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Contribution to the hydrogeology of Six Hills sandstone aquifer in East El-Oweinat area, south Western desert, Egypt

Contributo sull'idrogeologia dell'Acquifero arenario di"Six Hills", nella zona di East El-Oweinat, deserto sud-occidentale, Egitto

Saad Younes Ghoubachi

Riassunto: L'area di El-Oweinat si trova nel sud-ovest dell'Egitto ed è considerata uno dei nuovi progetti di bonifica del territorio nel deserto occidentale. L'Acquifero Arenario Nubiano ha un'alta capacità e una buona qualità delle acque sotterranee. I risultati di studi geologici e idrogeologici hanno dimostrato che l'acquifero di Six Hills rappresenta l'unica risorsa idrica sotterranea utilizzata a tutti gli effetti (agricoltura, acqua potabile, allevamento domestico e pollame) nell'area di East El-Oweinat e sovrasta direttamente il basamento Precambriano. La falda acquifera si trova in stato non confinato e le sezioni idrogeologiche mostrano che lo spessore saturo della falda acquifera oscilla tra 150.2 e 651 m e aumenta verso ovest. La direzione del flusso è verso nord-est con un gradiente idraulico medio dello 0,6‰. La capacità calcolata della falda nella zona di East El-Oweinat (4.340 km^2) raggiunge 350 miliardi di metri cubi di acqua dolce.

Il confronto della fratimetria nei stessi pozzi di monitoraggio durante 14 anni (2003 e 2016) rivela che l'abbassamento piezometrico è compreso tra 5 cm/anno e 80 cm/anno. Il tasso di pompaggio è aumentato da 600.000 m^3/giorno nel 2003 a 3.600.000 m^3/giorno nel 2016. La trasmissività media raggiunge i 2.060 m^2/giorno, riflettendo l'alto potenziale della falda acquifera di arenaria nella zona di East El-Oweinat.

Per studiare una gestione sostenibile dei prelievi di acqua è stato condotto uno studio utilizzando il codice MODFLOW. Sono stati considerati quattro scenari. Fra gli scenari presentati, il quarto risulta essere quello più adeguato a garantire la sostenibilità dell'uso della risorsa idrica sotterranea mantenendo il tasso di abbassamento della quota piezometrica intorno allo 0.66 m/anno riducendo l'attuale prelievo (pari a 10,000 m^3/giorno per pozzo) di circa il 40%.

Keywords: *hydrogeology, Six Hills sandstone aquifer, El-Oweinat area.*

Parole chiave: idrogeologia, acquifero arenario di Six Hills, El-Oweinat.

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Abstract: *El-Oweinat area is located in southwestern Egypt and is considered to be one of the new land reclamation projects in the Western Desert. The Nubian Sandstone aquifer has high potentiality and good groundwater quality. The results of geologic and hydrogeologic studies reveal that the Six Hills sandstone aquifer represents the sole groundwater resource used for all purposes (agriculture, drinking, domestic, livestock and poultry) in East El-Oweinat area. The Six Hills sandstone aquifer overlies directly the Precambrian basement rocks. The concerned aquifer exists under unconfined conditions as it is exposed on the surface. The hydrogeological cross sections show that the fully saturated thickness of the Six Hills sandstone aquifer ranges between 150.2 m and 651 m and increases towards the west. The groundwater generally flows towards the northeast direction with an average hydraulic gradient of 0.6 ‰. The calculated groundwater volume of the Six Hills sandstone aquifer in East El-Oweinat area (4,340 km^2) reaches 350 bcm of fresh water.*

The comparison of the depth to water in the same monitoring wells during 14 years (2003 and 2016) reveals that the head decline rate in groundwater depths were ranging between 5 cm/year and 80 cm/year. The pumping rate increased from 600,000 m^3/day in year 2003 to 3,600,000 m^3/day in 2016. The average transmissivity attains 2,060 m^2/day reflecting the high potential of the Six Hills sandstone aquifer in East El-Oweinat area.

The groundwater flow model (MODFLOW) has been used to investigate the impact of groundwater withdrawal on groundwater levels for sustainable groundwater management. Four scenarios were applied to predict the probable head changes in the Six Hills sandstone aquifer and their impact on the availability of groundwater. The fourth scenario is recommended in order to sustain the groundwater resources in the study area and keep the drawdown rates in the range of 0.66 m/year through reducing the present discharging rates (10,000 m^3/day/well) by about 40 %.

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Introduction

East El-Oweinat area is one of the most important developmental areas which drawn considerable attention of Egyptian government and investors in the last few decades. The soil and groundwater resources of this area cover the requirements of the reclamation projects and implementation of new communities. East El-Oweinat area is located in the southwestern part of the Western Desert, between latitudes 22o 00` (Egyptian-Sudanese border) and 23° 00` N and longitudes 27° 55` and 29° 00` E, covering an area of about 4,200 km^2 (1,037,400 acre) (Fig. 1). It is located 380 km to the south of the capital city of El-Dakhla Oasis and is accessible from Cairo to Assuit, via Kharga and Dakhla by good asphaltic roads about 1,200 km long. The huge sand plain occupies the majority of the East El-Oweinat area. The ground surface elevation varies from 320 m asl in south to 200 m asl in the north.

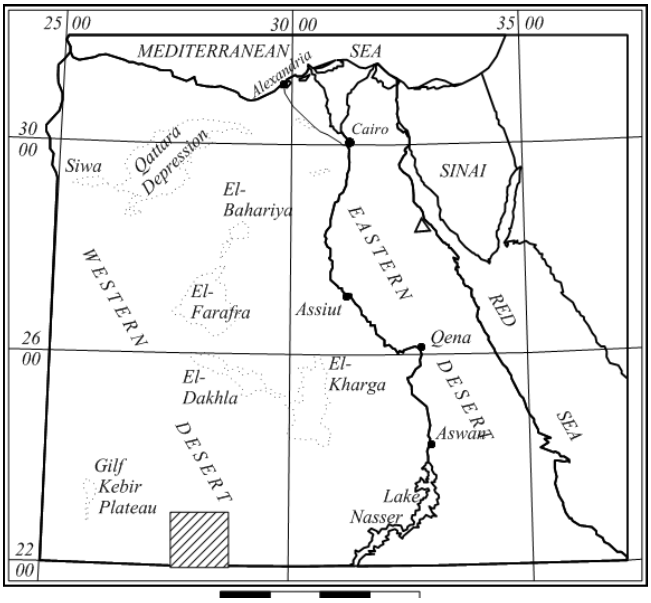

Fig. 1 - Location map of the study area.

Fig. 1 - Ubicazione dell'area di studio.

The study area is characterized by extreme aridity with minimal precipitation, virgin soils and huge groundwater storage. Maximum temperature during summer often exceeds 40°C, whereas minimum temperature during winter may decline close to freezing. Natural evaporation rate ranges between 10 mm/day during January to 31 mm/day during July, with an average of 22.2 mm/day. The relative humidity ranges between 11% in May and 41% in December (Nour 1996). The cultivated areas in East El-Oweinat area have increased from 42,600 acres in 2004 (Ghoubachi 2004) to 180,000 acres in 2016 (present work) in the frame of a plan of reclaiming 190,000 feddans by the year 2022 (Ebraheem et al. 2003). Therefore, the annual groundwater recharge for the Six Hills aquifer is too low to sustain the large scale irrigation system and further developmental activities (Heinl and Thorweihe 1993; Nour 1996; Ebraheem et al. 2003).

The present work delineates the hydrogeological characteristics of the Six Hills sandstone aquifer in East El-Oweinat area. In addition, a groundwater flow model with MODFLOW (3D-Groundwater modeling with PMWIN) has been used to extrapolate the feasibility of groundwater exploitation and to determine the maximum drawdown expected for the next 20 years through different groundwater extractions scenarios.

