



Characterization and management evaluation of the nubian sandstone aquifer in Tazerbo wellfield of the Libyan man-made river project

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Abstract

Tazerbo water wellfield, located in southeast Libya, was constructed as part of the first stage for the Man-Made River Project (Eastern System) during 1995–2003. A group of land subsidence forms was discovered approximately 30 km north of the wellfield two years after production, which began in March 2004. The wellfield production rate is only about one-third of its designed capacity. In addition to the land subsidence, there is a problem with the natural groundwater quality represented by high iron and manganese concentrations. This research aims to characterize the aquifer system and assess the current condition of the wellfield since its operation in 2004 in terms of groundwater quality and quantity. It further evaluates current groundwater management practices. The geographic information system was used to map hydrogeologic data of drilled water wells and groundwater monitoring data from 2003 to 2019. The aquifer system characterization showed that the exploited aquifer has excellent hydraulic properties and promising potential for future groundwater utilization. The measured drawdown during 2019 shows a maximum decline of 28 m. Moreover, the average water production is about 322,270 m³/day, equivalent to 32% of the total abstraction proposed to the end of the year 2020 of about 1907 million m³. As far as Groundwater quality is concerned, there has been no change in water quality since the beginning of abstraction. This research indicates that current policy and institutional approaches and practices promote the optimum management of the wellfield's water resources.

Keywords Sirte basin · NSAS · Al-Kufrah · Land subsidence · Transboundary aquifer

Introduction

Groundwater is a precious resource in Africa. The majority of Africa's groundwater resources are stored in 72 transboundary aquifers, covering 40% of the continent (IGRAC 2015; IGRAC and UNESCO 2016). These transboundary aquifers will play a critical role in reducing poverty, coping with population increase, and mitigating the impacts of climate change and variability. Africa is highly dependent on groundwater resources, with 33% of the population mainly

residing in arid or semi-arid areas and 75% of the population relying on groundwater for their daily needs (Scheumann and Alker 2009; Nijsten et al. 2018; Ahmed 2020).

The climate of the majority of Libya is classified as arid or hyper-arid. About 90% of the land is desert, with low rainfall rates, diurnal variations in temperature, poor soil, and seasonal winds. The demand for freshwater to sustain the Libyan economy, particularly its agricultural sector, exceeds its traditional supplies. About 97% of water use relies on groundwater due to the lack of permanent rivers, and the surface water supplies represented by the wadis runoff during rainy seasons account for approximately less than 3% of the water supply. The available figures show that the country's total groundwater abstraction is more than 6.5 billion cubic meters per annum (GWA 2006; Wheida 2012; Brika 2018; Hamad 2019; Hamad and Ahweej 2020). Furthermore, Libya's population is concentrated in coastal areas, where groundwater is scarce and of poor quality. In response to the water crisis a priority of the Libyan states to carry out

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technical, economic, and social studies related to ground-water development.

Libya shares four transboundary aquifers (see Fig. 1) with its North African neighbors (Tunisia, Algeria, Egypt, Sudan, Chad, and Niger); including Jefara Aquifer System, Lake Chad Basin, Northwest Sahara Aquifer System (NWSAS), and Nubian Sandstone Aquifer System (NSAS) (Nijsten et al. 2018; Ahmed 2020; Frédéric 2020). A proposal sought to transfer the large quantities of groundwater from these transboundary aquifers within the borders of the main geological basins of Libya to the densely populated coastal areas where agricultural development is promising. In an effort to

pursue this possibility, the Libyan government launched the Man-Made River (MMR) project in 1983. The objective of MMR is to transport groundwater from the interior to the coast for agricultural and urban development and reduce the abstraction from stressed coastal aquifers (McCloughlin 1991; Salem 1992; GWA 2006; MMRA 2020). The plan was to transport approximately 6.5 million cubic meters of freshwater daily by huge buried pipes (pre-stressed concrete cylinder pipes PCCP, with a diameter of 4 m) to cover the water demands for domestic, agricultural, and industrial purposes according to the main systems and subsystems (connections), (see Fig. 1 and Table 1).

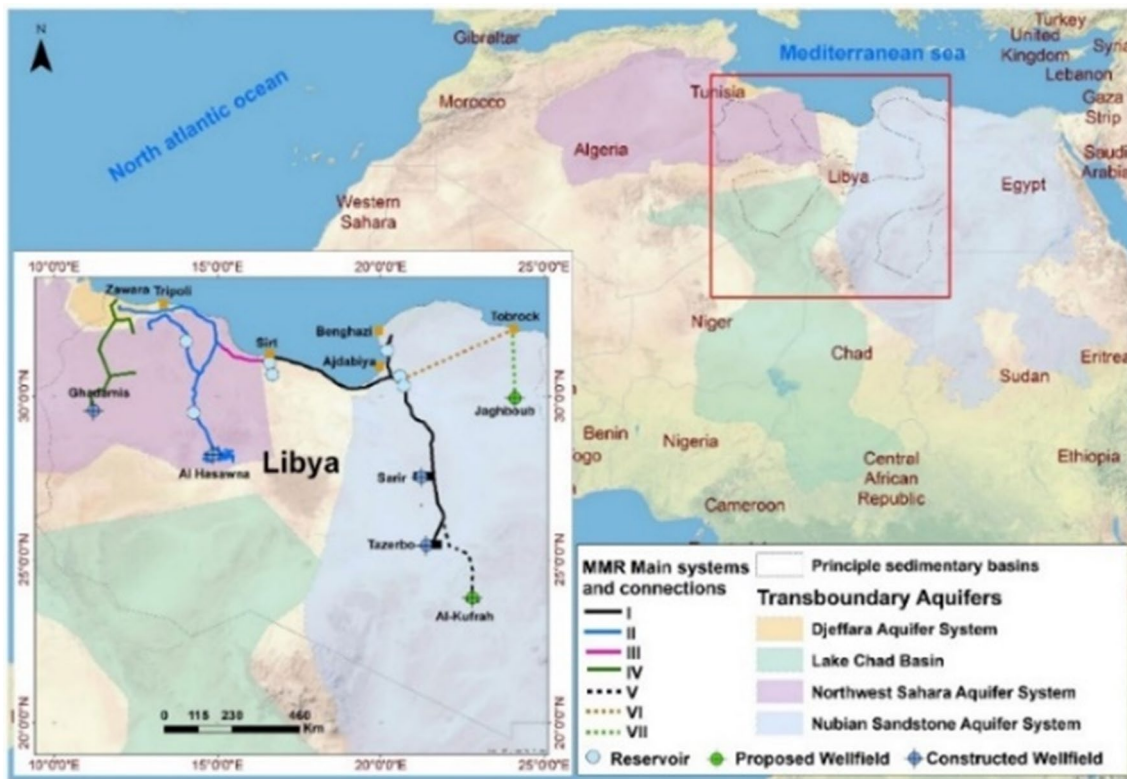


Fig. 1 Map of Libya transboundary aquifers and the main water conveyance systems and connections of MMR (map based on data from (GWA 2006; IGRAC and UNESCO 2016)

Table 1 Main water conveyance systems and connections of MMR (GWA 2006; MMRA 2020)

System	Subsystem (Connection)	Aquifer	Designed transport volume meter ³ /day	Completion %	
I	Eastern system	Sarir-Sirt-Tazerbo-Benghazi	NSAS	2,000,000	100
II	Western system	Hasawna-Jefara Plain	NWSAS	2,000,000	100
III	Bidirectional	Qurthabia-As Sdada	NWSAS/ NSAS	980,000	100
IV	Western system	Ghadams-Zawara-Al Zawyah	NWSAS	250,000	86
V	Eastern system	Al-Kufrah-Tazerbo	NSAS	1,860,000	70
VI	Eastern system	Ajdabiya-Tobrock	NSAS	700,000	0
VII	Eastern system	Jaghoub-Tobrock	NSAS	Under evaluation	–

