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Water Resources Evaluation in Ghadamis Basin, Libya

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Abstract

Ghadames basin is one of the important groundwater basins in Libya. This basin covers an area of about 215,000 km^2 in northwestern Libya. This groundwater basin consists of two major aquifer systems. The upper aquifer system mostly formed of carbonate rocks (Mizdah and Nalut formations). The lower aquifer system formed mostly of sandstone known as Kiklah formation. The two aquifer systems are separated by semi-confining layers known as Yefren marl. The lower aquifer system is considered as the main aquifer for water supply. The water resource (mostly from the lower aquifer system) in these systems is used for domestic, irrigation and fodder drinking. The domestic use of water is to supply water to the cities and towns in western part of the country and in the northern flanks of the basin, and plans to transport water to the coastal cities in northwestern part of the country. The existing total amount of extracted water is 132 Mm^3/year, and about 20% of it used for domestic uses. The planned water extraction is 223.8 Mm^3/year about 55% of it will be used for domestic uses. The hydrogeological situation for this basin has been studied in this study using data from previous hydrogeological exploration programs, evaluation of the data from the existing extraction and observation water wells, pumping tests data used to evaluate aquifers hydraulic parameters, and construction of hydrogeological cross-sections to know the aquifer systems geometry. Hydogeological computer model was constructed to evaluate the aquifer hydraulic parameters using the historical water extraction, and water levels and drawdowns. The model is then used to predict the future drawdown which has been found to be in the range 55 to 60 m after 50 years of extraction.

Keywords

Ghadamis Basin, Geomorphology, Stratigraphy Resources, Groundwater Modeling

1. Introduction

The Ghadamis Basin is located in the northwestern part of Libya. Its area is about

215,000 km^2. It is bounded to the north by the Jabal Nafusah escarpment and the Mediterranean Sea, in the west it extends into Tunisia and Algeria, in the east by Hun Graben, and to the south by Al Qarqaf Arch (Figure 1).

This study is aimed to evaluate the groundwater in Kiklah aquifer in Ghadamis Basin using the available information and exploitation requirements. The study is to determine the aquifers hydraulic characteristics and their distribution and to predict the future draw downs using the numerical groundwater modeling.

The study area is characterized by an arid climate, which is extremely hot in the summer and cold during the winter. Yearly mean temperature ranges between 20˚C and 30˚C. However, maximum temperature can be over 49˚C in some places in July and August [1].

The basin receives moderate rainfall in the north, along the southern slopes of Jabal Nafusah. The average annual precipitation is about 100 - 300 mm in the Jabal Nafusah area and rapidly decreases towards the south to about 33 mm.

The average annual potential evaporation computed by various methods is estimated to be about 1700 - 2200 mm in the Northern parts of the study area and between 2000 and 2700 mm in the southern par [2].

2. Geomorphology and Stratigraphy

The study area can be divided into three main geomorphological units: the coastal plain, Jabal Nafusah escarpment, and Al Hamadah al Hamra plateau. The coastal plain in the northeast is a flat area covered mostly by Tertiary and Quaternary deposits and

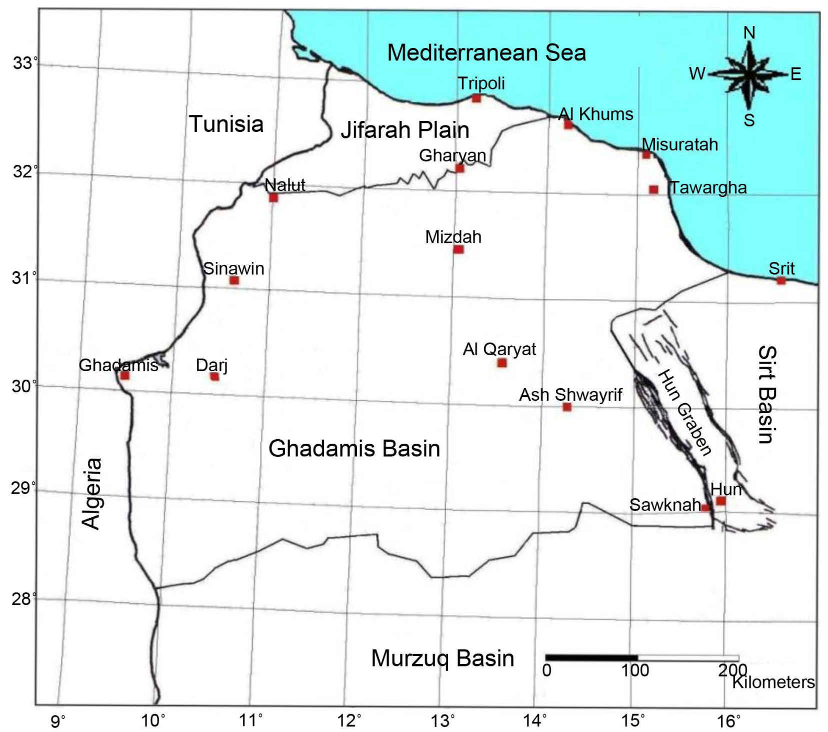

Figure 1. Map of the study area.

characterized by extensive sabkhas (Sabkhat Tawargha and Sabkhat al Hishah, etc.) developed at the estuaries of Wadi Suf Ajjin, Wadi Zamzam and Wadi Bayy al Kabir. The area has a relief which does not exceed 150 m above sea level (a.s.l) sloping gently towards the coast.

The Jabal Nafusah eacarpment in the north, with an elevation of 600 - 800 m a.s.l. consists of a sequence of Triassic to Upper Cretaceous rocks. The centre of Al Hamadah al Hamra plateau is a flat and bare desert at an elevation ranging from 500 - 600 m a.s.l and is covered by thick series of Palaeocene carbonates [3].

The Ghadamis area, west of Al Hamadah al Hamra, is hilly terrain sloping westward and partly covered by sand dunes. The area is dissected by a number of wad is which terminate at a group of sabkhas near Ghadamis town.

The Suf Ajjin area to the east and northeast of Al Hamadah al Hamra slopes gently NE towards the Mediterranean Sea. It is characterized by a group of large wide wad is.

A major part of the study area is covered by Paleocene and Upper Cretaceous rocks. The litholgy of water and oil wells drilled in the area shows that there are two distinct sets of deposits. The upper part, down to the base of the Upper Cretaceous, is dominated by limestone, dolomites, dolomitic limestone, marl and argillaceous sediments of different ages with occasional sandy, shaly, silty and gypsiferous bands. Some of these beds are often fractured.

In the deeper parts of the boreholes, from the Lower Cretaceous downwards, the beds are mainly comprised of thick layers of granular sediments (Mesozoic and Paleozoic sandstone) with interbeds of shale, clay, and silt. Beds of limestone with gypsum (Triassic and Jurassic) are also present. **Figure 2** shows lithologic columnar section representing the lithologic sequence in the study area [4].

3. Structural Geology

In the entire region, only a few minor faults are visible on the ground. But it is more probable that numerous faults exist since there is a large network of wad is in the region, which would suggest that they follow the axes of these faults. In Ghadamis area, there is a major fault, also extending to a NW-SE. The vertical displacement on this Ghadames fault is estimated to be 60 to 70 m. **Figure 3** illustrates the structural map of Ghadamis area.

Hun Graben is the main structure in the area. The Hun graben axis would be located to the north where the throw is minimal, while to the south, in the zone of Al Jufrah, the deepening into the graben reaches 1000 m. The first consequence of this structure, which probably occurred in the Miocene, is the preservation of the Tertiary, pre-Miocene formations over a large part of the graben and the burying of the aquifer formations of the Pre-Cenomanian Mesozoic. The hydrogeological role of the graben may be summed up as follows;

- The impacts of the structure are little sensitive to the north where the aquifer formations of Wadi Zamzam (Eocene, Nalut, Kikla) remain in continuity on both parts of the graben faults.

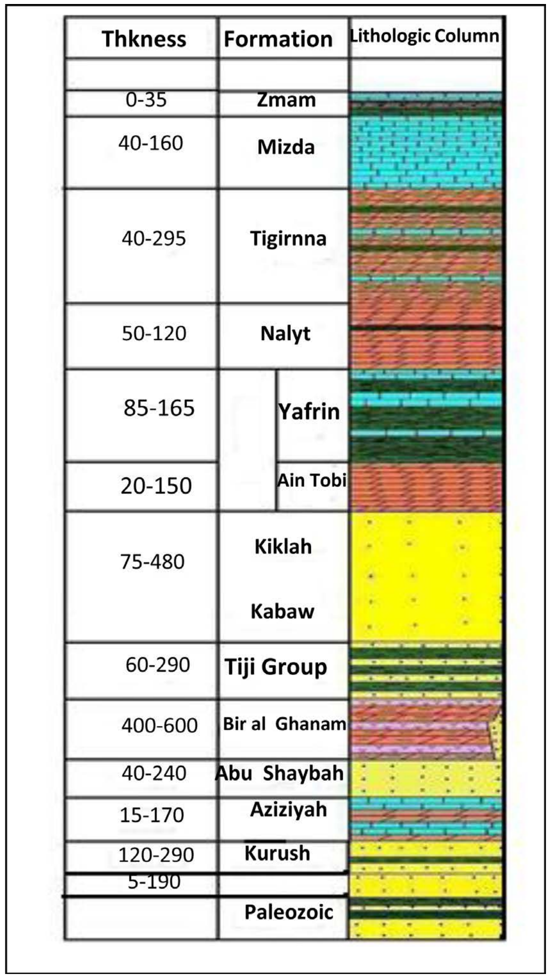

Figure 2. Stratigraphic columnar section of study area.