Geology

The study area is dominated by a sedimentary succession ranging in age from Cretaceous to Quaternary with exposures of igneous and metamorphic rocks belonging to the Precambrian basement rocks (Fig. 2). The Precambrian basement rocks are exposed on the surface in Bir Tarafwi area and are represented by Tarafwi-Abu-Husein Uplift extending in east-west direction (Ghoubachi 2004). This basement uplift affected the Bir Tarafwi area (northeast El-Oweinat area), where the sedimentary cover in this area is relatively thin. In Bir Tarafwi area, the basement uplift acts as a barrier against the lateral groundwater flow towards north direction causing the outflow of some springs in this area (e.g. Bir Tarafwi and west Bir Tarafwi springs).

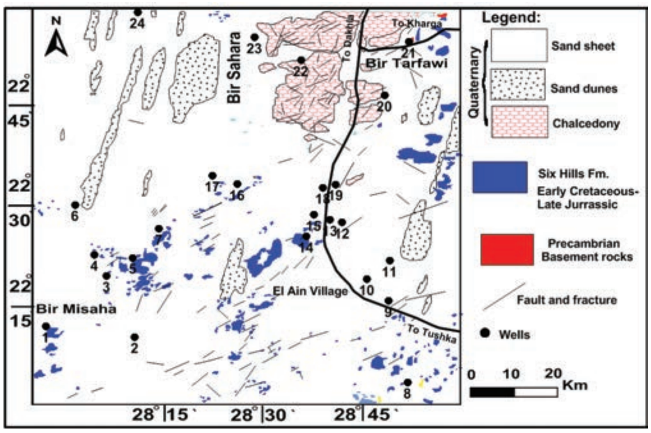

Fig. 2 - Geological map of East El-Oweinat area (Conoco 1987).

Fig. 2 - Carta geologica dell'area di East El-Oweinat (Conoco 1987).

Based on the data of the drilled wells, the basement rocks are reported in the subsurface at depths ranging between 161 m from ground surface in the northeastern part of the study area (Well No. 20) and 710 m west of study area (Well No. 6). While, the basement surface according to sea level varies from +90 m above sea level (asl) at the eastern part of study area (Well No.20) to -406.22 m asl at the west (Well No. 6) (Table 1) reflecting gradual dipping towards the west direction (Fig. 3). The thickness of the sedimentary cover increases towards the west direction. The Six Hills Formation is exposed on the surface in East El-Oweinat area and represents the oldest sedimentary rock unit and represents the sole aquifer in East El-Oweinat area. It overlies directly the Precambrian basement rocks and underlies the thin Quaternary deposits represented by sand sheet and sand dunes. It is made up of ferruginous sandstone and is assigned to the Late Jurassic to Early Cretaceous (Barthel and Boettcher

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1978). The maximum fully penetrated thickness reaches 712 m (Well No. 6) in the west, while the minimum thickness attains 161 m (Well No. 20) in northeast. Accordingly, the thickness of Six Hills Formation increases towards the west direction. The Quaternary deposits represent by sand sheet and sand dunes. The name of sand sheet is assigned to a sand area marked by an extremely flat surface and absence of any topographic relief. It is covered the Six Hills Formation in the study area. The sand dunes are well developed only in East El-Oweinat area, especially in the western portion and occupy an area of about 640 km^2.

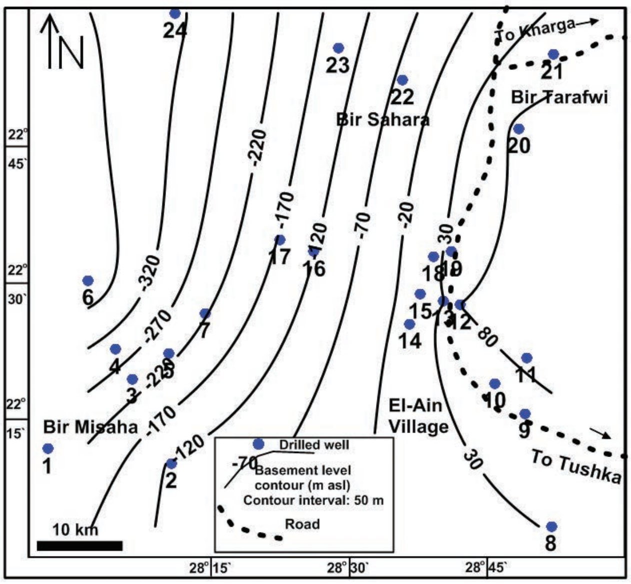

Fig. 3 - Basement surface contour map of East El-Oweinat area.

Fig. 3 - Andamento della superficie del basamento dell'area di East El-Oweinat.

The main factor controlling the structural pattern of the East El-Oweinat area is Misaha Graben, which occupies the majority of the study area. This Graben fault extends about 250 km wide and is bounded to the west by Gebel Kamil (basement rocks) and to the east by Bir Safsaf basement rocks. It runs approximately in the NNW-SSE direction and is responsible for formation of a large number of normal faults. The majority of these faults throw towards the west direction causing the large thickness of the sedimentary cover (Six Hills Formation) in the west direction. In East El-Oweinat area, the majority of the fault trends are Northeast-Southwest (Fig. 2; Ghoubachi 2004).

Hydrogeology

The Six Hills sandstone aquifer represents the sole source of water in East El-Oweinat area. This aquifer directly overlies the Precambrian basement rocks and underlies the sand sheet. In addition, it is exposed on the surface in some areas in East El-Oweinat area. The number of the pumping wells increased from 355 wells in year 2002 (Ghoubachi 2004) to 1600 wells in the present work (2016). The depths of these wells range between 70 m (well no. 1) and 722 m (well no. 6), Table 2.

These wells are expected to have great impact on the groundwater levels of the aquifer. The groundwater of the Six Hills sandstone aquifer occurs under unconfined conditions. The concerned aquifer is hydraulically connected with the underlying Precambrian basement rocks, as a result of faulting (Fig. 4). The groundwater salinity (total dissolved salts) of the concerned aquifer varies between 225 ppm (Well No. 12) and 962 ppm (well no. 23), Table 2. In East El-Oweinat area, the fully penetrated saturated thickness of the unconfined Six Hills sandstone aquifer is calculated as the distance from the

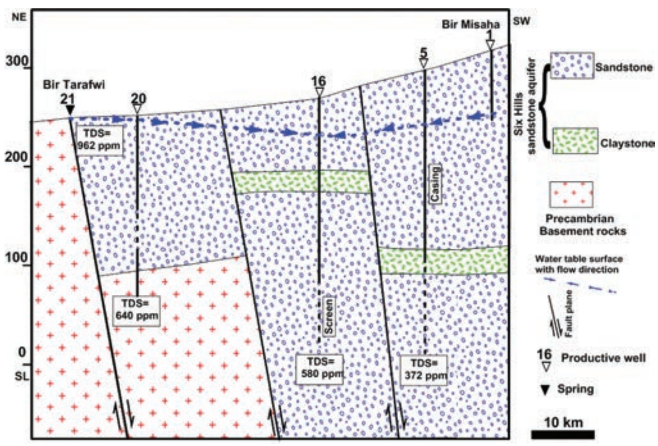

Fig. 4 - Hydrogeological cross-section, East El-Oweinat area.

Fig. 4 - Sezione idrogeologica dell'area di East El-Oweinat.

Tab. 1 - The encountered basement rocks in East El-Oweinat area.

Tab. 1 - Rocce del basamento incontrate nell'area di East El-Oweinat.

Well name	Well No.	Depth to basement rocks (m bgs)	Ground elevation (m asl)	Basement surface (m asl)
GPC IV	2	420	307.12	-112.88
GPC VII	6	710	303.78	-406.22
GPC III	8	257	288.8	+31.8
GPC I	12	192	273.26	+81.26
Kiloptra 18	13	233	273	+40
Piezometer 5	20	161	251	+90
GPC VI	24	625	290.33	-334.67

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Tab. 2 -Hydrogeological data of some pumping wells tapping the Six Hills sandstone aquifer, where T.D=Total Depth, G.E=Ground Elevation; D.T.W=Depth to Groundwater, W.L=Goundwater Level, SI=Screen Interval and T.D.S=Total Dissolved Solids (salinity).