This paper is concerned with one of the eastern components of the MMR project (subsystems; I, V, VI, and VII), as indicated in Table 1 and Fig. 1. The eastern system depends on NSAS, the world's most extensive fossil water aquifer system, and one of Libya's groundwater resources lying at the eastern end of the Sahara Desert and spanning the political boundaries of four countries in northeastern Africa. Over 2.2 million km² of land is covered by the NSAS, including north-western Sudan (376,000 km²), north-eastern Chad (235,000 km²), south-eastern Libya (760,000 km²), and ~80% of Egypt (826,000 km²) (Ahmed 2013). The eastern part of Libya depend on NSAS for domestic water supply and irrigation, and the total abstraction from NSAS in Libya has been estimated at 1020.7 Mm³ per year for all water uses (Hamad and Ahweej 2020). The subsystem (I) (see Fig. 1), which was implemented first, utilizes a conveyance pipeline system that pumps water from NSAS, where 2 million m³ of freshwaters are transported daily through two water conveyance lines; one extends from Tazerbo and the other from Sarir wellfields. Both conveyance lines head north to collect in a balance tank near Ajdabiya city, which has a capacity of 4 million m³. From the tank, the system is then divided into two branches. One branch head east to the Benghazi region to transfer 1.18 million m³ and ends in the Omar Al-Mukhtar reservoir, which has a capacity of 4.7 million m³. The other branch heads west to transfer 820,000 m³ which settles in the Al-Qardabiya reservoir near Sirte city, with a capacity of 6.8 million m³. The subsystem (V) aims to increase the production capacity in the eastern system, where exploratory wells were drilled and wellfield locations identified near Al-Kufrah oasis, and where 70% of the conveyance pipeline system was installed. Furthermore, the subsystem (VI) is still under engineering works, and the proposed subsystem (VII) was reconsidered following the results of the exploratory drilling and the cost of the drilling project (GWA 2006; MMRA 2020).

The water abstraction from Tazerbo wellfield began in March 2004, and after two years, a group of about 40 land subsidence occurrences was discovered about 30 km north of the wellfield. The groundwater also has high carbon dioxide, iron, and manganese concentrations, which require treatment before the water is suitable for domestic use. Despite the operational obstacles associated with Libya's political situation (2011-present), water field production has continued to this day. This research aims to assess the current condition of the wellfield since its operation in terms of groundwater quality and quantity and to evaluate current groundwater management practices.

Material and method

The study area

Tazerbo water wellfield (see Fig. 2) is located in southeast Libya, about 40 km northeastern of the Tazerbo oasis, and about 160 km of southern Sarir wellfield. This water wellfield also lies in a desert region that does not have ether topographic features nor remarkable land use/land cover, except for small, extended sand dunes. The wellfield height above sea level reaches 288 m.

The wellfield developed between 1995 and 2003 consists of 108 production wells, ranging from 450 to 600 m in depth, spaced at 1.3 km apart, and distributed in three rows at 10 km apart. Each row has two lines, each of which contains 36 water wells and 35 monitoring wells scattered throughout the wellfield. This configuration is optimized to minimize interference from the cone of depression around individual wells and designed for a total production rate of 1.00 MCM/day (Ahmad 1984). Two aquifer systems are known to exist in the Al-Kufrah basin, the NSAS aquifer; is represented by a lower Paleozoic aquifer and an upper Mesozoic aquifer (Pim and Binsariti 1994; Bakhbakhi 2010; TCGM 2017). Deep below the drilled production water wells in Tazerbo wellfield are three aquifers; surface, intermediate, and deep, separated by isolating layers (Aquitards). These aquifers consist mainly of sandstone (see in Table 2 and Fig. 3). There is also another even deeper aquifer (Cambro-Ordovician) not penetrated by the production water wells but intercepted by the piezometer no.1 about 90 km north of the wellfield (TCGM 2017).

Research methodology

Water and utility suppliers are increasingly challenged to deliver adequate quality and quantity of water to households. Accurate groundwater data is necessary for effective water management and for the characterization and assessment of groundwater resources (Hamad 2019; Alqadi et al. 2019). The data presented here is gathered from the technical reports of drilled exploration, production, and monitoring water wells in Tazerbo wellfield. Data includes geological lithology, geophysical logs, pumping test data, in addition to mathematical models prepared by specialized institutions, such as the Libyan General Water Authority (GWA) and the Man-Made Project Authority (MMRA) and conducted during the exploration, design, and implementation of the wellfield. Moreover, the study used groundwater monitoring data (quality and quantity) provided by the Technical Center for Groundwater Management (TCGM)

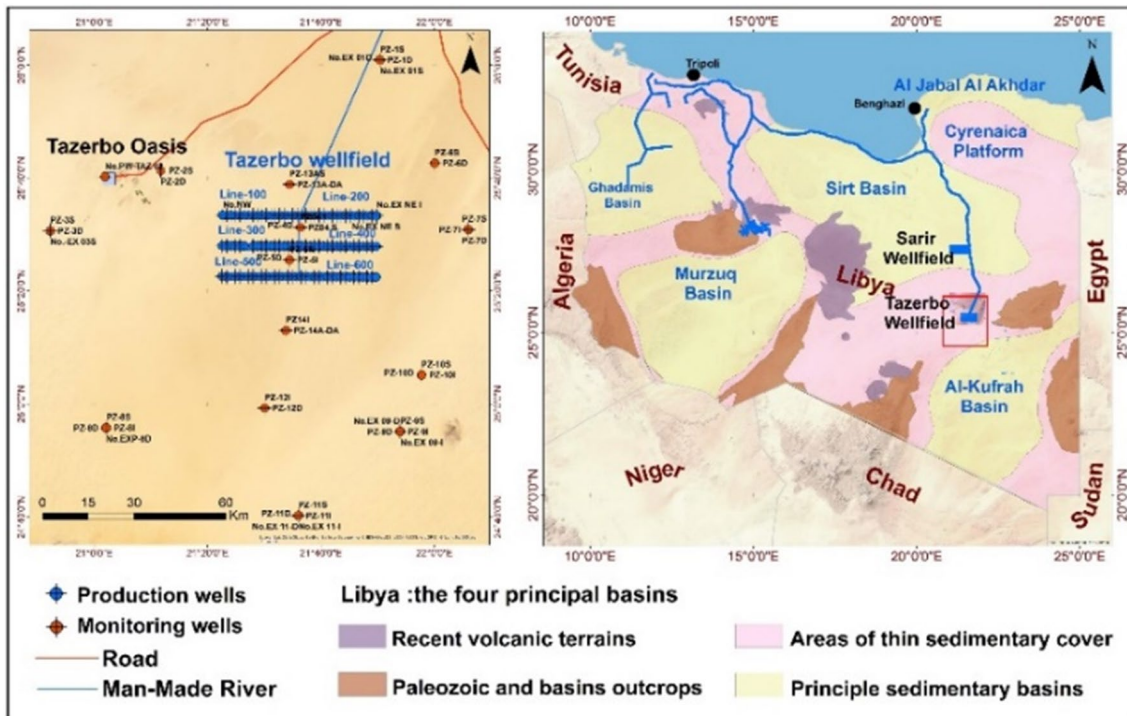


Fig. 2 Tazerbo water wellfield location map (Geological basins based on Hallett 2002) need to show regional groundwater piezometric contours on left hand diagram

Table 2 Stratigraphic geological succession of the Tazerbo wellfield (GMMP and LAVALIN 1999)

Age	Formation	Thickness (m)	Aquifer/Aquitard	Lithological descriptions
Pleistocene	–	40–50	Surface Aquifer	Sand/Gravel: Yellowish brown coarse to very coarse, subangular to subrounded, poorly sorted
Eocene	–	0–200	Aquitard	Calcareous Sandstone: Whitish, fine to medium grained well sorted, medium cemented layers of ferruginous sandstones dark brownish, hard Gravel-quartz granules, poorly cemented
Upper–Upper Devonian	Binem	40–100	Intermediate Aquifer	Sandstone: Yellowish brown to pale orange, fine to medium grained, well sorted, well cemented
Lower Devonian	Tadart	160–250	Aquitard	Siltstone: Dark reddish, greyish, dark green, hard to moderate hard Mudstone Light to grey orange, soft Sandstone: Fine to coarse grained, surrounded to rounded, well cemented, hard layers of ferruginous Sandstones/Siltstones, reddish to purple hard
Upper Silurian	Acacus	150–200	Deep Aquifer	Sandstone: Dark brown to dark yellow orange, pinkish, greyish red to very dusky red, fine to medium grained, well sorted, subrounded to subangular and medium to very coarse grained, angular to subangular and medium to very coarse grained, poorly sorted, poorly cemented Layers of reddish siltstone soft to hard Layers of black iron oxides

at MMRA. This data consist of water level data in the piezometric wells from 2003 to 2019, monthly water production, and periodic chemical analysis of the groundwater. Data were digitized and compiled on a Geographic Information System (GIS) to map and characterize the

aquifer hydrogeological properties, land subsidence, and water quality. Water quality data were also plotted in Piper and Wilcox diagrams and cross-checked with the World Health Organization (WHO) standards. Finally, an evaluation of groundwater management practices was carried