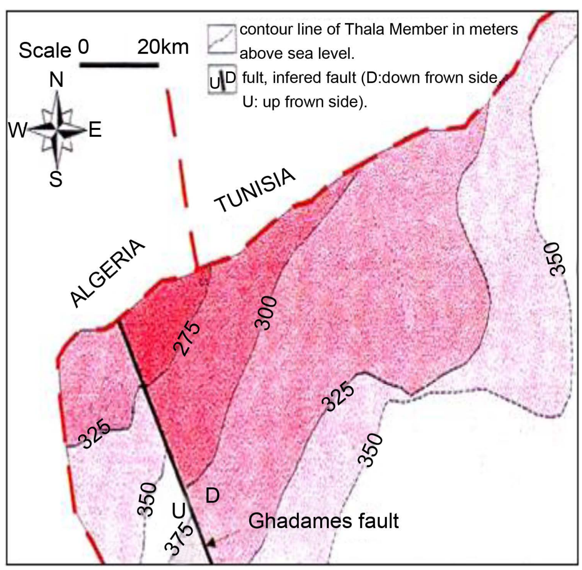

Figure 3. Structural map of top Mizdah formation in Ghadamis area [5].

- At the centre, in the Abu Njaym zone, and to the south, in the Al Jufrah zone, the aquifer layers (Cambro-Ordovician, Kikla, Nalut, and Mizdah) are completely disconnected on both parts of the western fault which interrupts the horizontal flow. By contrast, the western fault is the seat of vertical flow which allows recharge of the Eocene aquifers in the graben and, particularly, that of the Santonian aquifer (Mizdah) to the west of Suknah, as illustrated by the sketch of Figure 4.

4. Ground Water Resources

Groundwater is the main source of water supply in the Ghadamis Basin. Important aquifers are located in almost all geological formations from the Paleozoic to the Quaternary. Figure 5 shows the extent of these aquifers in the area.

The groundwater system in the Ghadamis Basin can be subdivided into three main aquifer groups as follows:

1) The Upper groundwater aquifer system: the aquifer system comprises of the upper Cretaceous Nalut, Mizdah and Zimam formations and may extend to Middle Miocene of Al Khums formations in the northeastern part of the area. The lithology of this aquifer is mainly dolomite, dolomitic limestone and limestone. These rocks are heavily fractured and cavernous. This aquifer system is considered to be unconfined [7] and [8].

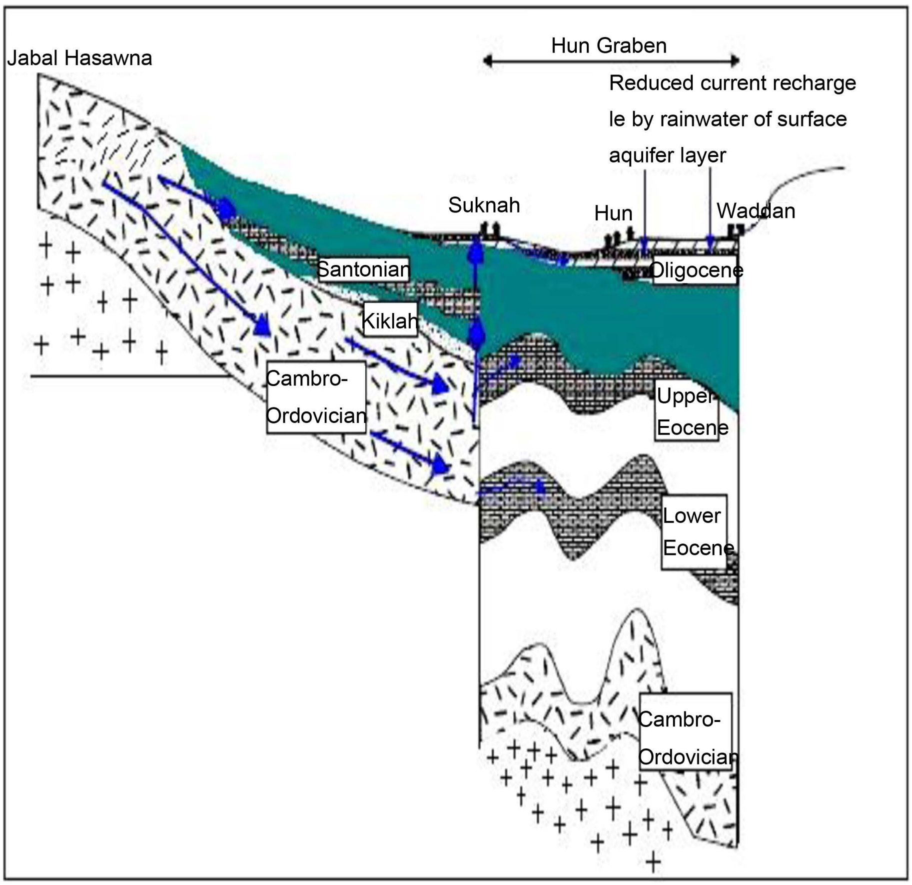

Figure 4. Role of the Hun Graben in Al Jufrah zone [6].

The saturated thickness of this aquifer ranges from 50 to 700 m (Figure 6). The pumping tests show that transmissivity is very low (50 m^2/day) except where the formation is fractured, where the transmissivity is high (2000 m^2/day).

The water level map of the upper aquifer (Figure 7) shows that high water levels occur in the northern part in the Jabal Nafusah area. This map also shows that the groundwater flows are outwards Jabal Nafusah in the north, towards the Sinawin area in the southwest and to Suf Ajjin and Tawargha area in the northeast.

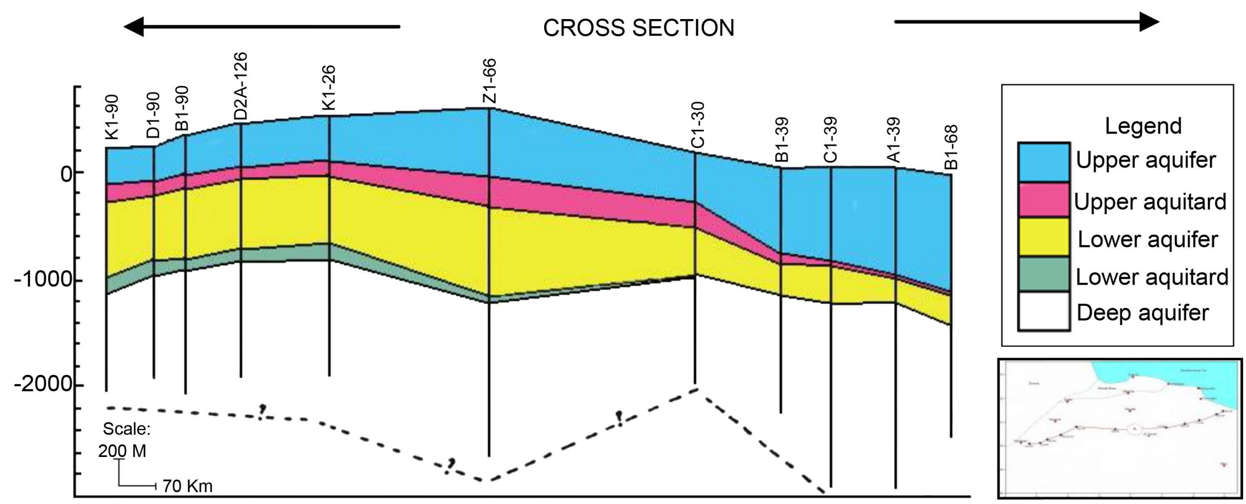

Figure 5. Hydrogeological cross section.