Tab. 2 -Dati idrogeologici di alcuni pozzi che insistono sull'acquifero di Six Hills. T.D. = profondità totale, G.E. = quota del piano campagna, D.T.W. = profondità del livello di falda, W.L. = livello di falda, S.I. = intervallo quote di finestratura del pozzo, T.D.S = salinità espressa come solidi disciolti totali.

Well name	Well No.	T.D (m)	G.E (m asl)	D.T.W (m)	W.L (m asl)	S.I (m)	T.D.S (ppm)
Bir Misaha 17	1	70	323	65	258	65-70	-
GPC IV	2	431	307.12	52.62	254.5	-	-
El Gisha	3	300	309	-	-	-	333
El Gisha80	4	300	307	-	-	200-300	224
El Gisha20	5	311	313	59.33	253.67	208-303	372
GPC VII	6	722	303.78	59	245.1	-	-
Sanabl	7	300	297	-	-	170-300	503
GPC III	8	253	288.8	39.62	249.08	-	-
Sahari Co.	9	-	274	34.07	239.93	-	611
GPC V	10	435	274.36	39.20	235.16	-	502
Sahari 15	11	-	265	-	-	-	467
GPC I	12	192	273.26	35.02	238.24	-	225
Kiloptra18	13	260	273	35.20	237.8	146-234	426
Kiloptra75	14	350	269	34.79	234.21	180-350	633
Kiloptra41	15	330	266	29.5	236.5	170-330	671
Al Zahra	16	350	281	49.72	231.28	180-350	580
Pizometer1	17	-	280	44.80	235.2	-	-
Gisha44	18	300	264	27	237	179-293	-
Gisha28	19	294	264	-		179-287	676
Pizometer5	20	186	251	10.80	240.2	99-124	-
Ain Tarfawi1	21	Ain	243			-	-
Bir Sahara	22	-	259	20.15	238.85	-	-
Ain Tarfawi2	23	Ain	244	-	-	-	962
GPC VI	24	632	290.33	49	241.98	-	-

water table to the basement rocks. It ranges between 150.2 m at the eastern side of study area (well no. 20) and 651 m at the western side (well no. 6), Table 3. The constructed fully saturated thickness contour map for the concerned aquifer reveals an increase of the saturated thickness towards the west (Fig. 5).

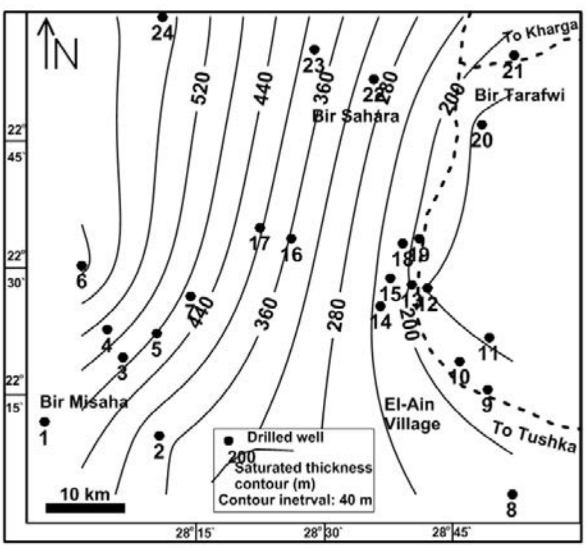

Fig. 5 - Fully saturated thickness map of Six Hills sandstone aquifer.

Fig. 5 - Mappa dello spessore saturo per l'acquifero arenario di Six Hills.

Tab. 3 - Fully saturated thickness of some wells tapping the Six Hills sandstone aquifer, East El-Oweinat area.

Tab. 3 - Valore dello spessore saturo valutato in alcuni sondaggi effettuati nell'acquifero arenario di Six Hills, nell'area di East El-Oweinat.

Well name	Well No.	Depth to water (m)	Depth to basement rocks (m bgs)	Fully Saturated Thickness (m)
GPC IV	2	51	420	369
GPC VII	6	59	710	651
GPC III	8	39.62	257	217.38
GPC I	12	35.02	192	156.98
Kiloptra 18	13	35.20	233	197.8
Piezometer 5	20	10.80	161	150.2
GPC VI	24	49	625	576

In East El-Oweinat area, the static depth to water was measured in 2016 during the present work in 17 productive and piezometer wells (Table 2). It varies between 10.8 m (Well No. 20) at the northeastern side of the study area near Bir El-Tarafwi Basement Uplift and 65 m (well no.1, Bir Misaha) in the southwestern side of the study area. Shallow groundwater in well no. 20 may be attributed to the basement uplift, acting as a barrier to groundwater flow.

A comparison between the present depth to water during field work (2016) and in 2002 measured by (Ghoubachi 2004) for same wells show an increase in depth to water with time (Table 4 and Fig. 6).

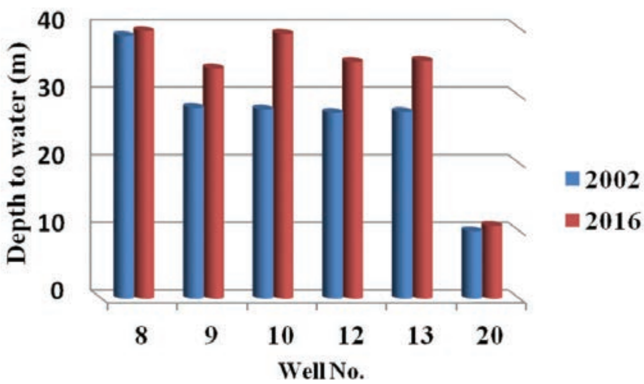

Fig. 6 - Relationship between depth to water measured inside pumping wells and time.

Fig. 6 - Misura della profondità di falda misurata in alcuni pozzi nel tempo.

Tab. 4 - Temporal variations of the depth to water in some wells in East El-Oweinat area.

Tab. 4 - Variazioni della profondità di falda in alcuni pozzi nell'area di East El-Qweinat

Well name	Well No.	Depth to the water (m)		Depth to water Difference (m)
		2016	2002	
GPC III	8	39.62	38.89	0.73
Ain 42	9	34.07	28.27	5.8
GPC V	10	39.20	28	11.20
GPC I	12	35.02	27.51	7.51
Kiloptra 18	13	35.20	27.64	7.56
Piezometer 5	20	10.80	10	0.80
Bir Sahara	22	20.15	18.6	1.55

The average depletion in depth to water during the last 14 years in groundwater ranges between 0.73 m (well no. 8, GPC III) and 11.20 m (well no. 10, GPC V) (Table 4). The maximum drawdown is recorded in well no. 10 and is due to intensive pumping in El-Ain Village (Capital of East El-Oweinat) farms of high groundwater discharge, while the low depletion recorded at well no. 8 is because this well is located away from the farms. The average annual depletion groundwater reaches 36 cm/year with an annual discharged of 13x10^8 m^3/year.

The water table map (Fig. 7) indicates that the highest observed water level attains 258 m asl (well no. 1) located in the southwest side of the study area, while the lowest level is 231.28 m.a.s.l (well no. 16) located in the central part of the study area of high discharge.

The constructed water table map also shows that the regional groundwater of the Six Hills sandstone aquifer flows from southwest to the northeast direction, except the northeast portion of the study area where the groundwater flows to the center with an average hydraulic gradient of 0.6 %o. This is because this area is located in the highest groundwater discharging area and the effect of the Tarafwi basement uplift at north area causing return of groundwater flow to the south.

The huge increasing in groundwater yield of productive wells is attributed to the increasing of the number of productive wells.