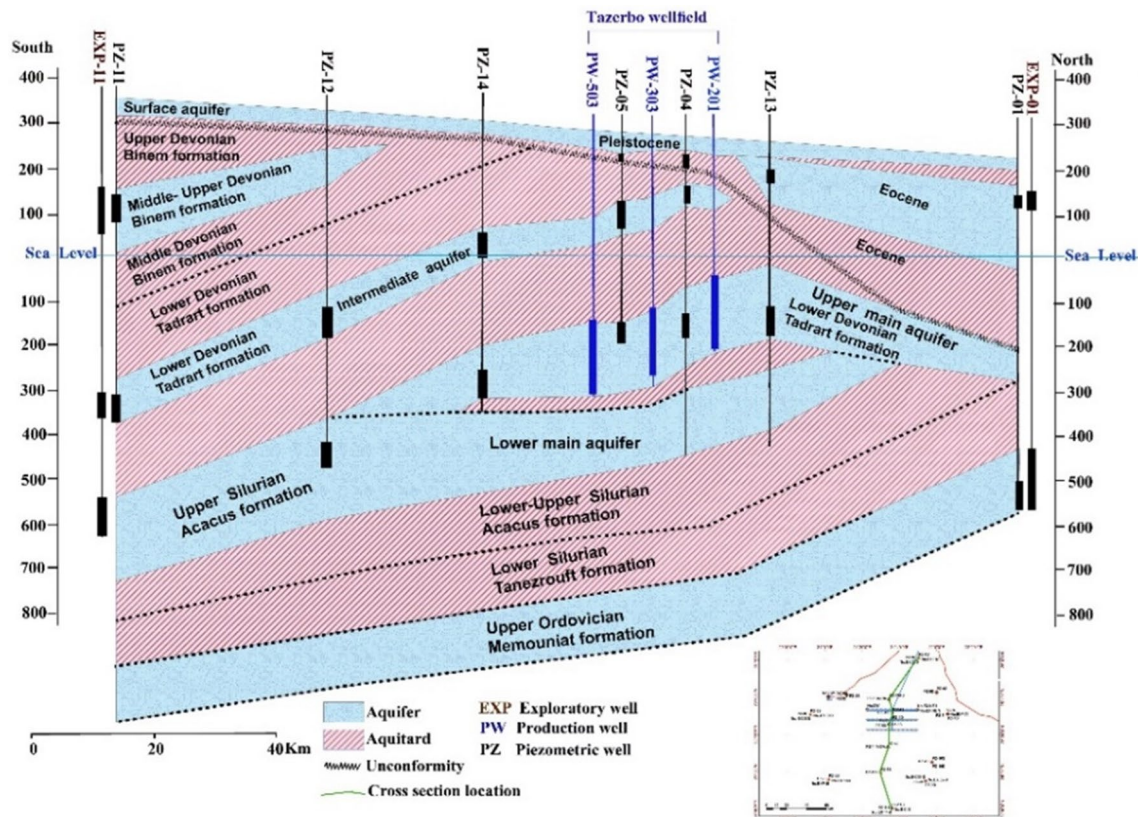


Fig. 3 Regional North–South the geological cross section, modified after (TCGM 2017)

out, focusing on the organizational management structure, institutional arrangements, operations of the wellfield, existing monitoring systems, and the components of enabling environmental indicators evaluated based on the framework of Integrated Water Resource Management (IWRM) (Cap-Net 2010; Hamad and Ahweej 2020).

Result and discussion

Geology

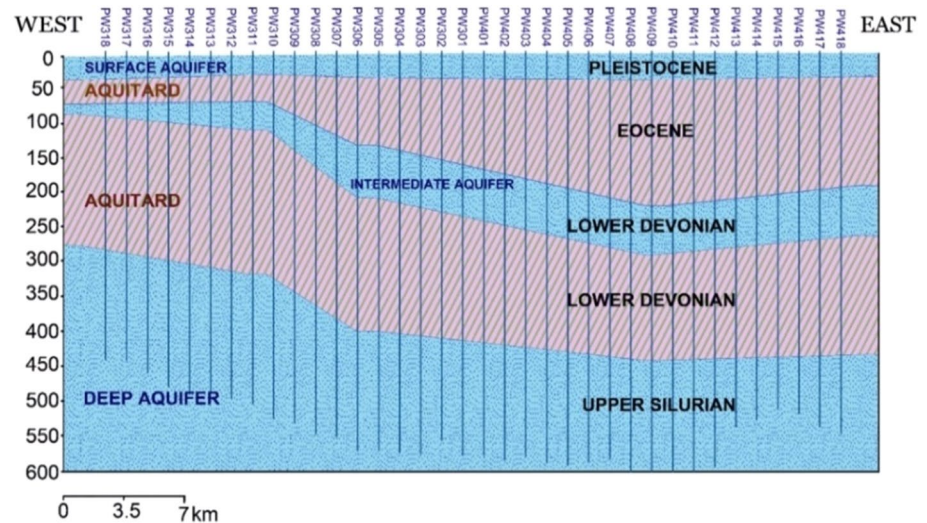
The stratigraphic geological succession is given in Table 2. Figure 3 shows the regional north–south geological cross section, and Fig. 4 shows the geological cross section for row 2 (wellfield middle row) drawn from the water wells' lithological logs. The wellfield lies above the south-west-north-east alignment of the Hercynian uplift's southern flank, which forms the boundary between the Al-Kufrah and Sirte basins, where a pre-existing (Caledonian) northwest-southeast transects that uplift aligned (Wright et al. 1982; Hallett 2002). The syncline creates a sedimentary neck that provides a flow path from one basin to the next between the adjacent Jabal Nugay and Jabal Thalma. The wellfield is

also close to the Sirte Basin's Late-Cretaceous collapse and subsequent Tertiary marine deposition. As a result, the pre-tertiary deposits of the Al-Kufrah Basin were transected and overlaid by a wedge of Eocene clay, which begins near the wellfield, plunges northward, and quickly thickens (Pim and Binsariti 1994; Hallett 2002). The post-Tassilian (Nubian) continental deposits, which form the Al-Kufrah Basin's primary and uppermost (unconfined) aquifer, extend to the Tazerbo area at a thickness of about 700 m, according to geological interpretation based on widely spaced exploratory wells. Drilled piezometers and exploratory wells after 1988 have, on the other hand, provided cores and other evidence demonstrating that the entire sedimentary sequence above approximately 800 m depth is Lower Devonian in age (Pim and Binsariti 1994; Bakhbakhki 2010).

Hydrogeology

The wellfield is designed to exploit the water from the deep aquifer and the surface and intermediate aquifers were isolated during water well construction. According to the lithological logs of the drilled wells, the deep aquifer is an Upper Silurian Acacus formation that consists of unconsolidated medium to very coarse-grained sandstone, containing

Fig. 4 Geological cross section row 2 (Line 300–400) drawn based on data (GMMP and LAVALIN 1999)



quartz and iron oxide with clay and siltstone components. The aquifer is overlaid by the aquitard (Lower Devonian Tadrart formation) and under-laid by the aquitard (Acacus formation Lower–Upper Silurian) (see Figs. 3, and 4). The hydrogeological properties of the deep aquifer acquired from the steady rate pumping test and recovery data are mapped (see Fig. 5a, b, c, d, e, and f). The depth of the aquifer ranges from 263 to 514 m and increases in the southeast direction of the wellfield. The aquifer thickness (see Table 3) ranges from 105 to 192 m, and the thickness increases toward the west. The effective core porosity ranges from 10 to 35%. The water level map shows that the southern parts of the wellfield levels are deeper than the northern parts. Table 3 shows the hydraulic properties of the deep aquifer based on pumping test data, where the transmissivity ranges from 865 to 8484 m²/day, and hydraulic conductivity ranges from 12 to 61 m/day. Both parameters are classified as very high and showed high values in the northern and northwestern parts of the wellfield. The average water well yields 120 l/s, its specific capacity ranges from 2.8 to 9.32 l/m/s, and its storativity ranges from 0.00001 to 0.00038.

