	5324.058
Kursh	0	0	0	0	0	0	0	0
all layers	341872.6	577054.04	365048.4	503017.5	657083.7	491588.7	555074.4	783641.4

Tab. 6.2 Horizontal flux related to aquifers and sections corresponding to Fig. 6.6 – model of simulated pumping. Positive value indicates groundwater flow from south to north, negative value indicates the reverse.

Horizontal flux for aquifers transient model ers _ model with pumping									total flux
Layer	section1	2	3	4	5	6	7	8	9
Yefren	449.351	-287.639	381.277	1088.956	315.907	1834.173	0	0	0
Ain topi	329.326	-344.537	1237.347	955.54	504.143	1396.216	0	0	0
Arajban	375.113	0	0	1295.689	0	0	0	0	0
Nalut	0	0	519.555	0	0	114.839	0	0	0
Kikla	429.596	-11.962	489.11	1635.861	214.899	4550.207	1635.861	0	0
Takbal	215.431	0	0	734.455	0	0	0	0	0
Alkums	0	0	18.888	0	0	774.566	1	0	0
Miocien	0	0	0	0	0	0	0	0	93363.84
Quaternary	0	0	0	0	0	0	25760.6	0	0
Birelgnam	569.493	-124.915	0	1810.611	210.298	0	0	0	0
Abousheba	2682.895	-159.568	12713.21	8321.337	554.705	16272.98	0	39996.78	105335.4
Aziziya	1480.163	130.857	13664.03	4451.8	3186.783	32705.64	55552.34	4589.768	21923.38
Kursh	2535.611	9611.777	132553.3	6408.156	37909.42	198929.2	0	0	0
all layers	9572.573	8814.084	161566.7	28375.49	42896.25	256713.5	95428.04	107853.7	324656.7

Horizontal flux for aquifers transient model ers _ model with pumping								total flux
Layer	10	11	12	13	14	15	16	17
Yefren	0	0	0	0	0	0	0	0
Ain topi	0	0	0	0	0	0	0	0
Arajban	0	0	0	0	0	0	0	0
Nalut	0	0	0	0	0	0	0	0
Kikla	0	0	0	0	0	0	0	0
Takbal	0	0	0	0	0	0	0	0
Alkums	0	0	0	0	0	0	0	0
Miocien	0	58339.73	32533.04	36198.79	44044.91	3330.975	-3199.22	-6236.102
Quaternary	116003.7	0	159597.9	7842.621	0	72334.27	-112290	0
Birelgnam	0	0	0	0	0	0	0	0
Abousheba	0	34883.25	17177.57	14698.56	17616.559	14334.89	-31442.6	-5914.91
Aziziya	147883.6	2207.009	48275.76	46224.72	936.56	7961.555	-9119.87	-1260.16
Kursh	0	0	0	0	0	0	0	0
all layers	265586.4	389195.6	277821.6	213743	393565.3	101853.9	-144266	-203409

-flux = the flux to the south
+ flux = the flux to the north

6.2. Main results of the model of current groundwater extraction (conditions changed due to anthropogenic impacts)

According to water-extraction data in the past years 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 water extraction distribution schemes from (El-Baruni, and others 2004). The resulting groundwater levels show large depression cones around Tripoli and west of Azizia. As a steady state model, it shows the piezometric levels after balance has been achieved.

Then the model has been calibrated to match the current piezometric levels in the region. The total water extraction in this model is about half the previously estimated value. Also the distribution of extraction is different. If we assume the current state in Jifarah Plain to be steady/stationary/balanced, the result implicates that the return flow from irrigation and municipal water losses must be about half the total amount of extracted water. However, 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 actual groundwater extraction creates an irregular cone of depression along the coast, which is deepest around Tripoli (Fig. 6.7). Pumping forces sea-water to infiltrate the aquifers. Steady state computations have shown that specific discharge of sea-water is 3 – 6 m^2/d through the western part of coast and 10.5 – 12 m^2/d through coast around Tripoli. However, groundwater still discharges (0 – 5 m^2/d) into the sea through the eastern part of coast.