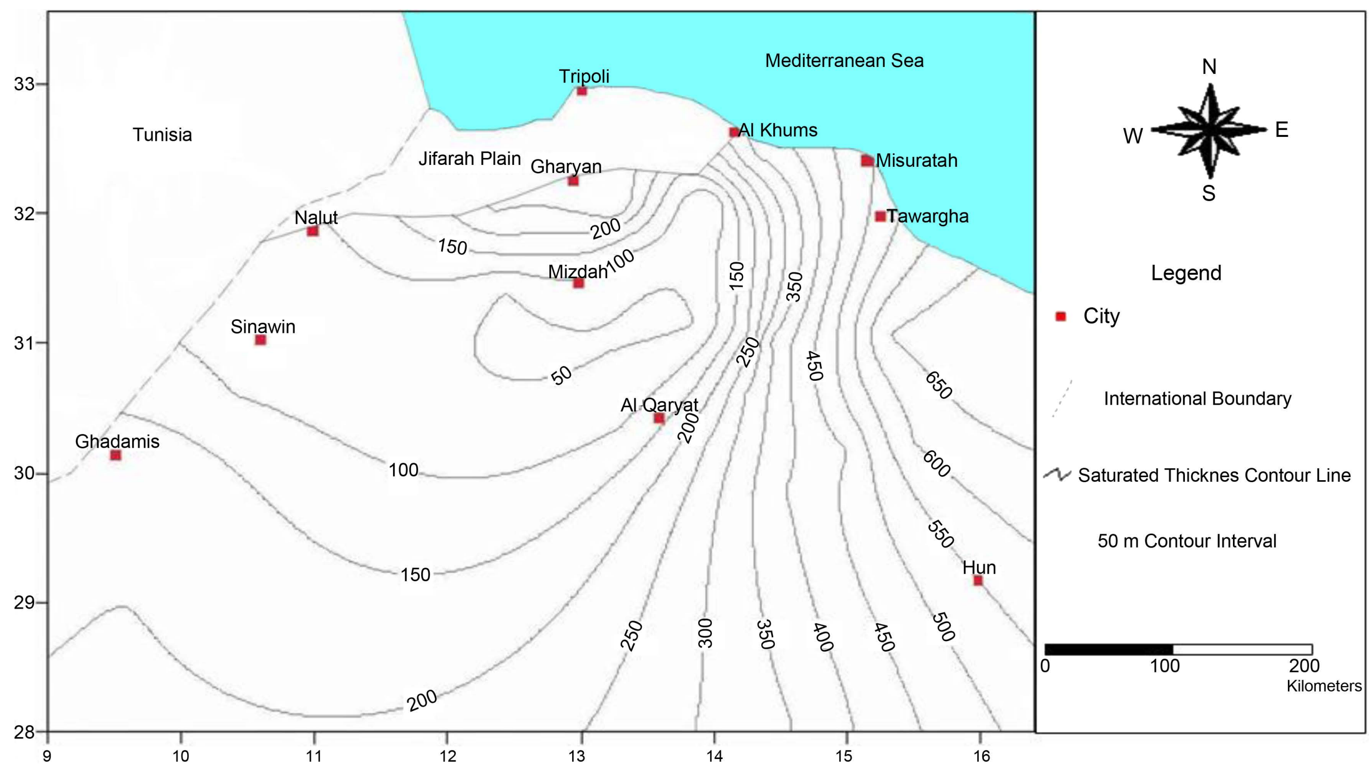

Figure 6. Saturated thickness contour map of upper aquifer.

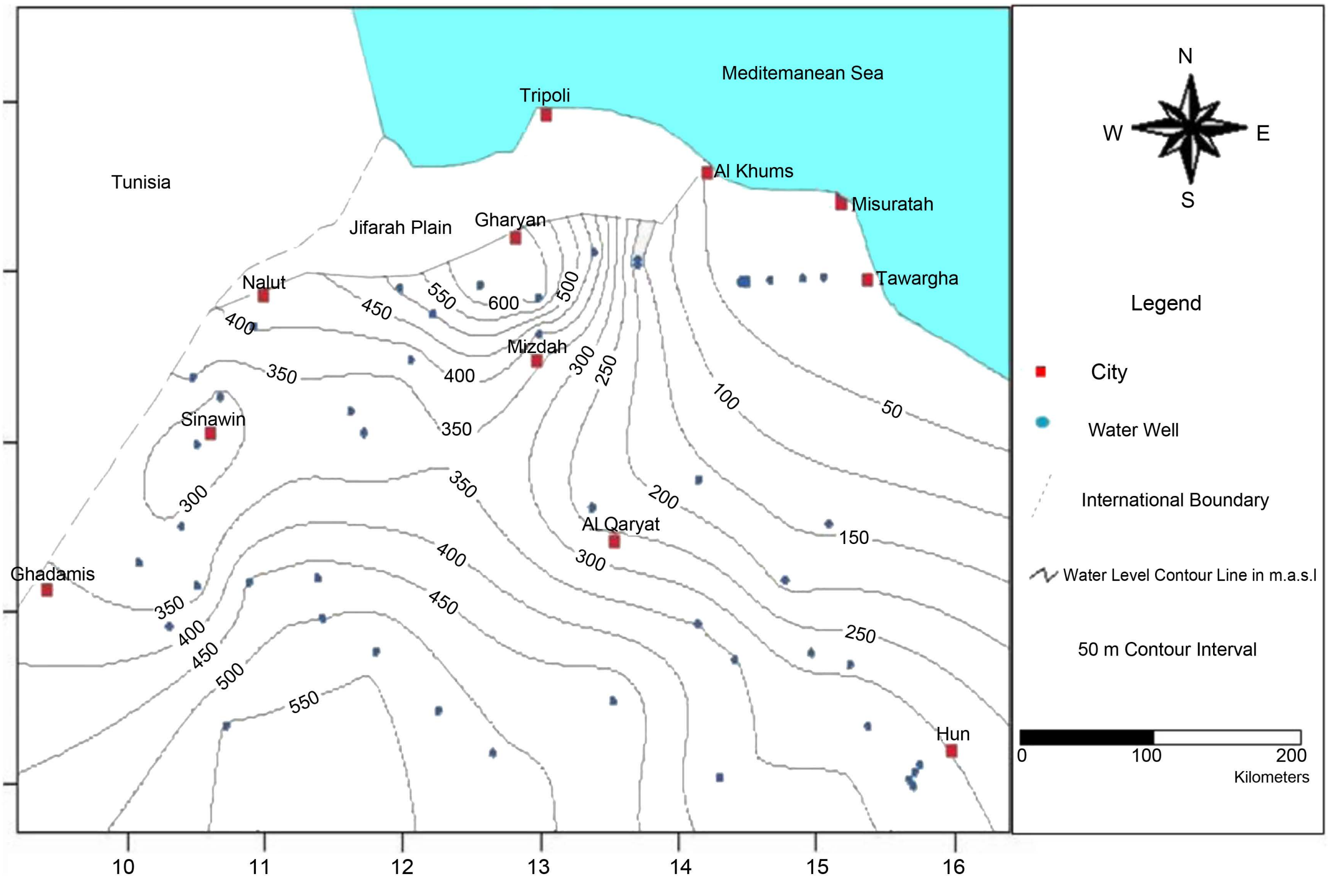

Figure 7. Water level contour map of upper aquifer (meters a.s.l).

2) The lower groundwater aquifer system: The aquifer system comprises the lower Cretaceous and upper Jurassic, composed of sands from Kiklah and Kabaw formations. This lower system behaves essentially as confined aquifer [9].

The thickness of this aquifer decrease in the southern parts of the basin, from a maximum of about 700 m at Ghadamis town to a minimum of less than 50 m north of Al Qarqaf (Figure 8).

Kiklah Formation consists of continental, unconsolidated to semi-consolidated sediments of Jurassic and early Cretaceous age which are composed of white to pink, fine to very coarse quartizitic sandstone and gravel with intercalations of silt, clay, shale and limestone. The Kabaw Formation underlies the Kiklah formation is mainly composed of sand and shale. It is in hydraulic continuity with Kiklah Formation [10].

The bottom bed of Ain Tobi, which consists of fractured dolomitic limestone, is also in hydraulic continuity with Kiklah Formation.

The upper and lower limits of the aquifer is marked by overlying Yifren marl beds and the lower limits is marked by the underlying shale, marl and marly limestone beds of Takbal and Bir al Ghanam formations.