Previous studies (Pim and Binsariti 1994; Fisk et al. 1983) indicate that the three aquifers are hydraulically connected because the aquitards that separate the intermediate and deep aquifers are relatively permeable, allowing vertical leakage between the two aquifers to occur. After a period of wellfield operation, the piezometers have confirmed leakage between the aquifer units (TCGM 2017). The head of the deep and shallow aquifers are equivalent in the southern part of the well-field indicating considerable leakage across the intervening aquitard. In the northern part of the wellfield, the shallow and deep aquifers have different static heads indicating a less leaky aquitard. This head difference migrates groundwater toward the surface aquifer, through the aquitards, and into the Sirt Basin.

Similarly, it will control downward leakage once development pumping reverses the vertical hydraulic gradient (Pim and Binsariti 1994).

Wellfield abstraction

The wellfield was designed for a production capacity of 1 MCM. Production from the wellfield began gradually in March 2004 and reached 500,000 m³/day in October 2004. Since then, the production rate has fluctuated from 200,000 to 500,000 m³/day. The current average production is about 322,270 m³/day, representing 32% of the total proposed abstraction predicted from during wellfield design, according to mathematical models. The emergence of land subsidence in 2006 and the instability of the financing for wellfield operations and maintenance led to production reduction. Currently, only 40 of 108 water wells are in operations. As a result, MMRA's management decided to modify operation to reduce land subsidence and reduce operating costs. To ensure the safety of the wellfield infrastructure (electrical networks, pipelines, and operation buildings), MMRA further adopted an abstraction reduction policy, extensive monitoring, and an operational plan to stagger individual wells operations (interoperability operational plan).

The predicted production capacity was designed to supply expanding agricultural projects that have not been realised. Water production is currently for domestic use only. The total abstraction volume by the end of 2020 was about 1907 MCM (see Fig. 6). Also, there is another abstraction area closer to the Tazerbo oasis that supplies the Tazerbo agriculture settlement project, consisting of private farms, and a potable water factory, with 30 MCM per year.

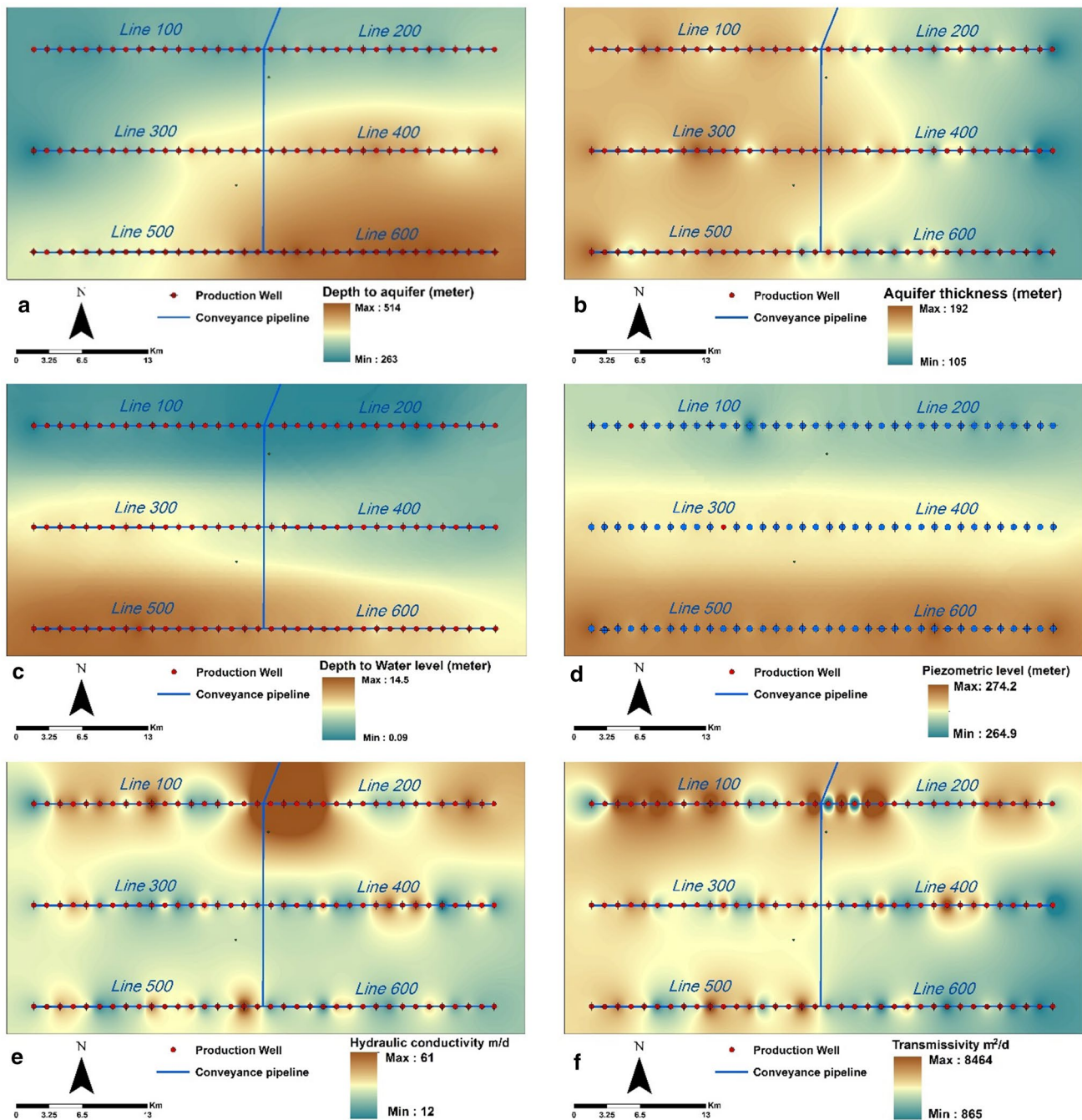


Fig. 5 Maps for deep aquifer properties; depth to aquifer (a), aquifer thickness(b), depth to water level (c), water level (d), hydraulic conductivity (e), transmissivity (f)

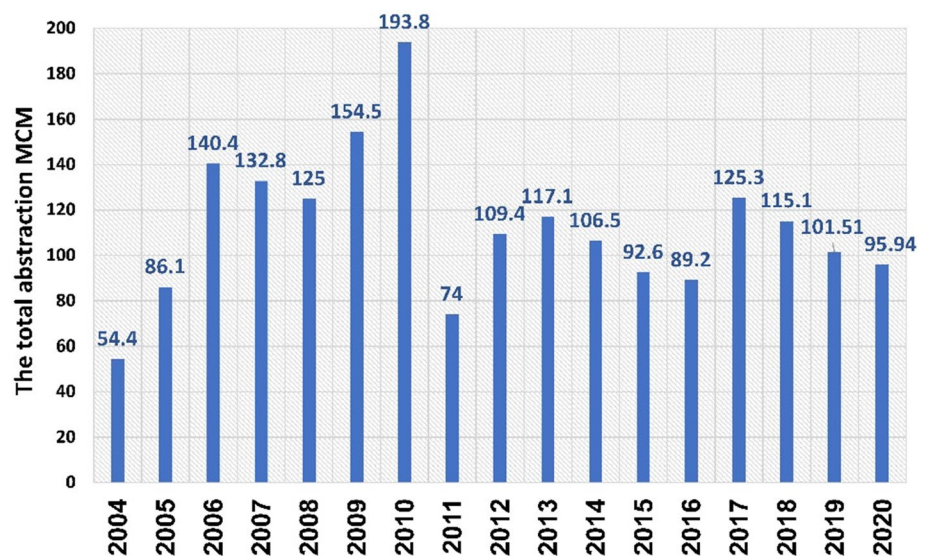
Water levels

There are 35 monitoring wells at 14 sites (see Fig. 2). These wells were set up to monitor the water level in the three aquifers at each site. Prior to political conflicts in 2011, water levels were monitored monthly by MMRA and the Libyan General Water Authority (GWA). Some monitoring wells exist in rugged desert areas up to 80 km

from the wellfield, representing an issue for staff security. The lack of equipment dedicated for field measurements along with damage incurred on some monitoring wells has limited data delivery. However, MMRA continues to measure water levels in the monitoring wells near the wellfield. The graphs of the monitoring data for water levels (see Fig. 7a, b, and c) show that the water levels