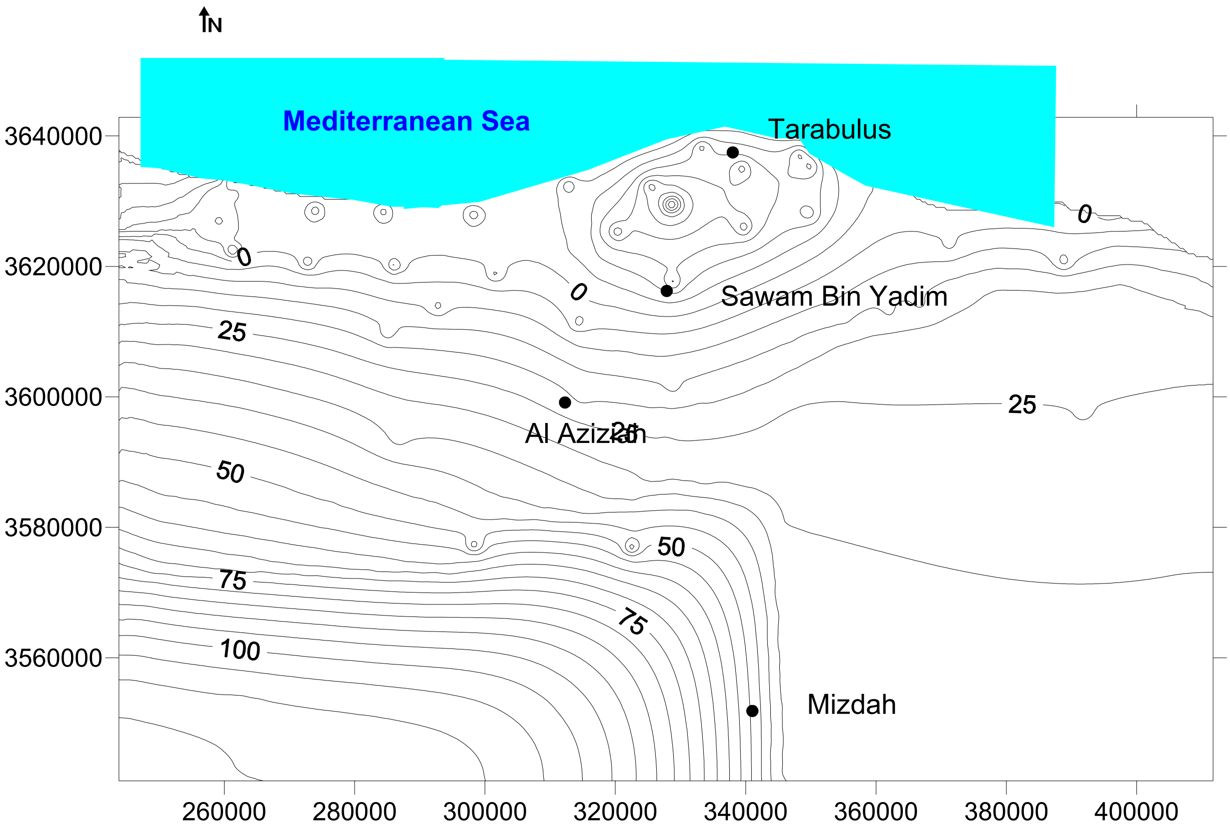


Fig. 6.7 Regional steady-state conditions under antropogenically changed conditions

Tab. 6.3 Fluxes (in m^3/d) through the sections 1-2-3 under different conditions.

hydr.head [m]	section			Total Flux	
	1	2	3	m^3/d	M^3/s
natural condition	462506.4	247201.1	512024.4	1221732.0	14.1
2	89964.2	51867.3	66589.8	208421.3	2.4
1.5	87553.5	47984.5	60781.9	196319.8	2.3
1	85160.0	43933.3	54909.4	184002.7	2.1
0.5	82767.0	39713.6	48965.6	171446.2	2.0

Tab. 6.4 Fluxes (in m^3/d) through the sections 4-5-6 (along the Aziziya fault and its extension) under different conditions.

hydr.head [m]	Section			Total Flux	
	4	5	6	m^3/d	m^3/s
natural condition	370952.81	150361.2	399385	920699.1	10.7
2	151952.72	31440.71	206604.2	389997.7	4.5
1.5	150164.72	29474.46	203896.8	383536	4.4
1	148354.74	27450.08	201137.8	376942.7	4.4
0.5	146532.12	25363	198324	370219.1	4.3

Tab. 6.5 Flux to north and flux to south (in m³/d) on line 4-5-6 (along the Aziziya fault and its extension) under different conditions

Hydral. Head [m]	Section	Flux to N	Flux to S	Total Flux
2	4	152125.7	-172.9	151952.7
2	5	31540.0	-99.3	31440.7
2	6	207118.4	-514.2	206604.2
1.5	4	150342.2	-177.5	150164.7
1.5	5	29616.9	-142.5	29474.5
1.5	6	204450.0	-553.2	203896.8
1	4	148535.9	-181.2	148354.7
1	5	27722.3	-272.2	27450.1
1	6	201732.3	-594.5	201137.8
0.5	4	146715.8	-183.7	146532.1
0.5	5	25915.6	-552.6	25363.0
0.5	6	198962.1	-638.2	198324.0

Tab. 6.6 Yield (in m^3/d) from line 1-2-3 with different water tables

Hydraul. Head [m]	1	2	3	Total Flux m^3/d	m^3/s
2	216231.3	97513.6	188328.3	502073.2	5.8
1.5	226474.5	102816.2	196526.3	525817.0	6.1
1	234180.8	108336.4	205121.0	547638.3	6.3
0.5	245193.8	114412.8	214667.6	574274.2	6.6

Tab. 6.7 Yield from line 4-5-6 with different water tables.