In the southeast part of the basin the aquifer shows both lateral and vertical hydraulic continuity with the underlying Cambro-Ordovician groundwater aquifer, while in the

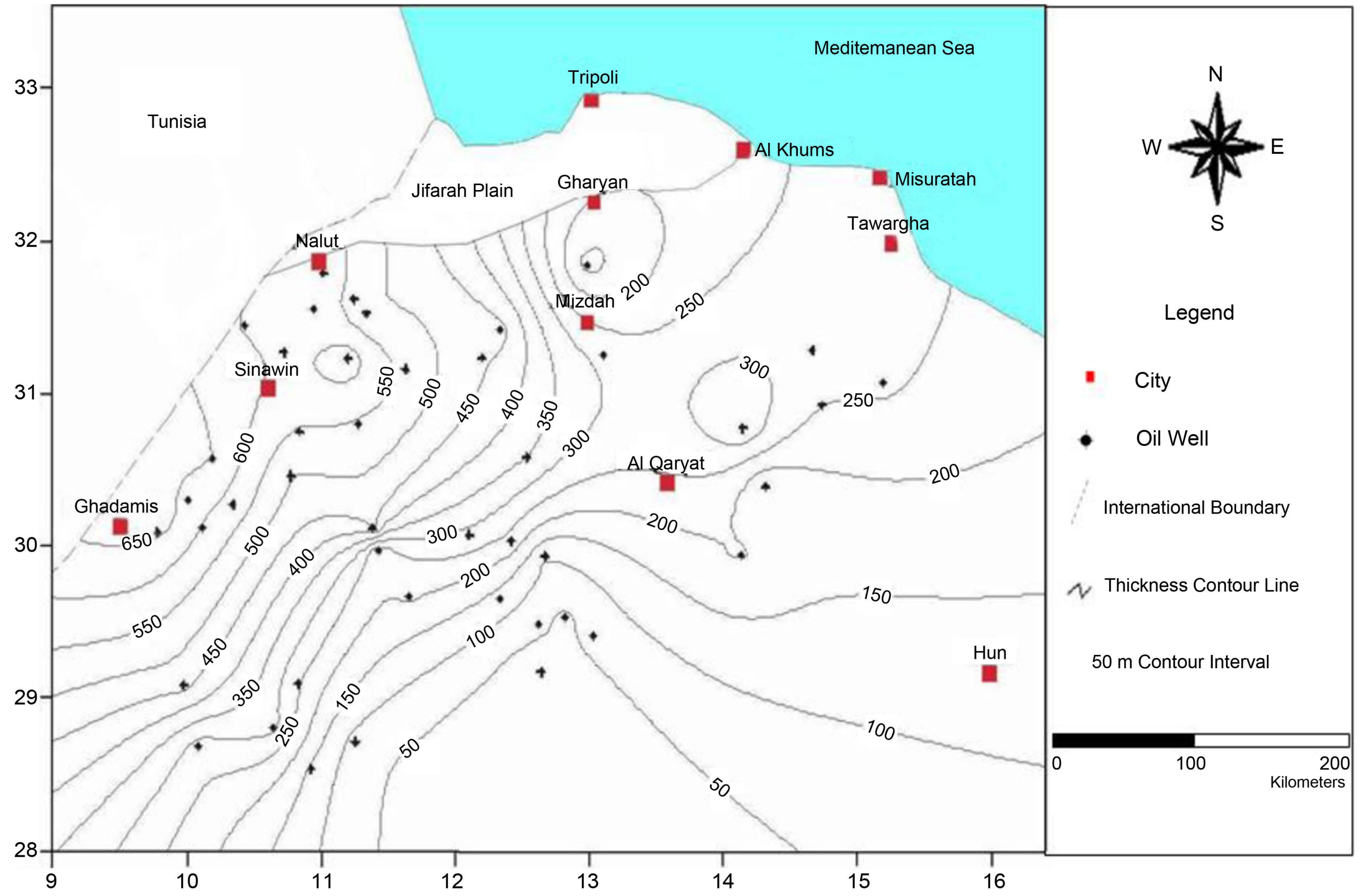

Figure 8. Thickness contour map of lower aquifer.

southwest part of the area the lower aquifer seems to be in hydraulic connection with Aziziyah and Kurrush aquifers [5].

The pumping tests show that transmissivity of the aquifer varies from 400 to 7300 m^2/d; the wide spread of the transmissivity is controlled primarily by the aquifer thickness, and also by the horizontal and vertical lithological variations. Storage coefficients, determined for only a limited number of wells, are in the order of 10^{-5} to 10^{-4}.

The water level map of the aquifer (**Figure 9**) shows that the flow in the eastern part of the basin is from south to north and is controlled in the east by the Hun Graben which acts as a no-flow boundary. In the western part of the basin, flow is from south to north and to the northwest. In the northern part, flow is radial from central Jabal Nafusah resulting from a local water level high due to direct recharge to the upper aquifer and leakage. A great percentage of this flow converges towards the Mediterranean coast at Tawargha.

Water quality of this aquifer is good to fair, and is suitable for most agricultural and domestic uses. The TDS generally falls between 1000 and 1500 mg/l (**Figure 10**).

The lower aquifer water varies in temperature from 20˚C to 70˚C. The highest temperature is recorded in the deep-flowing wells located in the eastern part of the basin and seems to be associated with the tectonic nature of the area.

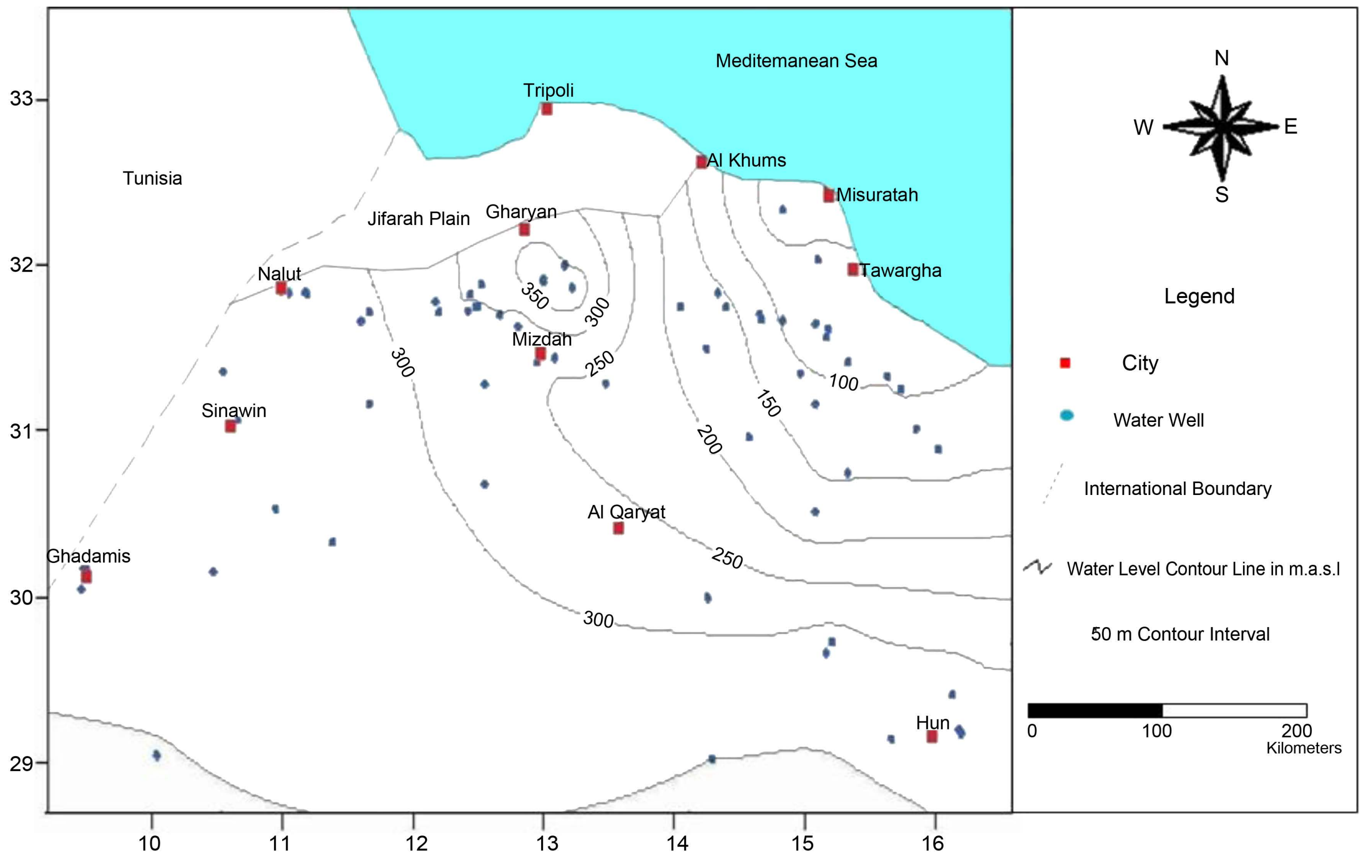

Figure 9. Water level contour map of lower aquifer (meters a.s.l).

The deep groundwater aquifer system: the aquifer system comprises of the Middle Triassic (Kurrush, Al Azizha, and Paleozoic formations).

Kurrush Formation, comprising of 120 to 290 meters thick deposit of sandstone intercalated with shale and limestone. The overlying Azizia formation is composed of highly fractured dolomitic limestone with shale and gypsum. The arenaceous sediments of underlying Ouled Chebbi formation, although relatively thin, are also in hydraulic continuity with the same aquifer [7].

The Paleozoic formations overlying the basement rocks (Precambrian basement) unconformably and consist mainly of clastic rocks from Cambrian to Carboniferous. It consists of Devonian and Cambro-Ordovician sandstone separated by thick layers of Lower Silurian shale (Tanezzuft shale). It occurs at great depths usually in excess of 1500 m below ground surface. Its thickness varies from 500 to 1500 m. Due to its considerable depth, it has been poorly investigated.