Table 3 Hydraulic properties of the deep aquifer (GMMP and LAVALIN 1999)

	Well field lines	Depth to water level (meter)	Thickness (meter)	Discharge l/s	Specific capacity l/s/m	Hydraulic conductivity m/day	Transmissivity m ² /day
Line -100	Min	0.09	150	114.94	2.8	16.5024	2738.88
	Max	1.97	181	122.06	8.34	56.5056	8484.48
Line -200	Min	0.52	111	117.29	3.71	20.9088	865.728
	Max	1.86	166	121.26	8.8	61.344	8424
Line -300	Min	6.21	145	145	3.76	16.416	2782.08
	Max	8.64	192	192	7.8	32.832	5287.68
Line -400	Min	3.3	105	117.29	3.4	12.096	1918.08
	Max	6.76	173.5	120.46	7.59	39.744	6264
Line -500	Min	11.64	132	118.08	4	15.8112	2557.44
	Max	14.53	188	122.87	9.32	45.1008	6099.84
Line -600	Min	7.48	118	118.02	4.03	15.552	2324.16
	Max	11.33	170	122.06	7.75	31.104	4613.76

Fig. 6 Tazerbo wellfield Abstraction, 2004–2020

of the surface aquifer have decreased slightly. In contrast, a significant drawdown in the intermediate and deep aquifers was observed. The maximum drawdown found in the piezometric wells of the deep aquifer was 28.22 m in well PZ-4D and 27.57 m in well PZ-5D. While in the intermediate aquifer, the drawdown was 13.34 m in well PZ-4I. Given that abstraction is only from the deep aquifer the decline in the static head in the intermediate aquifer supports the hydraulic connection between the deep and the intermediate aquifer discussed above. The intermediate aquifer thickness was also observed to have declined or nearly disappeared in the north of the wellfield (see Fig. 3). Drawdown (see Fig. 7d) is greatest at the center of the wellfield.

Land subsidence occurrence

Land subsidence associated with groundwater extraction can be an important geo-hazard (Ren et al. 2015). According to Terzaghi (1943), a reduced hydrostatic pressure associated with groundwater abstraction can cause the overlying soil to subside with consequences including building structural failure, pipelines, railroads, flooding of tidal areas, and the collapse of water well casing (Engi 1985; Ren et al. 2015). In Tazerbo wellfield, land subsidence (see Fig. 8 and Table 4) appeared after two years of the commencement of the production (at the end of November 2006). Land subsidence normally takes place after an extended period of abstraction and the early expression at Tazerbo is unusual. Land subsidence appeared approximately 30 km north of

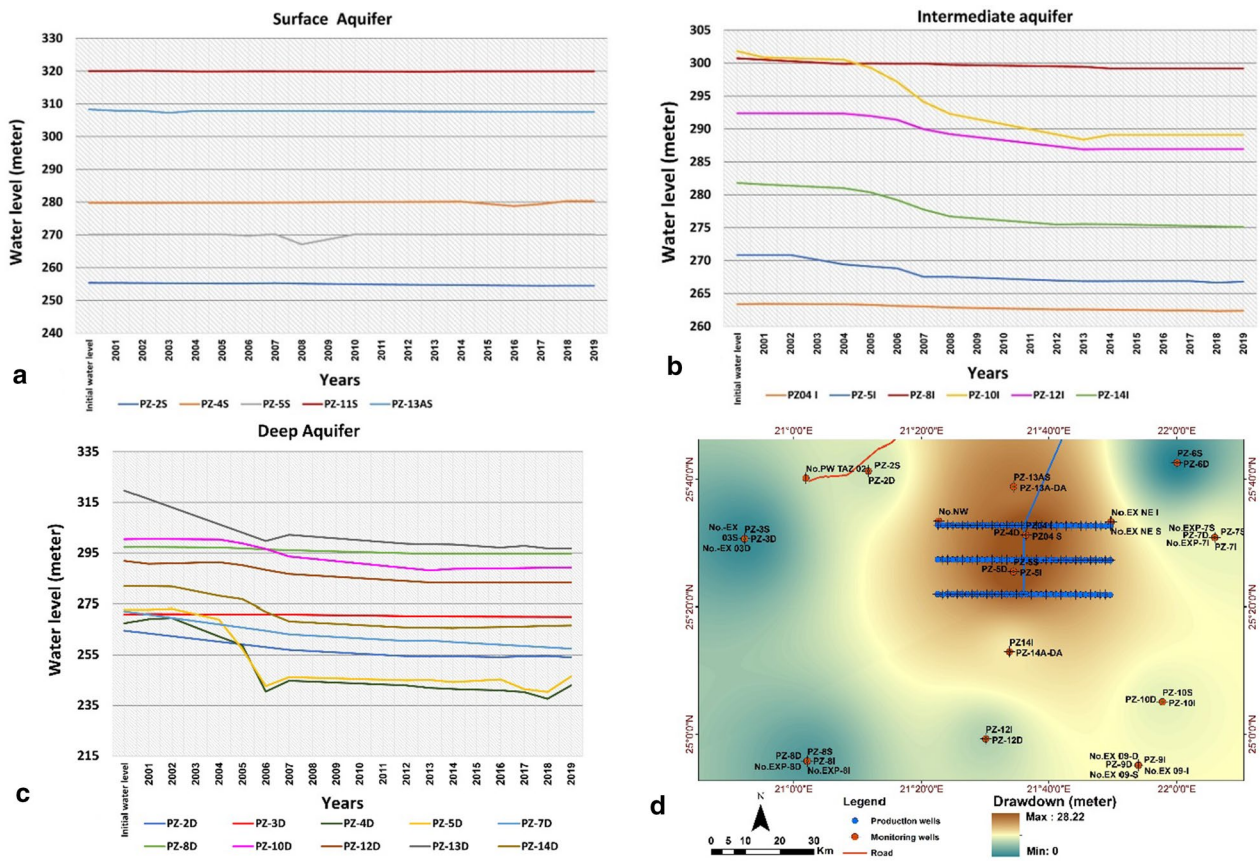


Fig. 7 Water level 2001–2019 for the three aquifers (a, b, and c), drawdown of the deep aquifer (d)

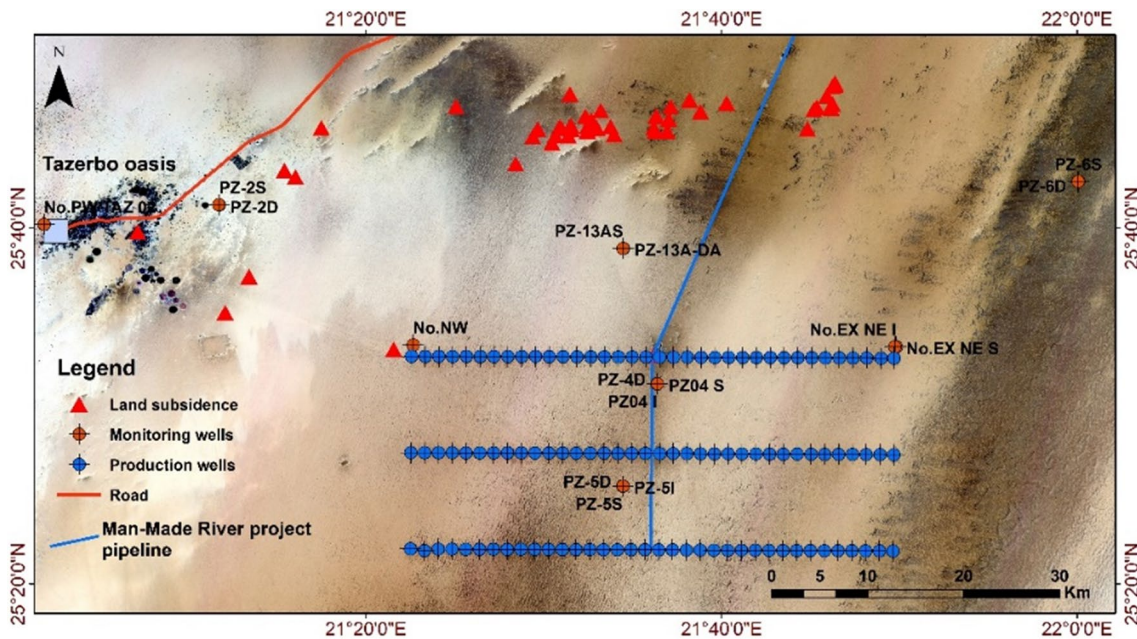


Fig. 8 Land subsidence location map (TCGM 2017)