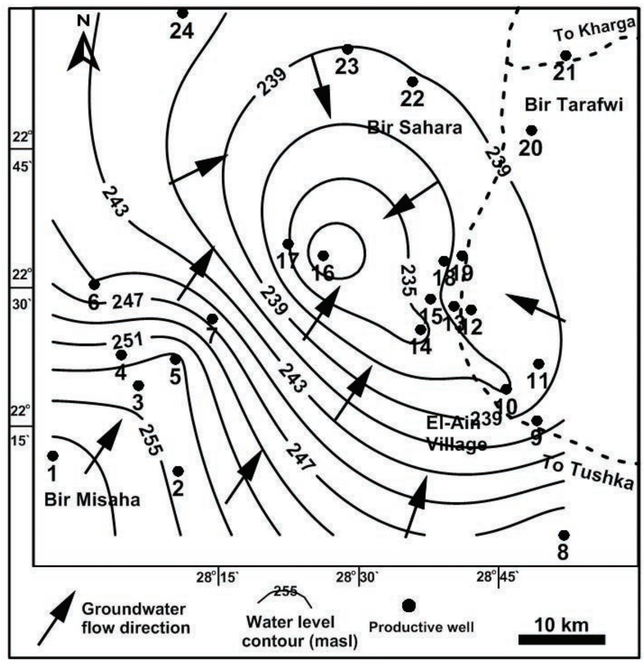

Fig. 7 - Water table map of the Six Hills sandstone aquifer (Dec. 2016), East El-Oweinat.

Fig. 7 - Carta piezometrica dell'acquifero arenario di Six Hills (dicembre 2016), East El-Oweinat.

The constructed water table map also shows that the regional groundwater of the Six Hills sandstone aquifer flows from southwest to the northeast direction, except the northeast portion of the study area where the groundwater flows to the center with an average hydraulic gradient of 0.6 ‰. This is because this area is located in the highest groundwater discharging area and the effect of the Tarafwi basement uplift at north area causing return of groundwater flow to the south.

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The aquifer hydraulic parameters in East El-Oweinat area are estimated based mainly on the interpretation of the constant discharge pumping tests according to Cooper and Jacob method (1946). The results of the hydraulic parameters are listed in Table 5.

The results show that the transmissivity values of the studied aquifer range between 1020 and 3231 m^2/day (Table 5) with an average of 2060 m^2/day. The high transmissivity of Well No. 5 is attributed mainly to the high water saturated thickness of this well. The transmissivity values of the concerned aquifer indicate that the Six Hills sandstone aquifer is a high potential (>500 m^2/day) according to Gheorhge (1979) classification.

The hydraulic conductivity is expressed by (K = T/D), where is the hydraulic conductivity (in m/day), T is the transmissivity (in m^2/day) estimated from the pumping test analyses and D is the aquifer saturated thickness in (m).The aquifer hydraulic conductivity values average between 5,4 and 14.3 m/day (Table 5).

The effective porosity (Φ_{eff}) of the Six Hills sandstone aquifer is calculated from the value of hydraulic conductivity of according to the equation of Martoz (1968): Φ_{eff} = 0.462 + 0.045Lnk, where Φ_{eff} is the effective porosity in decimal and k, the hydraulic conductivity in centimeters per second. The effective porosity of the studied aquifer ranges from 23% (well no. 19) to 27% (Well No. 9) with an average value of 24.5 % (Table 5).

In East El-Oweinat area, the estimated groundwater quantity of the Six Hills sandstone aquifer depends principally on the fully saturated thickness and effective porosity. It is obtained approximately by equation:

$$Q = D*A*\Phi_{eff}$$

Where Q is the groundwater quantity in m3, Φ_{eff} is the average effective porosity in decimal (0.245), D is the average fully saturated thickness in meter (331m) and A is the aquifer area in m^2 which is $434*10^7$ m^2 for the Six Hills sandstone. The estimated groundwater quantity of the Six Hills sandstone aquifer is 350 bcm (billion cubic meters) of fresh water.

Groundwater management

A numerical groundwater flow model was developed to estimate the impact of the long-term groundwater extraction from the Six Hills sandstone aquifer. In addition, the possible means investigated to sustain the present reclamation projects in East El-Oweinat area. The MODFLOW (Chiang 2005) was used to simulate the groundwater flow system. It is a numerical representation that represents an approximation of the groundwater flow system by means of governing equations (Anderson and Woessner 1992). The steady state can be described by the following partial differential equation:

$$O = \frac{\delta}{\delta x}\left(Kx\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(Ky\frac{\delta h}{\delta y}\right) + \frac{\delta}{\delta z}\left(Kz\frac{\delta h}{\delta z}\right)$$

where x,y and z are the Cartesian coordinates [L} Kx, Ky and Kz are the hydraulic conductivity [L/T], and h represents the hydraulic head [L].

on the other hand the transient conditions can be expressed by the following equation:

$$S_s = \frac{\delta h}{\delta t} + W\frac{\delta}{\delta x}\left(Kx\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(Ky\frac{\delta h}{\delta y}\right) + \frac{\delta}{\delta z}\left(Kz\frac{\delta h}{\delta z}\right)$$

where S represents the specific storage {L-1} , t is the time [T} and W is the source and/or sink [L^3/T].

Model Discretization, Hydraulic properties and Boundary Conditions

The model domain was subdivided into a regular grid of 65 rows and 68 columns to cover the modeled area as 1Km^2/cell. So, a grid of 4420 cells was constructed to represent the hydrologic system of the Six Hills sandstone aquifer. Regarding the hydrological properties of the Six Hills sandstone aquifer, a conceptual model is constructed to describe the groundwater flow system and the boundary conditions controlling the flow through the groundwater system (Fig. 8A). The constructed model indicated that the Six Hills sandstone aquifer is a one layered aquifer, occur under unconfined conditions and groundwater generally flows from southwest to northeast. General head boundary (GHB) was used to define the southwest and northeast boundaries where the heads on the boundary and the fluxes are affected by the rate of pumping. The GHB package is used to simulate the head dependent flow boundary (Cauchy boundary) and it is defined by two cell values; GHB hydraulic conductance Cb [L^2 T^{-1}] and Hydraulic head at the boundary hb [L]. The flow through the GHB [L^3 T^{-1}] is calculated by Qb = Cb (hb - h) where h is the hydraulic head in the aquifer. No flow boundary delineated the northeastern portion of the simulated area where the impervious basement rocks occupy this portion of the study area (Fig. 8B)

Tab. 5 - Hydraulic parameters of some wells tapping the Six Hills sandstone aquifer (2016).

Tab. 5 - Parametri idraulici di alcuni pozzi che insistono nell'acquifero arenario di Six Hills (2016).

Well No	Pumping rate (m^3/day)	Depth to water (m)	Drawdown (m)	Fully saturated thickness (m)	Transmissivity (m^2/day)	Hydraulic Conductivity (m/day)	Effective porosity (%)
5	6000	59.33	19.07	480	3231	6.7	24
9	6000	34.07	6.76	160	2289	14.3	27
18	5760	59	17.66	240	1701	7.1	24
19	6120	63.90	16.46	190	1020	5.4	23