These three main aquifers are separated by semi-permeable layers (aquitards), the namely following:

The lower Cenomanian represented by the Yafrin marl (upper aquitard) is composed mainly of marl, marly limestone with gypsum and anhydrite. It is a semi-permeable layer and its thickness varies from 85 - 165 meters between the sandy aquifer (lower aquifer) and the upper unconfined carbonate aquifer.

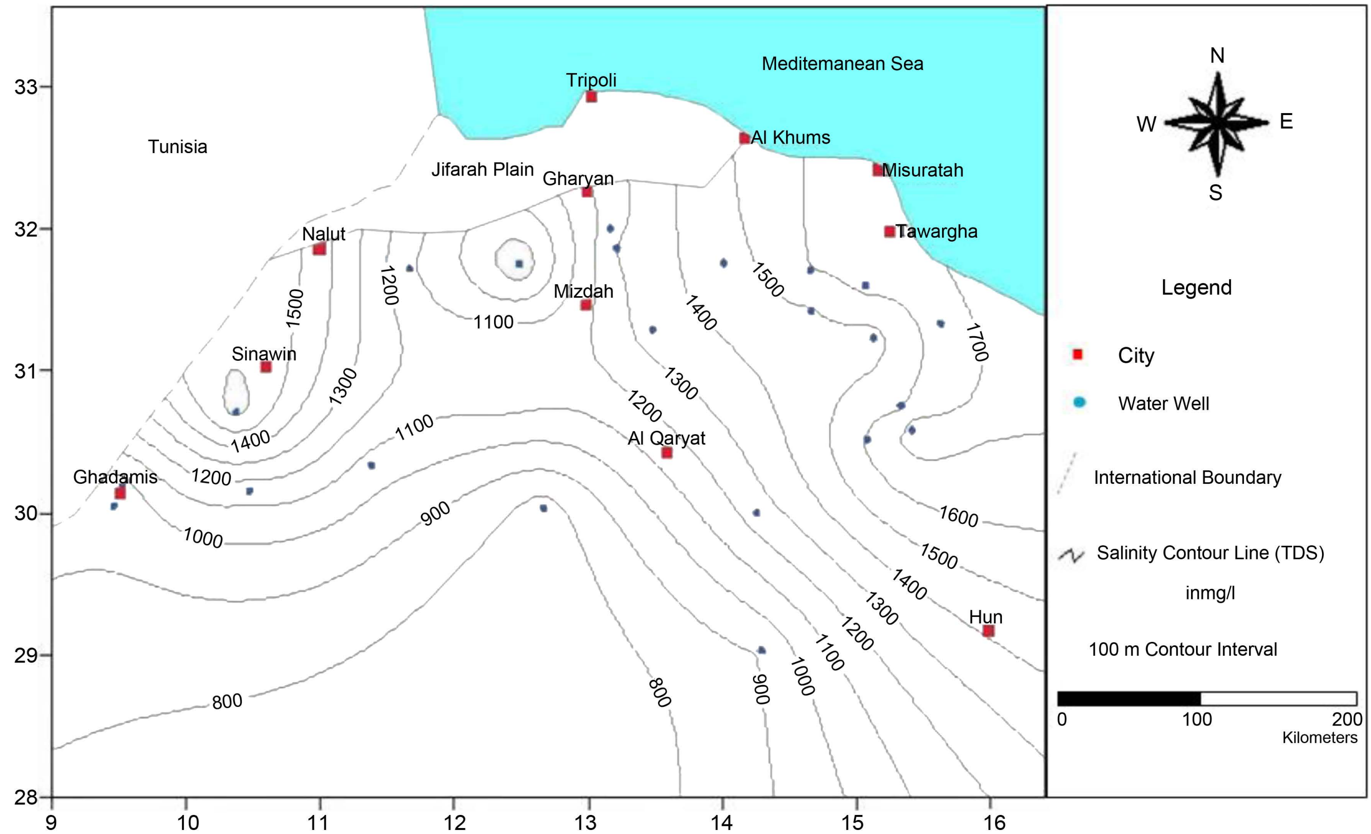

Figure 10. Salinity map (TDS—mg/l) of Kiklah aquifer.

The upper Triassic and lower Jurassic represented by Bir Al Ghanam and Tacbal formations (lower aquitard). These formations are mainly composed of shale with gypsum and karstenite and some dolomitic limestone and clay forming a thick layer between the sandy and dolomitic limestone aquifer of the Middle Trias and the sandy aquifer of Kiklah Formation.

The groundwater abstraction in the area is to supply water for agriculture, domestic and industrial uses. Table 1 shows the groundwater abstraction during the period 1970 the starting of the development to 2005. The total abstraction during 2005 was 132 Mm^3/year most of it has been used for agriculture and about only 20% has been used for domestic uses.

5. Groundwater Modeling

Numerical model has been constructed using MODFLOW software [11]. The model was designed to cover the study area of about 215,000 km^2. The schematic representation of the areal finite difference mesh used to discretize the study area. Two layers have been identified for this model with 80 columns and 50 rows and the spacing of the grids is 10,000 m.

The boundary conditions for the model are:

- In the upper aquifer: The following boundary conditions have been imposed:

Table 1. Estimated groundwater abstractions in Ghadamis Basin (modified after [6]).

Aquifer and Production Zone	Production in Million (m^3/year)							
	1970	1975	1980	1985	1990	1995	2000	2005
Upper aquifer (Mizdah-Nalut)								
Coastal Zone (Al Khums-Tawurgha)	5	9	42	51	48	45	42	42
Sufajjin Catchment	0	1	1	2	5	10	15	15
Al Jufrah	6	13	90	111	114	97	73	73
Total Upper Aquifer	11	23	133	164	167	152	130	130
Lower Aquifer (Kiklah)								
Sufajjin Catchment	0	0	0	65	57	59	59	59
Eastern Flank of Hamadah Al Hamra	0	15	37	54	50	51	51	51
Southern Flank of Jabal Nefusa	0	1	9	13	15	15	16	16
Western Flank of Hamadah Al Hamra	0.1	0.1	5	6	6	6	6	6
Total Lower Aquifer	0.1	16.1	51	138	128	131	132	132

-No flow boundary along the northern, eastern and western boundaries of the aquifer.

-Constant head boundary along northeast boundary of the aquifer (Tawargha-Misuratah area) and southern boundary. During the steady state simulation, these boundary conditions have been applied, while during the transient runs, these boundary conditions are changed to fixed flux.

- In the lower aquifer: The following boundary conditions have been imposed:

-No flow boundary along the eastern and southwest boundary of the aquifer.

- Constant head boundary along the northern-southern limit and northeast northwest boundary of the aquifer. During the steady state simulation, these boundary conditions have been applied, while during the transient runs, these boundaries have been changed to fixed flux boundary.

6. Model Calibrations

The steady state model calibration consisted in the reproduction of the natural regime of the aquifer systems in the area prior to development [12]. The hydraulic head in year 1970 (assumed as the pre-development hydraulic head distribution), has been taken as representative of the natural regime of the aquifer system and utilized as reference piezometric distribution for the steady state model calibration.

During the steady state calibration of the model, the transmissivities and vertical leakage between the two aquifers were used as calibration parameters. The best agreement between the computed results and the observed piezometric data obtained are shown in Figure 11 and Figure 12. As shown in these figures, the computed hydraulic head fits reasonably well with the observed hydraulic head distribution.

Figure 13 and Figure 14 represent the comparison between the computed and observed values of hydraulic head, for the considered control points, in order to evaluate