Hydraul. Head [m]	4	5	6	Total Flux m^3/d	m^3/s
2	219000.09	118920.5	192780.8	530701.4	6.1
1.5	220788.08	120886.8	195488.2	537163.1	6.2
1	222598.07	122911.2	198247.2	543756.4	6.3
0.5	224420.69	124998.2	201061.1	550480	6.4

Difference of fluxes between natural conditions and prescribed head.

Fluxes to the south through sections 1-2-3 are zero (natural conditions) or negligible (order -3). Fluxes to the south through sections 4-5-6 are shown in table 6.2, other tables 6.3 to 6.7 offer additional information on yields in some specific cases.

6.3 Future prognosis

Based on census conducted in 2006 the population in the Jifarah Plain was 2,927,143 million, with growth rate of 1.8. The population in the study area which model provided was about 2.546 million. Estimation of future groundwater demand in the Jifarah Plain as presented in table 6.8 shows that due to the supposed increase in population and water demand in all the economic branches also the deficit will increase (comp. tables 5.5, 5.6). This means measures should be taken to as e.g. to reuse the sewage water for industrial and agricultural use or widely introduce modern technological processes as desalination of sea water for domestic and agricultural use. In Jabal Naffusa region building more dames and reservoirs should be considered to catch more surface runoff from torrential rainfalls.

Tab. 6.8 Estimation of future groundwater demand in the Jifarah Plain

Year	Agriculture demand Mm^3/day	Population of Jifarah Million	Demand domestic use Mm^3/day	Total demand Mm^3/day
2007	3.591838	2.59	0.6475	4.239338356
2015	4.183685	2.96	0.74	4.923684932
2020	4.553589	3.226	0.8065	5.360089041
2025	4.923493	3.516	0.879	5.802493151
2030	5.293397	3.832	0.958	6.25139726
2035	5.663301	4.177	1.04425	6.70755137
2040	6.033205	4.547	1.13675	7.169955479
2045	6.40311	4.956	1.239	7.642109589
2050	6.773014	5.402	1.3505	8.123513699
2060	7.512822	6.42	1.605	9.117821918
2070	8.25263	7.63	1.9075	10.16013014
2080	8.992438	9.064	2.266	11.25843836
2090	9.732247	9.88	2.47	12.20224658
2100	10.47205	12.797	3.19925	13.67130479

7. Conclusions and suggestions

Based on available data a conceptual model of hydrogeologic conditions in the north-western part of Libya – in the Jifarah Plain and its surrounding – was implemented. Occurring lithostratigraphic units were hydrogeologically characterised and their geometry and anatomy assessed. This enabled implementation of a numerical model on groundwater situation in a regional scale. Past natural situation was compared with man-made changes that have occurred in the last decades and a prognosis was made for the following years.

The main results of the study are as follows:

- Under natural conditions groundwater flows from the southernmost part of the study region to the north to the regional discharge zone represented by the Mediterranean Sea. Part of the groundwater, however, flows also to the east.
- It has been estimated that in addition to the water recharged in the remote southern part some water might be recharged also in the Plain itself possibly in the rate of several m^3/s.
- Thus the total amount of water discharged under natural groundwater conditions along the Mediterranean coast can be assessed as high as 14.8 m^3/s.
- Specific discharge was assessed in particular sections and some of their parts. Important differences have been found. The highest specific discharge (12-13 m^2/d) occurs along the coast east of Tripoli, while the lowest occurs around Tripoli (5-6 m^2/d). The specific discharge is about 10 m^2/d along the western part of coast.
- Under man-made conditions regional groundwater flow has been changed considerably. To the areas with heavy groundwater abstraction groundwater flows not only from former (natural) recharge areas but also from the seacoast. Due to decrease in piezometric head an upward vertical component of groundwater flow has been increased. In irrigated, industrial and urban areas artificial contamination occurs, too. All this results in groundwater quality deterioration in extended regions.
- Very important practical result of the numerical model might be an assessment of the abstraction rate in the current zones of depression caused by the intensive artificial groundwater withdrawals: calibrated to present available data on the piezometric surface the amount of water abstraction should have been smaller than previously estimated values: after the model it could be only about 6 m^3/s in total (see Tab.6.6) compared with a previously mentioned assessments 7.9 m^3/s (Mott Mac Donald 1994).
- The reason of this difference could be either the fact that real withdrawn groundwater is less than recorded amounts or that return flow and/or artificial recharge should be considerably high and do not permit to extend the depression as it should be from the model results.
- This conclusion highlights the importance of input data for groundwater balance. Indicated differences in assessed withdrawn groundwater volumes seem to be quite high and might influence considerably the future possibilities of groundwater use in the study region and all the water-depending activities in this part of Libya.

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