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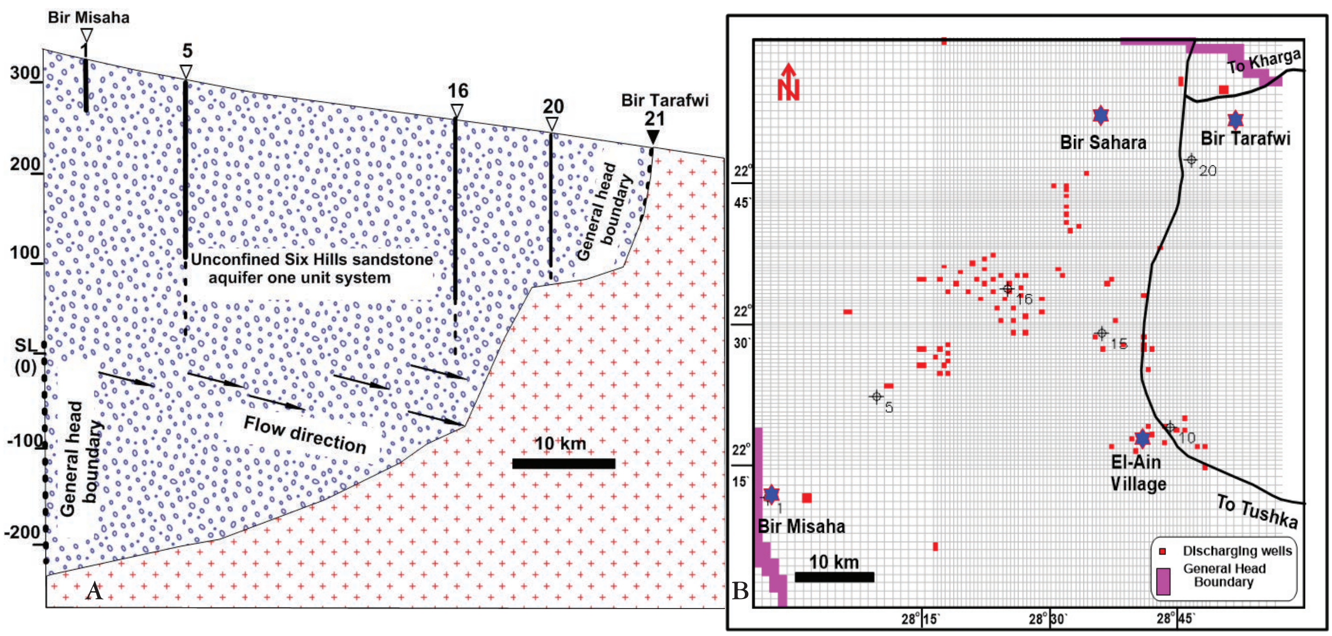

Fig. 8 - A) Conceptual cross section for flow model. B) The boundary conditions and Model discretization.

Fig. 8 - A) Sezione del modello concettuale usato per definire il modello numerico di flusso. B) Condizioni al contorno e discretizzazione del modello.

Model Calibration

Due to the importance of the calibration process, two calibration stages were implemented in the unsteady state conditions using the groundwater head measurements in year 2002 (Fig. 9). (Ghoubachi 2004) and the other one by using the present measurements at year 2016. The results of the calibration were checked using the observation/calculated head relation and by matching the measured and modeled water table contour map (Fig. 10).

Model results

A simulation period of 20 years was proposed from year 2016 to year 2035 to predict the head changes in the groundwater system under different proposed plans. Four scenarios were applied to predict the probable head changes in the Six Hills sandstone aquifer and their impact on the availability of groundwater in the study area as follows (Table 6):

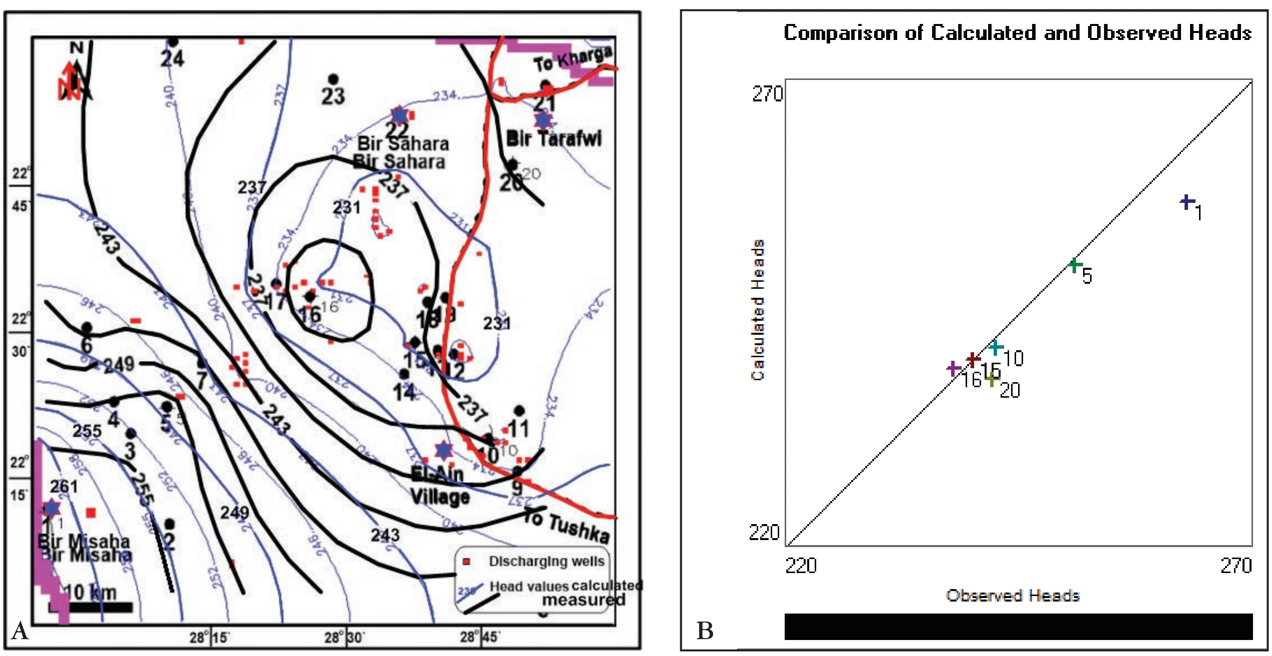

Fig. 9 - A)The matched measured/calculated water table map. B) The calculated/observed head relation (unsteady calibration run year 2002).

Fig. 9 - A) Mappa del confronto fra piezometria misurata e piezometria simulata. B) Grafico di correlazione fra valori di quota piezometrica simulati ed osservati (riferiti alla calibrazione del modello transitorio - anno 2002).

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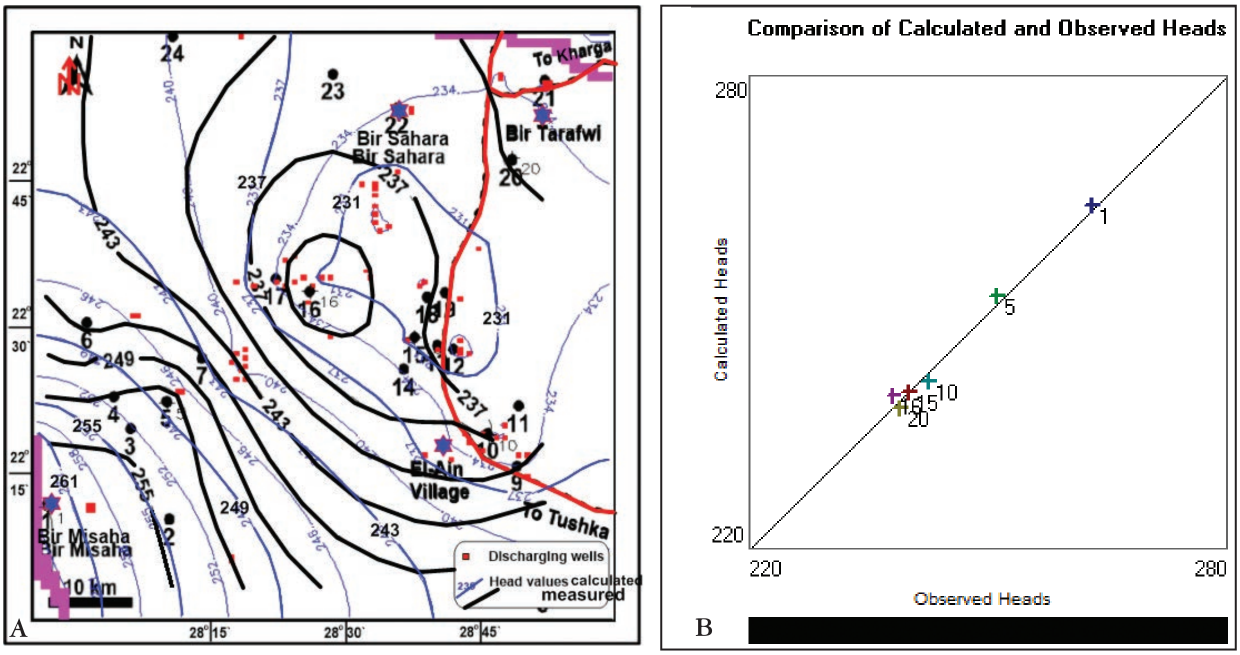

Fig. 10 - Calculated heads distribution map and the calculated/observed head relation of the study area (unsteady calibration run, year 2016).