the wellfield and became more extensive between 2007 and 2010. Subsidence did not extend further until September 2017, when a sinkhole with a diameter of 28 m and a depth of 7 m appeared northwest of the wellfield, at the same level of the surface aquifer water level. The subsidence is generally expressed as conical or circular features and varies in size from one location to another. The diameter of the features ranges from 5 to 30 m, and depths range from 10 cm to 7 m. Longitudinal surface cracks around pivot irrigation circles occurred with groundwater abstraction at the Sarir agricultural projects located approximately 140 km north-east of Tazerbo wellfield. Land subsidence in the area was predicted by Fisk et al. (1983), who explained that the lithology of the region has considerable potential for land subsidence. The clays are unable to withstand intergranular stress as entrained groundwater is squeezed from capillary space. In addition, reduced aquifer head may accelerate consolidation, a slow process due to the extremely low permeability of clay. Because of this process subsidence is predicted to become even more significant in future (Fig. 9).

Seismic data in Al-Kufrah basin (El-Shari 2013) indicate east to northeast-trending faults across the entire study area. The frequency of faults increases toward the areas of land subsidence, where the surface propagation of the basement fault could have weakened the bedrock beneath the area of the wellfield. Furthermore, monitoring and investigations by MMRA led to the conclusion that the deep aquifer is artesian in the northern parts; thus, groundwater withdrawal results in a fluid pressure change in the layers, and, as a result, the pressure change in the geological layers induces both elastic and inelastic land compaction. The artesian pressure for the deep aquifer in Tazerbo wellfield ranges from 0.3 to 1.4 bar and reaches about 6 bar in the very deep aquifer (Cambro-Ordovician). The withdrawal of water leads to a pressure decline, leading to a dislocation in the weakest places of the topsoil. Therefore, pressure decline has resulted in land subsidence in Tazerbo wellfield after abstraction, especially in the north and northeast of the wellfield (TCGM 2017).

Fig. 9 Tazerbo land subsidence (TCGM 2017)

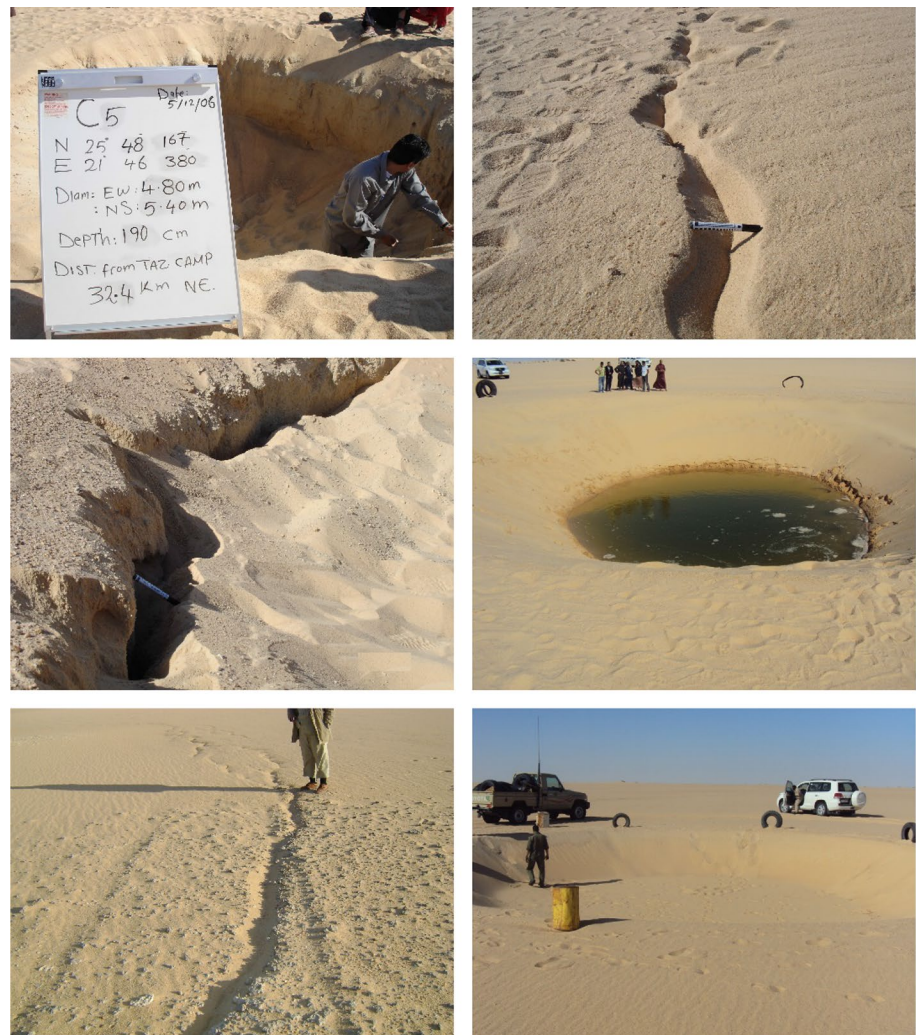


Table 4 Land subsidence inventory (TCGM 2017)

No	Date	Diameter	Depth
1	22.11.2006	13.30	0.28
2	22.11.2006	10	0.70
3	22.11.2006	19.70	0.10
4	22.11.2006	5.40	1.90
5	22.11.2006	30	0.10
6	29.11.2006	12.80	0.15
7	26.11.2006	90.70	0.70
8	03.12.2006	5	0.10
9	05.12.2006	11.70	Crack
10	05.12.2006	20	0.20
11	05.12.2006	9.50	0.10
12	05.12.2006	6.10	0.80
13	09.12.2006	1.40	Crack
14	11.12.2006	1.20	Crack
15	27.02.2007	14.00	15.5
16	10.03.2007	10.00	0.05
17	01.08.2007	6.00	1.5
18	02.08.2007	7.00	2.00
19	17.10.2007	15.00	0.05
20	05.11.2009	Crack	Crack
21	05.11.2009	Crack	Crack
22	05.11.2009	Crack	Crack
23	05.11.2009	Crack	Crack
24	08.11.2009	Crack	Crack
25	10.10.2010	6	2
26	05.11.2010	12.6	1.5
27	05.11.2010	25	Crack
28	05.11.2010	6	Crack
29	30.11.2010	20	0.15
30	30.11.2010	13.5	2
31	27.12.2010	18	11
32	29.12.2010	14.7	10.5

Water quality

The statistics of the chemical parameters and major ions for the wellfield’s water wells are shown in Table 5. The major types of water, according to the Piper diagram (see Fig. 10), are Mg–K–Na–HCO₃, Mg–K–Na–HCO₃–Cl, and Mg–Na–K–HCO₃, which reflect the carbonate and silicate weathering and cation exchange of ferromagnesian minerals. The average water temperature is 31.15 °C. The electrical conductivity (EC) of groundwater is generally moderate to low, with an average of 337.00 µS/cm, reflecting the water’s comparatively low total dissolved solids (TDS) concentration, which ranges from 181 to 254 mg/L. The TDS spatially increases east of the wellfield, as shown in Fig. 11. The pH levels exhibit variability between 5.92 and 6.84, with an average value of 6.35. Carbon dioxide concentration

Table 5 The statistics of the chemical parameters and major ions for the wellfield water wells