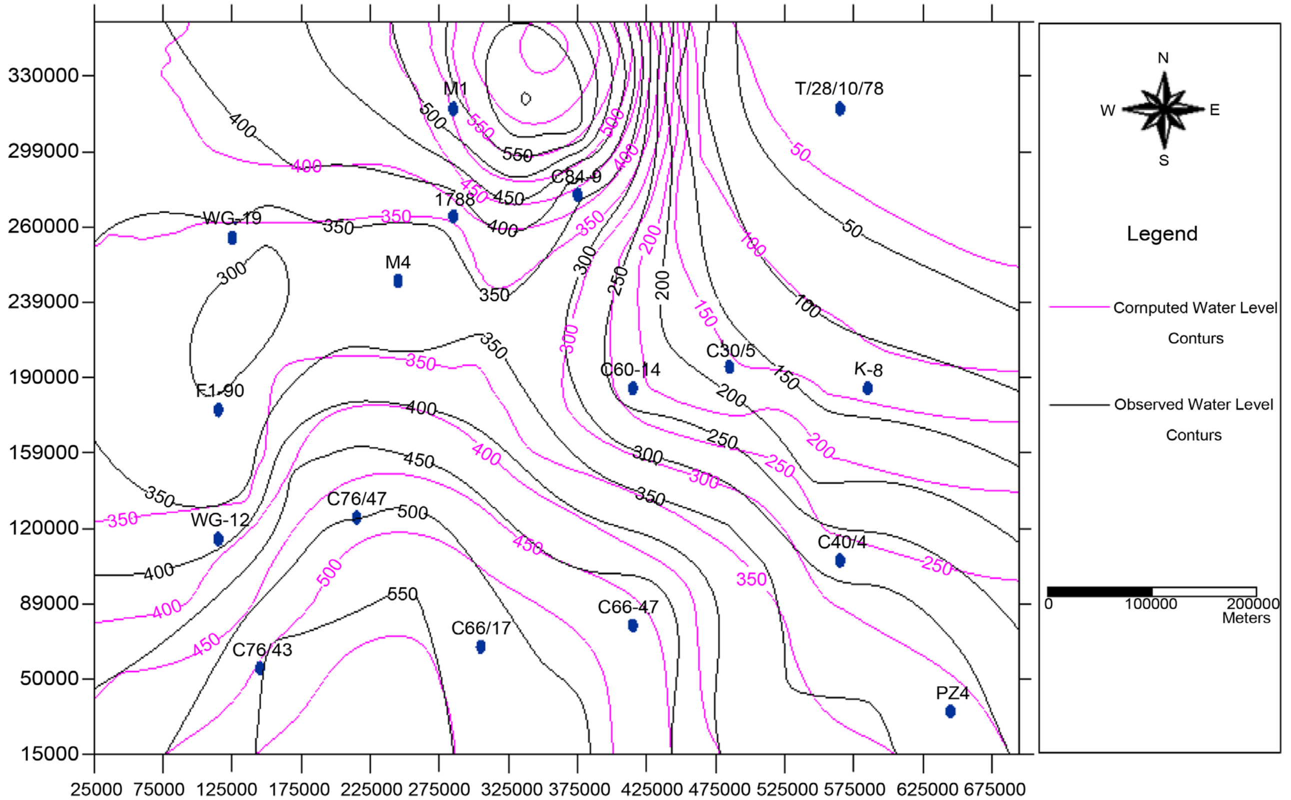

Figure 11. Observed and computed hydraulic heads in the upper aquifer.

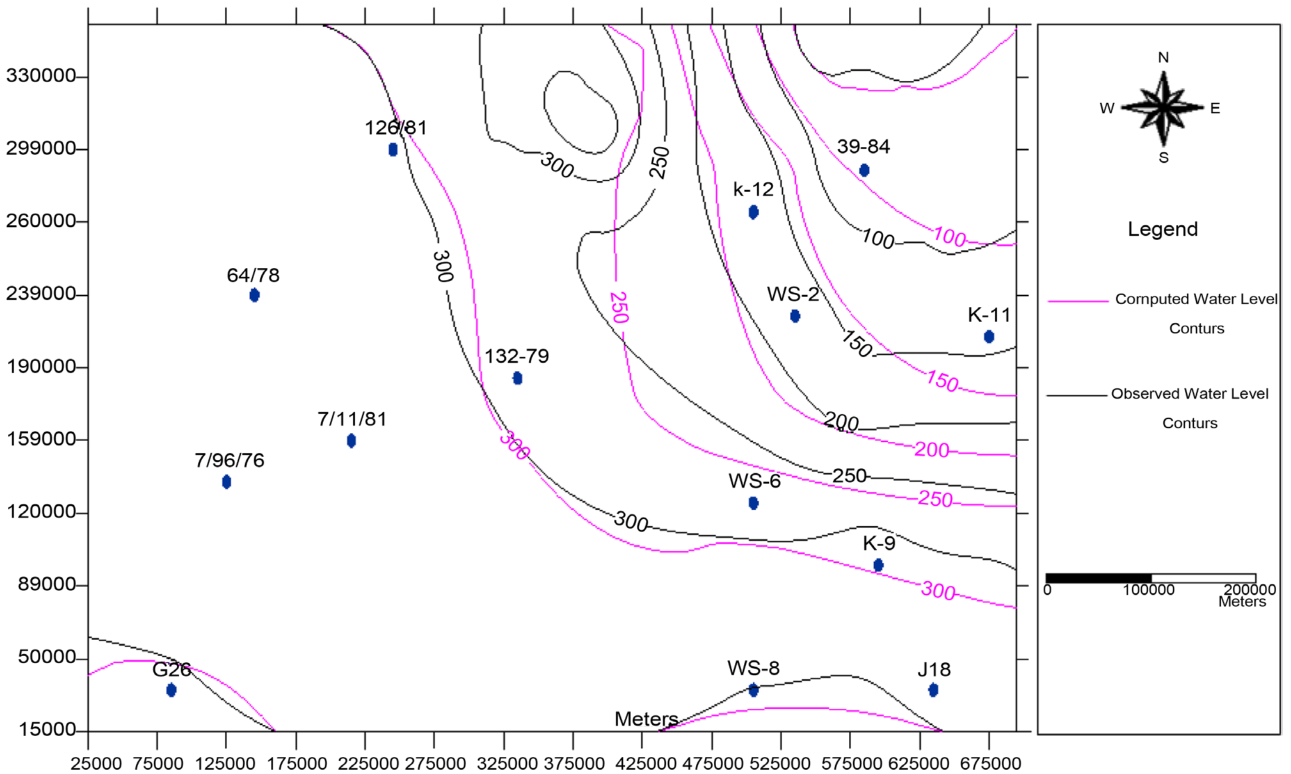

Figure 12. Observed and computed hydraulic heads in the lower aquifer.

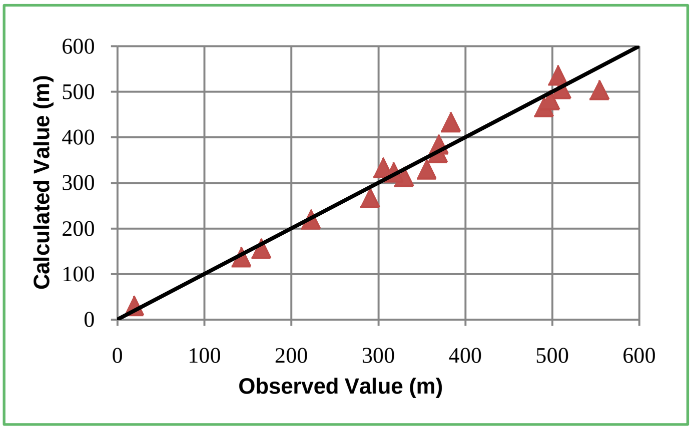

Figure 13. Observed head value versus computed value of upper aquifer.

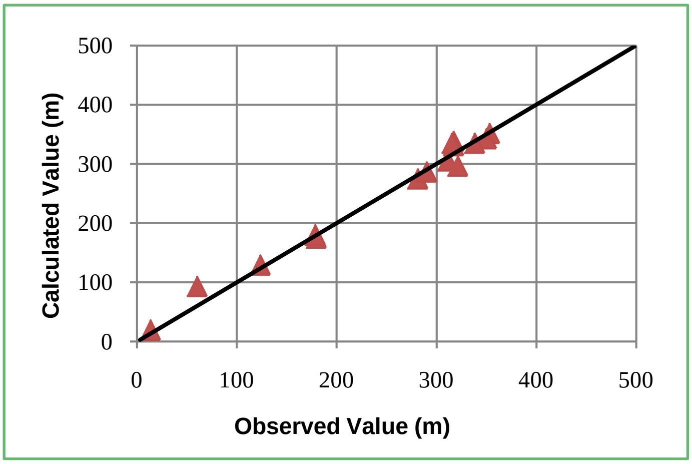

Figure 14. Observed head value versus computed value of lower aquifer.

the calibration performance in the upper aquifer system and lower aquifer system respectively. Figure 15 and Figure 16 show the distribution of transmissivity after calibration in the upper and lower aquifer respectively. Figure 17 show the distribution of vertical leakage after calibration between the upper and the lower aquifers.

The model water budget indicates that the total inflow to the groundwater system in the study area through the upper aquifer is 5,906,479 m^3/day and through the lower aquifer is 3,121,201 m^3/day. The total outflow from the groundwater system is 9,027,647 m^3/day of which 5,906,474 m^3/day from the upper aquifer and 3,121,173 m^3/day from the lower aquifer.

7. Model Verifications and Predictions

The non-steady state model calibration consisted in the reproduction of the hydrodynamic response of the groundwater system to exploitation during the period 1970-2005 [12].

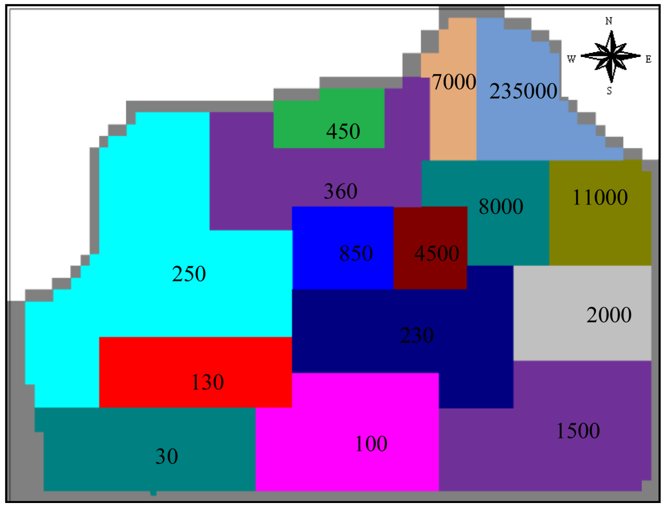

Figure 15. Model transmissivity distribution in the upper aquifer (in m^2/d).