Fig. 10 - A) Mappa del confronto fra piezometria misurata e piezometria simulata. B) Grafico di correlazione fra valori di quota piezometrica simulati ed osservati (riferiti alla calibrazione del modello transitorio - anno 2016).

Tab. 6 - Drawdown at different scenarios.

Tab. 6 - Abbassamento della quota piezometrica calcolato per i differenti scenari.

Scenario No.	Scenario aspects	Expected Maximum Drawdown (m)								
		5 years			10 years			20 years		
	Area	SW	Central	NE	SW	Central	NE	SW	Central	NE
1	Present conditions (project capacity 1200 well)	0.5	5.5	0.5	0.5	9.0	1.0	0.9	12.6	1.8
2	Full capacity project (1600 well)	1.0	14.4	1.2	1.5	22.5	1.5	2	32.0	2.0
3	Reduce pumping rates by 25%	0.8	9.6	0.8	1.0	15.0	1.0	1.0	21.0	1.0
4	Reduce pumping rates by 40 %	0.5	7.0	0.5	0.8	9.6	0.8	1.2	13.2	1.2

The First Scenario (present conditions)

This scenario investigates the impact of the present discharging rates on the groundwater levels of the Six Hills sandstone aquifer in East El-Oweinat area. The extraction rate is 3,000,000 m^3/day for 1200 wells and the simulation period was 20 years. The model was run under these conditions. Groundwater heads and drawdown values were calculated using the result extract tool of the program (Fig. 11).

As a result, the expected drawdown after 5 years will ranges between 0.5 m in southwest and northeast areas to 5.5 m in central of study area of high discharge. While the expected drawdown after 10 years (year 2025) will vary between 9 m in center of the study area. At the end period after 20 years, the expected drawdown will range from 0.9 m in southwest and northeast of the study area to 12.6 m in central part of the study area of highly concentrated pumping wells.

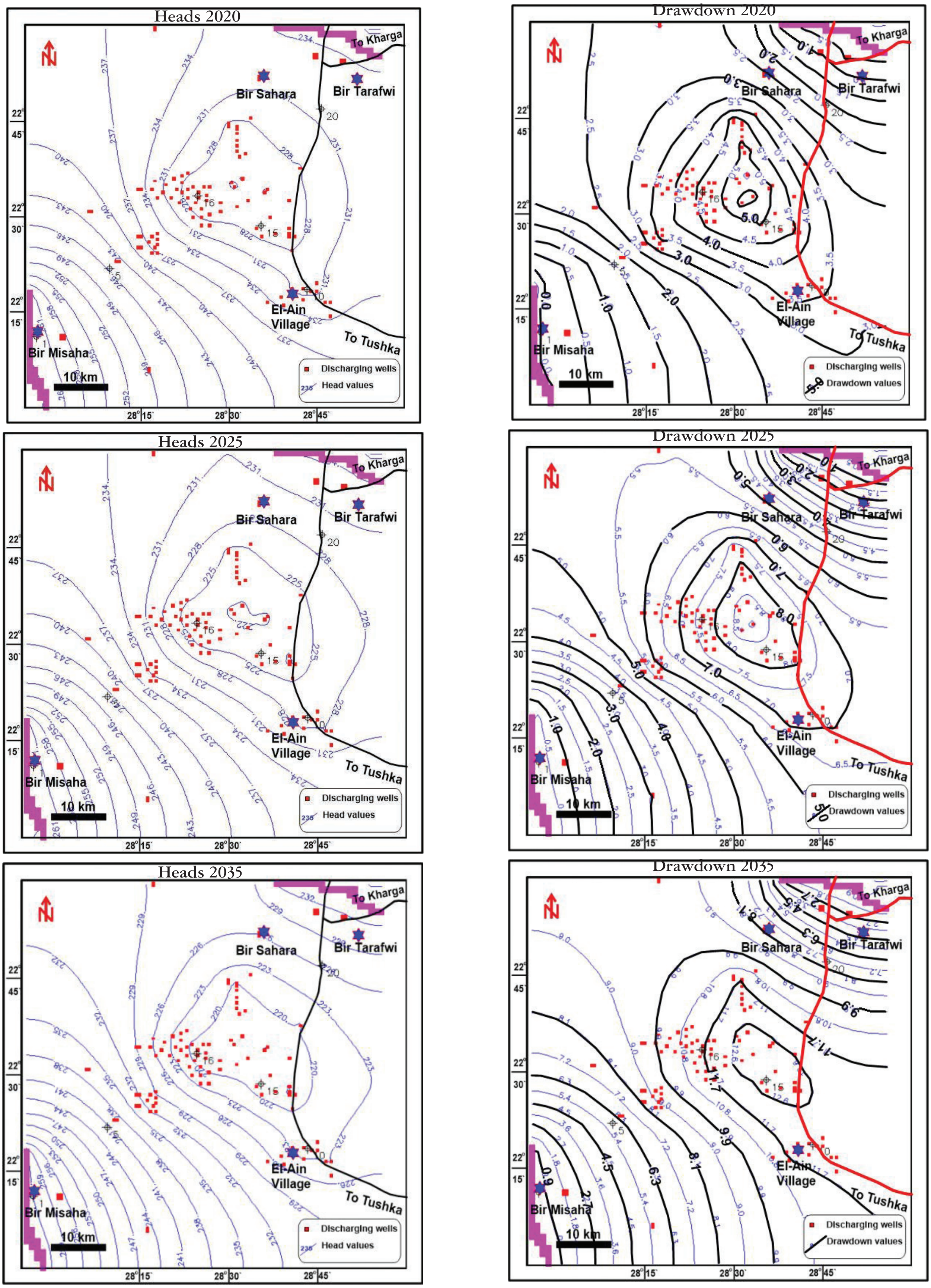

Fig. 11 - Predicted heads distribution and expected drawdown maps (first scenario) of the study area.

Fig. 11 - Mappa della piezometria e dei relativi abbassamenti previsti dal modello (primo scenario).

The Second Scenario (full capacity project)

This plan examines the response of the Six Hills sandstone aquifer to the process of the continuous increase of the pumping rate of the aquifer due to the new wells imposed in the aquifer due to the increase of reclamation activities and executing new investments in the study area. This scenario assumes a discharge rate i.e. 4,000,000 m^3/day.These new pumping rates were assigned to the model domain in the form of discharging well groups. The number of wells will increase from 1200 wells to 1600 wells where active reclamation processes are expected. The model was run under these new conditions. Groundwater heads and drawdown values of every time step were calculated and the expected head and drawdown maps were constructed (Fig. 12). The extraction rate is 4,000,000 m^3/day for 1600 productive wells. As a result, the expected drawdown (year 2020) ranges between 1.2 m (southwest and northeast parts of the study area of low discharge) and 14.4 m in central part of the study area of high discharge (Fig. 11). While the expected drawdown (year 2025) varies from 1.5 m in southwest and northeast parts of the study area to 22.5 m in center of study area. On the other hand, at the end of the simulation time (year 2035) the expected drawdown ranges between 2 m in the southwest and northeast parts of the study area to 32 m in central part of the study area of high discharge.