Parameter	Symbol	Unit	Min	Max	Average
Temp	T	°C	28.60	34.90	31.15
Electric conductivity	EC	µs/cm	259.00	420.00	337.00
pH-value	pH		5.92	6.84	6.35
TDS calculated	TDS	mg/L	181.00	254.00	203.98
TDS by EC	TDS	mg/L	200.00	286.00	229.45
Bicarbonate	HCO ₃	mg/L	111.00	178.00	143.64
Boron	B	mg/L	0.20	1.80	0.46
Calcium	Ca	mg/L	8.00	21.00	10.40
Calcium hardness	CaCO ₃	mg/L	20.00	50.00	25.70
Carbonates	CO ₃	mg/L	0.01	0.08	0.02
Chloride	Cl	mg/L	20.00	30.00	23.10
Magnesium	Mg	mg/L	8.00	15.00	12.45
Manganese	Mn	mg/L	0.02	0.23	0.12
Nitrate	NO ₃	mg/L	≤LOD	0.10	0.02
Potassium	K	mg/L	16.00	41.00	29.76
Silicium (as SiO ₂)	SiO ₂	mg/L	12.00	20.00	14.72
Sodium	Na	mg/L	10.00	41.00	19.50
Sulfate	SO ₄	mg/L	5.00	33.00	19.30
Total Alkalinity	CaCO ₃	mg/L	91.00	146.00	117.81
Total Hardness	CaCO ₃	mg/L	70.00	88.00	77.23
Total Iron	Fe	mg/L	0.94	4.25	1.99
Carbon dioxide	Co ₂	mg/L	26.00	77.00	54.95
Hydrogen sulfide	H ₂ S	mg/L	12.00	20.00	0.012

is high in most of the water wells, with an average of 54.95 mg/L. As a result of this high concentration, treatment is required, and unlike carbon dioxide, the concentration of dissolved hydrogen sulfide is very low, with an overall average of 0.012 mg/L. The average total alkalinity (CaCO₃) is 117.81 mg/L, and the average calcium concentrations is 10.40 mg/L. Magnesium levels are very low, with an average of 12.45 mg/L. According to the measured total hardness, indexed by the concentration of CaCO₃, the water is soft, and the average value is 77.23 mg/L. Manganese exists as Mn⁺⁺ since the water’s pH is too low to form complexes of manganese oxide, and the solubility of iron compounds (as Fe⁺⁺) is low (El Mabrouk and Sahli 2006). The average concentration for manganese is 0.12 mg/L, and for iron is 1.99 mg/L. According to the World Health Organization (WHO) (WHO 2017) the iron concentration is about seven times higher and the manganese concentration is twice the permissible level for drinking water defined by the WHO. Therefore, the water is processed within treatment units at the well’s head before transferring it to the consumer. Carbon dioxide is removed by aeration and iron and manganese extracted through sand filters, then discharged on the surface next to the wells (see Fig. 12). Chlorination units are installed on the collector pipelines of water wells, but

Fig.10 Piper diagram for the wellfield water wells

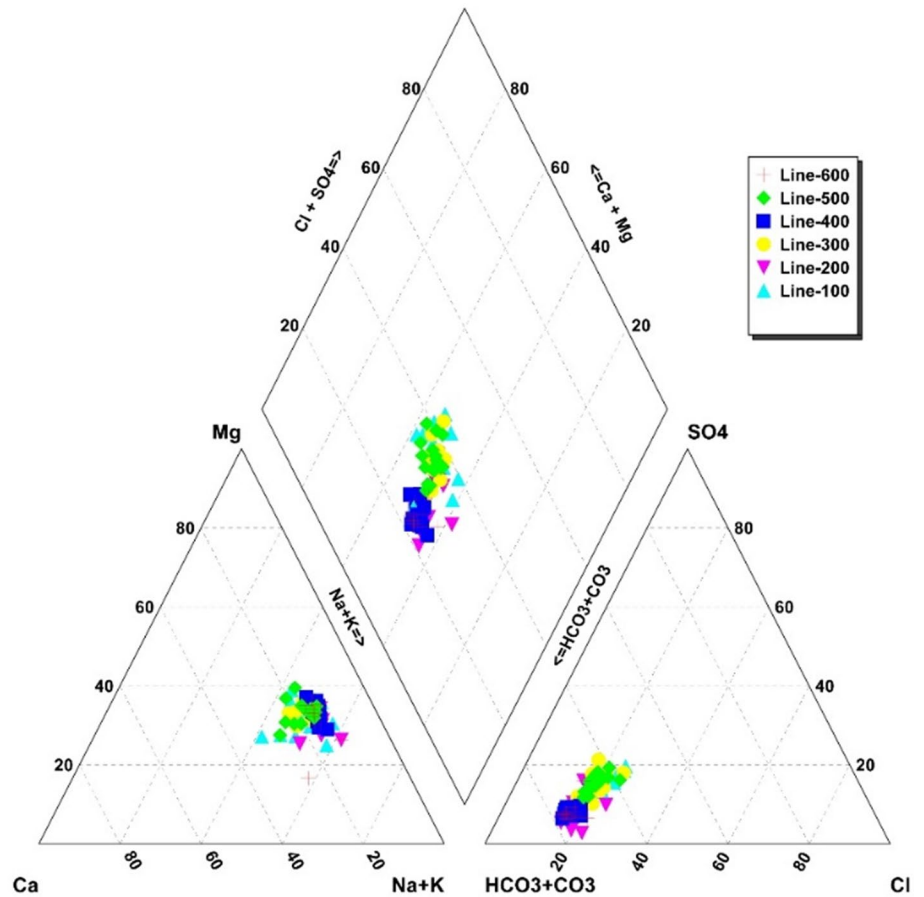
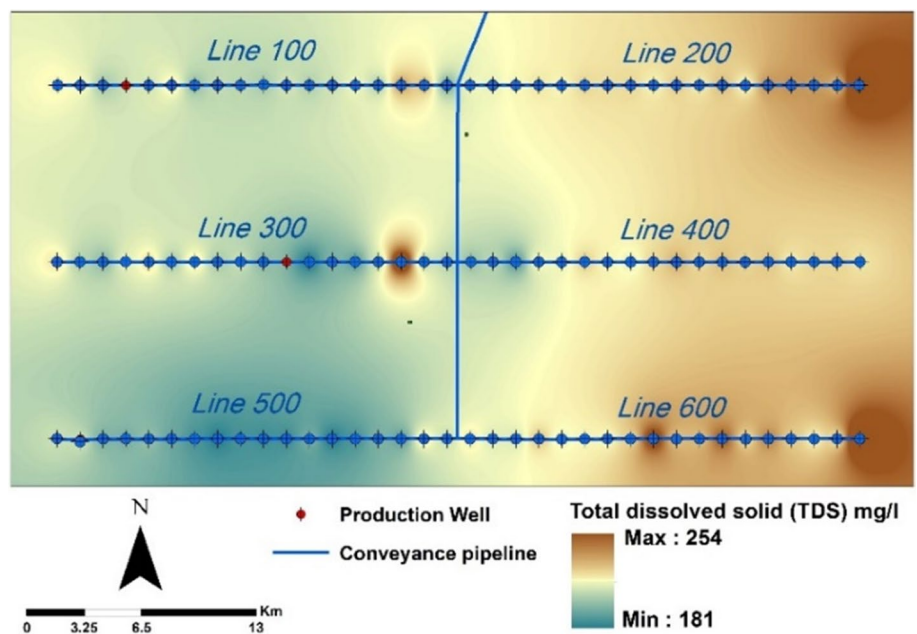


Fig.11 TDS Map of Tazerbo wellfield



currently, chlorination is carried out at the storage tanks. The average potassium concentration is 29.76 mg/l, which is considered very high but has no significant impact on

water quality (WHO 2017). Furthermore, the water is suitable for agriculture (Fig. 13), and as per sodium adsorption ratio and residual sodium carbonate in Table 5. Based on

Fig. 12 Iron and manganese sludge at Tazerbo wellfield



the results of MMRA's periodic monitoring of water quality, there is no change in water quality since the start of wellfield abstraction.