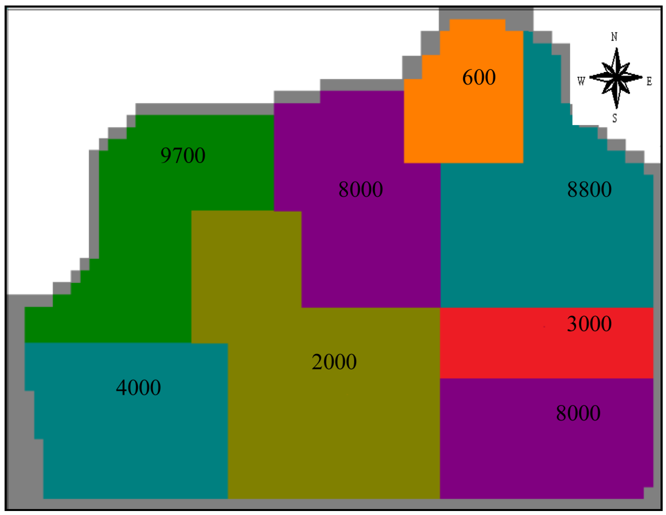

Figure 16. Model transmissivity distribution in the upper aquifer (in m^2/d).

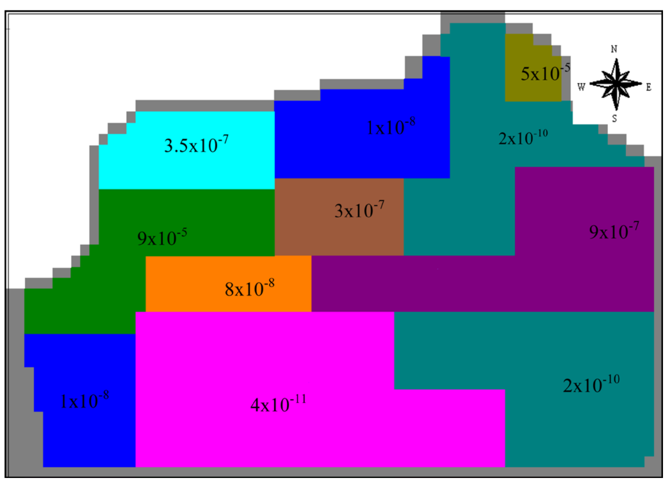

Figure 17. Model vertical leakage distribution in the upper aquifer (in day^{-1}).

During this period the aquifer system has been subjected to water abstractions which caused, in some places of the groundwater system, drawdown of water levels. The non-steady state simulation was constructed using the following hydraulic parameters, obtained from steady state simulation of Ghadamis Basin aquifers, for the aquifer systems: transmissivity, vertical leakage, initial head, natural recharge and discharge.

To reproduce the history of the groundwater system in the period 1970-2005, the historical exploitation has been introduced as input in the model by use of a histogram of considered magnitude at an established reference time. The abstraction values are used as input in the model for each abstraction zone.

The hydraulic parameters adjusted during the non-steady calibration of the model are the storage coefficient and the specific yield of the aquifers. The storage coefficient values of the lower aquifer are found to be in the range of 10^{-5} to 7×10^{-3}. The specific yield of the upper aquifer is found to be in the range of 10^{-3} to 2×10^{-2}.

Figure 18 shows the computed versus observed well hydrographs are presented. The hydrographs of two observation wells represent the upper aquifer. Figure 19 shows the hydrographs of two observation wells representing the Lower aquifer.

8. Model Predictions

After the fitting of the computed and observed past historical of the water levels obtained, the model has been assumed as representative of aquifer systems and the non – steady state simulation was prepared to predict the draw downs during the period (2005-2055) of pumping. This prediction includes the previous, preset and the planned production including the Ghadamis well field of Great Man-Mad River, which includes 106 production wells. The planned abstraction of this field is equal 90 Mm³/year. This well field is located in the region of Ghadames-Derj.

The groundwater production from the lower aquifer in the period 2005-2055 is shown in Table 2. Figure 20 and Figure 21 show the computed drawdown of the lower

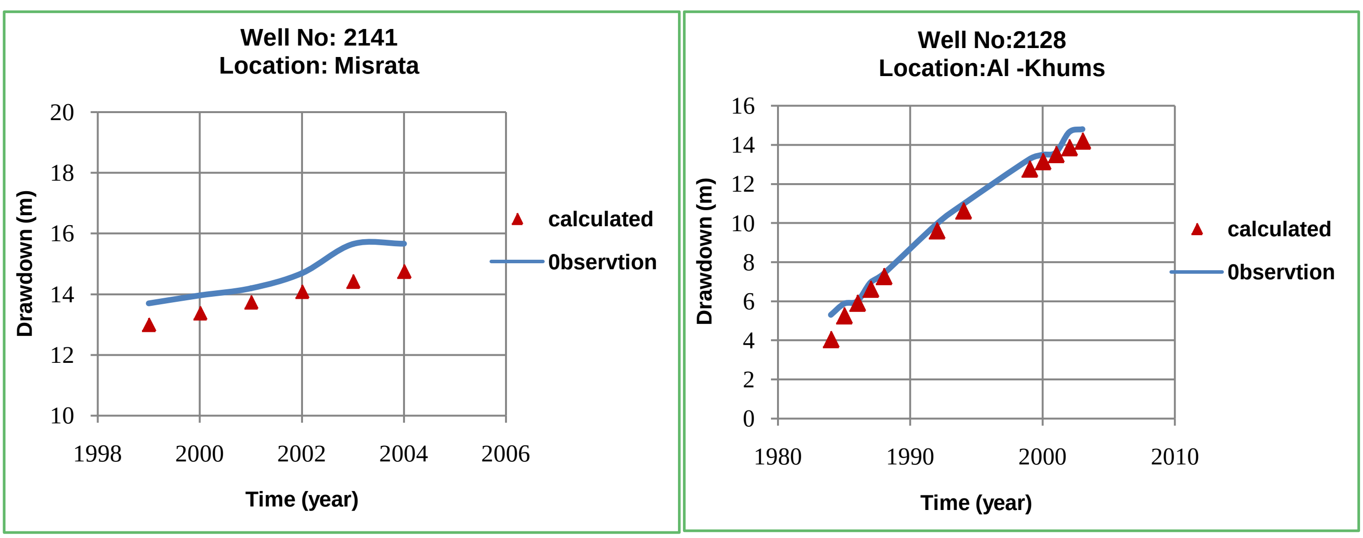

Figure 18. Non-steady state model calibration-computed versus observed hydrograph of upper aquifer.

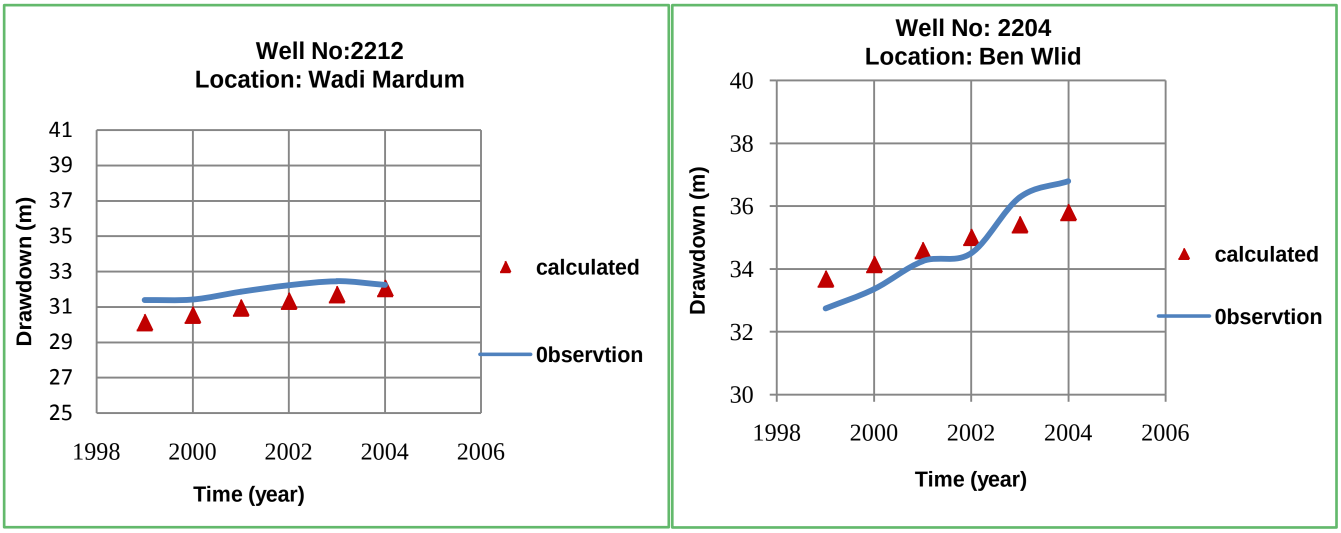

Figure 19. Non-steady state model calibration-computed versus observed hydrograph of lower aquifer.