The Third Scenario

This Scenario suggests a plan to control and mitigate the head deterioration of the investigated aquifer in the study area especially central part. This scenario tries to look for the suitable pumping rates applied to the study area. The discharging rate attains 4,000,000 m^3/day for 1600 productive wells. This rate was decreased by a ratio of 25% and the impact of this pumping ratio on the distribution of head and drawdown values were checked.

It is found that the total drawdown will range between 0.5 m in the southwest and northeast and 9.6 m in the center of the study area of high discharge over the stress period (2020 year), Figure 13. While the drawdown (2025 year) varies between 1 m in the southwest and northeast and 15 m in center of the study area. On the other hand, the total drawdown of the Six Hills sandstone aquifer ranges from 1 m in the southwest and northeast parts of the study area (Bir Misaha and Bir Tarafwi areas) to 21 m in central part of the study area of high discharge.

The Fourth Scenario (Solution Scenario)

In this scenario, the water extraction rate is reduced by 40% of the total discharge (4,000,000 m^3/day) reaching rate 1,600,000 m^3/day from 1,600 productive wells. This scenario (no. 4) and Figure 14 show the drawdown contour map at year 2035.It is found that when reducing the present pumping rates of the different wells by a ratio of 40%, the total drawdown will exceed 7 m after 5 years (2020 year) and reach 9.6 m after 10 years (2025 year). It will attain 13.2 m at the end period after 20 years (2035 year). The pervious drawdown values will take place in the central part of the study area of high discharge from concentrated productive wells.

Conclusion and Recommendations

The Six Hills sandstone aquifer represents the sole aquifer in East El-Oweinat area and this aquifer exists under unconfined conditions. The basement rocks are exposed on the surface northeast of the study area (Bir Tarafwi Uplift), while in subsurface the basement surface dips gradually towards the west direction and the sedimentary cover thickness increases towards the west direction as well. As a result, the saturated thickness of the Six Hills sandstone aquifer increases towards the west direction. Groundwater flows from southwest to northeast direction. The calculated hydraulic parameters of the Six Hills sandstone aquifer show a high potential aquifer comparison of groundwater depth in years 2002 and 2016 reveals that the average drawdown in groundwater level calculated from the monitoring wells is 0.36 m/year with annual discharge of $13*10^8$ m^3/year.

The saturated thickness increases towards the west direction in East El-Oweinat area, it is recommended that the extension of reclamation areas on groundwater will be in the western part of the East El-Oweinat area. Due to the absence of subsurface data in the western portion of the East El-Oweinat area, it is recommended to drill some wells to reach the basement rocks to identify the subsurface section and to know the fully saturated thickness of the aquifer.

A numerical groundwater flow model was developed to estimate the impact of the long-term groundwater extraction from the Six Hills sandstone aquifer to sustain the present reclamation project in East El-Oweinat area. A simulation period of 20 years was proposed i.e. from year 2016 to year 2035. Four scenarios were applied to predict the probable head changes in the concerned aquifer and their impact on the availability of groundwater. From the model application results, we can conclude that the groundwater levels of the study area are expected to suffer from continuous groundwater head drop with the continuous increase in the water extraction. About 32 m head drop is expected in the next 20 years with a drawdown rate of about 1.6 m/year in the central area of high discharge. The study recommends the fourth scenario to sustain the groundwater resources in the study area which keeps the drawdown rates in the range of 0.66 m/year through reducing the present discharging rates (10,000 m^3/day/well) by about 40 %.

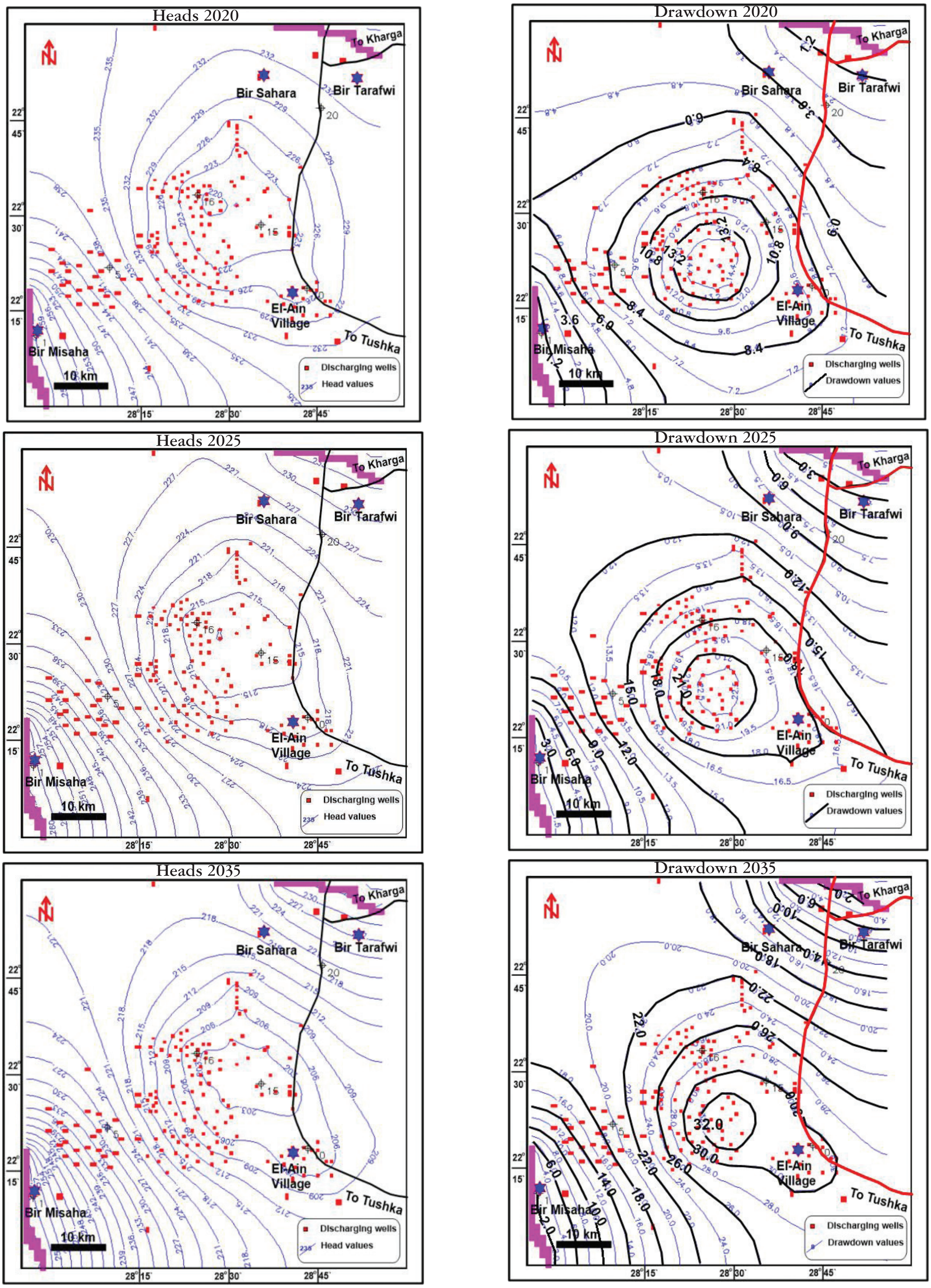

Fig. 12 - Predicted heads distribution and expected drawdown maps (second scenario) of the study area.

Fig. 12 - Mappa della piezometria e dei relativi abbassamenti previsti dal modello (secondo scenario).