Table 2. Planned groundwater abstractions from lower aquifer in the period 2005-2055.

Production Zone	Production in Million (m^3/year)										
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Sufajjin Catchment	59	59	59	59	59	59	59	59	59	59	59
Eastern Flank of Hamadah al Hamra	51	51	51	51	51	51	51	51	51	51	51
Southern Flank of Jabal Nefusa	16	16	16	16	16	16	16	16	16	16	16
Western Flank of Hamadah Al Hamra	6	6	6	6	6	6	6	6	6	6	6
G M R Ghadamis Willfield	0	0	90	90	90	90	90	90	90	90	90
Al Jufrah	0	0	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Total Lower Aquifer	132	132	223.8	223.8	223.8	223.8	223.8	223.8	223.8	223.8	223.8

aquifer in the period 2005-2055. The maximum value of the computed drawdown is centered in the well field and range between 55 - 60 m in the year 2055. The total planned abstraction is 223.8 Mm^3/year of which 55% of it will be used for domestic uses.

9. Conclusions

From this study it can be concluded that Ghadamis Basin is considered as a major groundwater basin in northwestern Libya with an area of about 215,000 km^2. The most important groundwater resources in the Ghadamis Basin are represented by the two main aquifer systems which are the Kiklah sandstone aquifer and Upper Cretaceous carbonate aquifer systems.

The steady state simulation used in the area was constructed in order to compute the transmissivity, recharge, the vertical leakage distribution and to determine the inflow and the outflow for the aquifer systems by matching the observed and the computed hydraulic heads. The results obtained from the steady state can be summarized as follows:

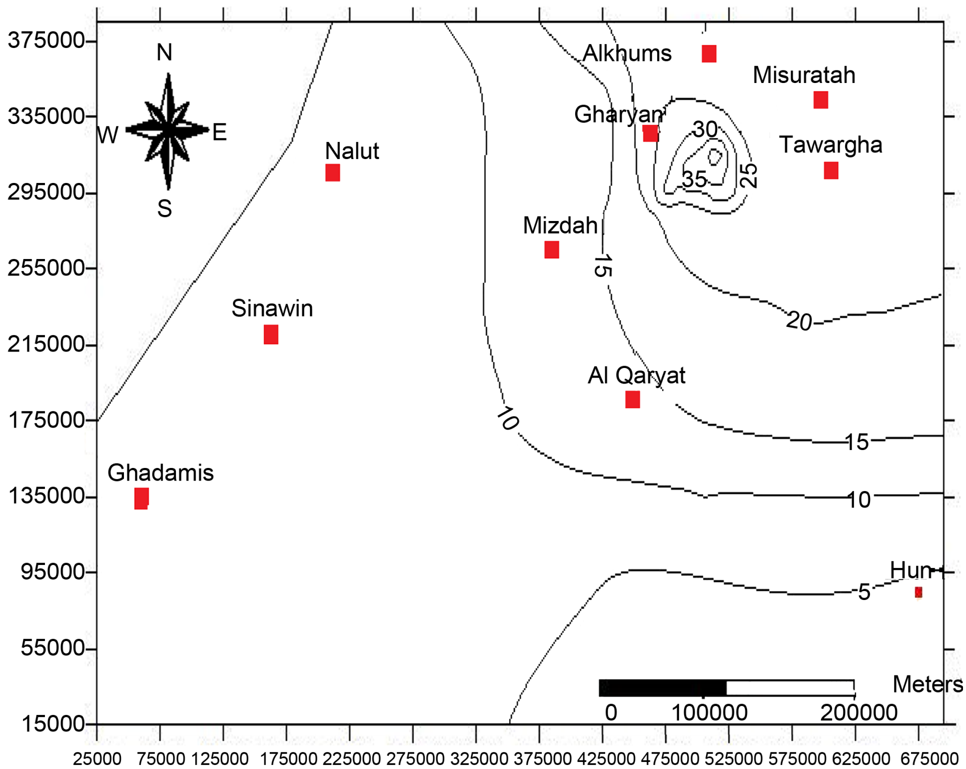

Figure 20. Computed drawdown in the lower aquifer in the period 1970-2005 (in meters).

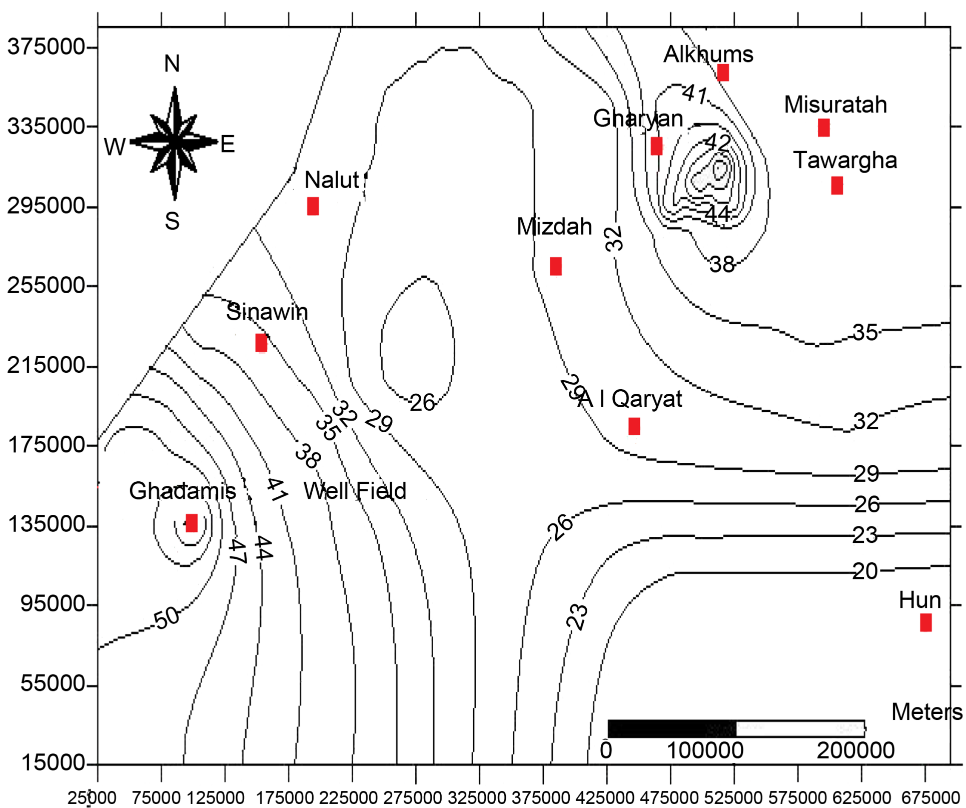

Figure 21. Computed drawdown in the lower aquifer in the period 1970-2055 (in meters).

- The transmissivity ranges from 30 to 23,500 m^2/day for the upper aquifer and from 600 - 9700 m^2/day for the lower aquifer.
- The vertical leakage between the two layers ranges from $4 \times 1^{0-11}$ to $9 \times 1^{0-5}$ da^{y-1}.
- The total inflow to the upper aquifer is 5,906,479 m^3/day, and the total inflow to the lower aquifer is 3,121,201 m^3/day. The total groundwater outflow from the upper aquifer is 5,906,474 m^3/day, and the total groundwater outflow from the lower aquifer is 3,121,173 m^3/day.
- The verification of the non-study state simulation was achieved by using the historical groundwater decline and historical exploitation for the period from 1970 to 2005. The results obtained from this model can be summarized as follow:
- Specific yield for the upper aquifer ranges from 1×10^{-5} to 2×10^{-2}.
- Storage Coefficient for the lower aquifer ranges from 1×10^{-6} to 7×10^{-3}.
- The maximum computed drawdown after 50 years of continuous pumping is 60 meters in the lower aquifer in the center of the Great Man-Mad River well field.

10. Recommendations

1) Exploration wells and observation wells should be drilled, especially in areas of no data, and the necessary field and laboratory tests should be conducted to determine the hydraulic and hydrochemistry properties of the different groundwater aquifers to help close existing gaps in the hydrogeological data.

2) Over the whole Ghadamis Basin, the knowledge of the abstractions and a periodical monitoring are necessary in order to allow an appreciation of the reliability of the model. It is important, in this regard, to urge the users to install meters which would allow a monitoring of the volumes exploited.

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