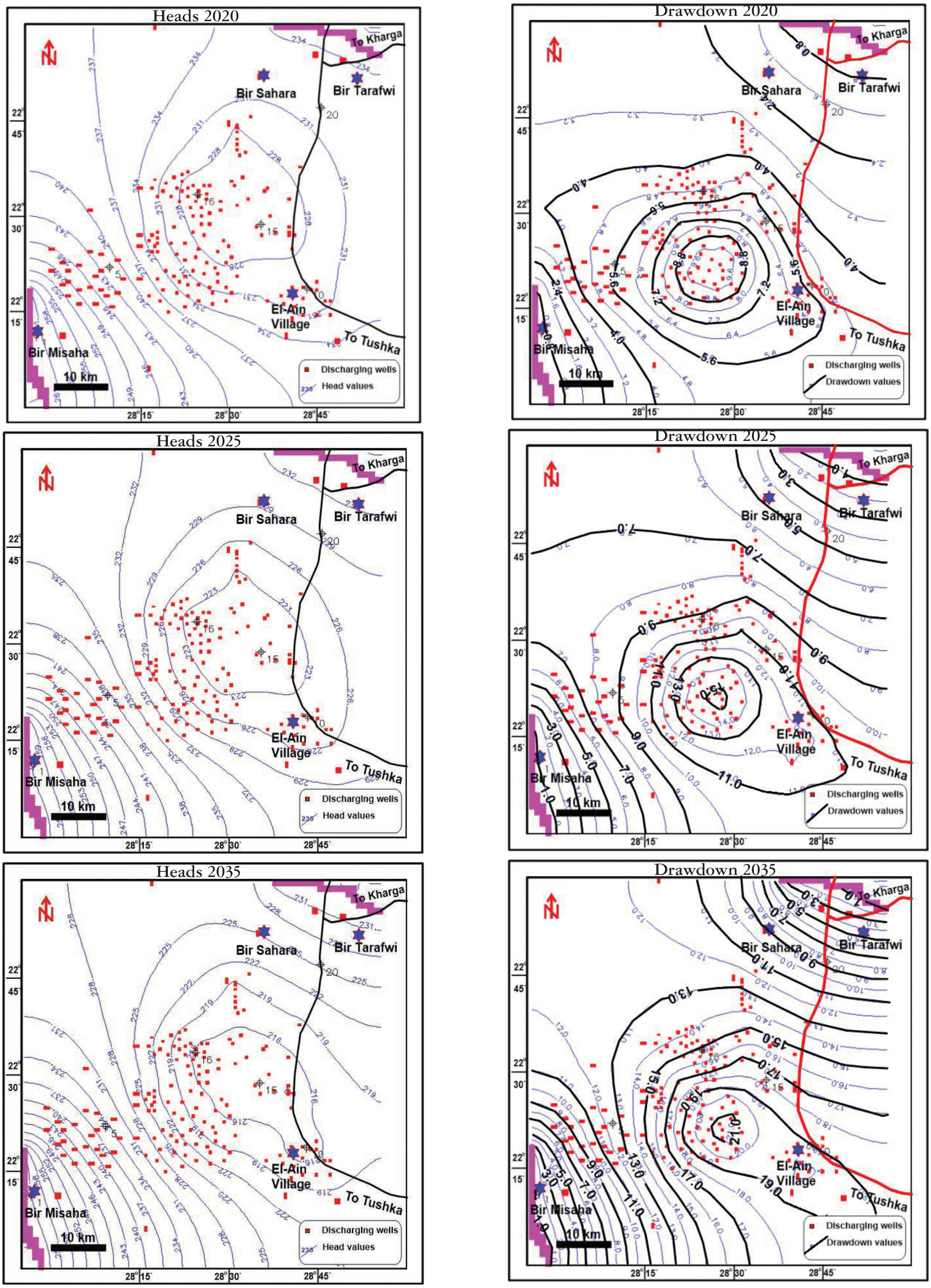

Fig. 13 - Predicted heads distribution and expected drawdown maps (thrid scenario) of the study area.
Fig. 13 - Mappa della piezometria e dei relativi abbassamenti previsti dal modello (terzo scenario).

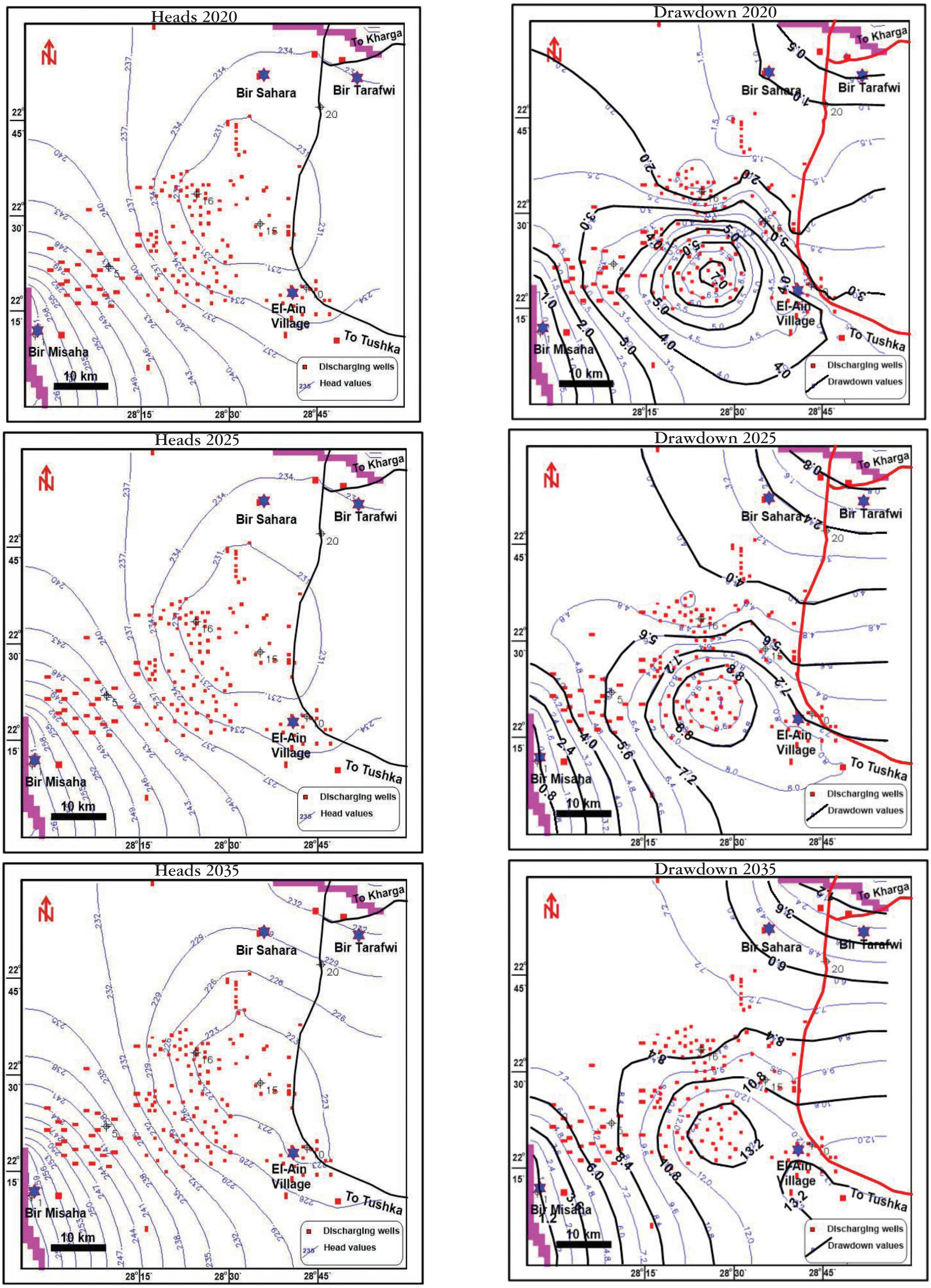

Fig. 14 - Predicted heads distribution and expected drawdown maps (fourth scenario) of the study area.

Fig. 14 - Mappa della piezometria e dei relativi abbassamenti previsti dal modello (quarto scenario).

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