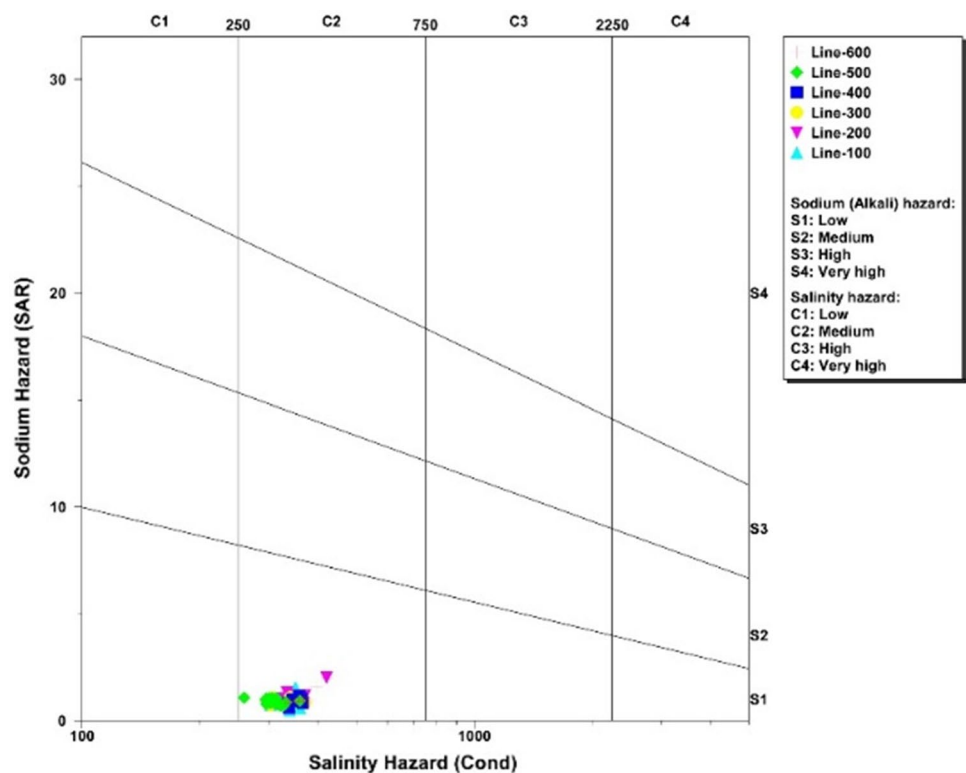
Wellfield management

Effective groundwater management can protect scarce and valuable groundwater resources; while improper management can result in water scarcity including insufficient supplies of drinking water (Alqadi et al. 2019; Hansen et al. 2013; Cudennec et al. 2007). The objectives of wellfield management include the supply of water of appropriate quality to be consistent with demand at an affordable price (Schnieders 2018). Wellfield management also represents a systematic application of the knowledge and practices necessary to achieve sustainability. So often, wellfield managers, consultants, and contractors, as well as regulatory bodies, look at wellfield only for the duration of operation, maintenance, and rehabilitation or a wellfield protection zone and abstracted water quality assessment. But, on the other hand, wellfield management is an integrated process in which all

the IWRM principles should apply to ensure water resources and supply sustainability.

MMRA was established after the decision to finance and implement the MMR project drafted in October 1983. Accordingly, in the same year and as affected by law No (11), MMRA was established in Benghazi city to implement and manage the MMR under the Council of Ministers (formerly General People's Committee). MMRA had broad contracting powers to implement the project, the facilities, and the construction necessary for it and to supervise the project's implementation and management. MMR's administrative and organizational structure consists of general technical management at the level of each water production area (MMR's wellfields) to oversee and implement all civil, electrical, mechanical, hydrogeological, communications, materials science, and other specializations. In addition, MMR's structural scope also includes the General Technical Assistance Departments and departments of Service and Administration (Regulatory and Financial Affairs). Another essential department established in each production area is the Operation and Maintenance Department, which performs

Fig.13 Wilcox diagram



operations and periodical, preventive, and emergency maintenance for MMR's components. It further controls the well-field operations by monitoring the produced water from the wellfields to the urban networks through an advanced communication system linking wellfields, main/sub-transport systems, and storage tanks to the control rooms. In addition, among the established technical departments are departments that monitor buried concrete piping systems PCCP at a depth of 4 m by using corrosion protection technology and acoustic monitoring technology to predict any damage or corrosion of the pre-stressed metal wires involved in the manufactured pipes. There is also an equipped chemical laboratory in each wellfield linked to the central laboratory at the headquarter of MMRA. These laboratories carry out periodic analyses to monitor the chemical concentration of essential elements and monitor bacterial contamination.

The Technical Center for Groundwater Management (TCGM) in MMRA is responsible for groundwater management in terms of supervising drilling and maintenance of wells required after long operating periods. The center also monitors the quality/quantity of groundwater as well as assesses the impacts of groundwater abstraction. TCGM further monitors groundwater levels in wellfield areas through an extensive network of monitoring wells (141 monitoring wells) in all MMR's wellfields and through which it sets appropriate operating plans for the wellfields. It also monitors the components of the water wells

through periodic inspections and evaluates sand content and the yield of the water wells. In addition, the TCGM monitors the environmental impacts on wellfields areas and compares this with the results of previously prepared hydrogeological mathematical models for the wellfields.

The wellfield lies about 1000 km from MMRA's headquarters and is equipped with housing buildings for workers, administrators, groundwater monitoring equipment, and laboratories. Although all departments in MMRA are responsible for the direct and indirect management of the wellfield, the wellfield operation and management are carried out on-site to achieve an optimum management approach (bottom-up rather than top-down) and to involve stakeholders in groundwater management. Also, employment policy is based on creating opportunities for town residents who live in the vicinity of the wellfield.

Due to the geological and hydrogeological situation of the wellfield and the environmental impacts of the land subsidence, MMRA places the management of this wellfield among its priorities by developing appropriate plans for operation and monitoring. From time-to-time, MMRA organizes public awareness programs to showcase its activities at the national level and its dedication to emerging issues, such as land subsidence causes and risks. In addition, the components of the enabling environmental indicators and institutional arrangement in the wellfield are evaluated, and the results are shown in Table 6.

Table 6 Enabling environmental indicators and institutional arrangement

Indicator	Unit	Year: 2020
Water resources policies based on IWRM principles	Yes/No	Yes
Water institutions	Number	2
Inter-institutional integration	Yes/No	yes
Stakeholder participation	Yes/No	yes
The existence of a supreme national authority	Yes/No	Yes
Application of laws to violators of the Water Law	Yes/No	yes
Academies that provide training in the field of water in the region	Number	3
Awareness and water awareness activities per year	Number/YEAR	4

Conclusion and recommendations

The stated goal at the launch of the MMR project is to overcome the scarcity of water in the cities of the Libyan north, especially with population increase and water resources scarcity. The project aims to supply the cities of the north with available groundwater from the southern basins through water wells and a vast conveyance pipeline system. Presently, there is still controversy over the viability of the MMR project, primarily as it depends on non-renewable groundwater. However, previous studies before and during project implementation and the current records of the operations demonstrated encouraging results on groundwater sustainability. On the other hand, since the outbreak of the political conflict in Libya (2011-present), MMR was exposed to theft, looting, and armed attacks by the conflicting parties. This puts 75% of Libyans who rely on MMR for their water demand under the threat of water scarcity.

Tazerbo wellfield is considered the most recent in water production compared to the rest of MMR's wellfields; the study results show that the exploited aquifer has excellent hydraulic properties and promising potential for groundwater. Also, the water abstraction from the wellfield continues despite some disturbances resulting from operational problems caused by financial and security conditions. However, since the first wellfield operation in 2004, water production has not exceeded half the designed production capacity. Moreover, the groundwater level drawdown is still beyond the levels indicated by mathematical models and is only concentrated around the center of the wellfield. Even with the land subsidence phenomenon in the north of the wellfield, there was no associated drawdown in water levels observed at the land subsidence locations. The land subsidence was interpreted as the result of the aquifer's hydrostatic pressure decline that led to dislocation in the weakest places of the topsoil and the effect of the deep faults. Therefore, adopting the interoperability operational plan that TCGM recommended will effectively reduce the increase in land subsidence. In terms of water quality, the wellfield water is suitable for urban use and agriculture, except for an increase in the

elements of iron, manganese, and carbon dioxide that are treated before water is transported to the consumer. Also, no change in the water quality with abstraction was observed. Wellfield management is carried out almost according to the objectives and principles of integrated water resources management.

Finally, this research recommends that more studies be conducted on the phenomenon of land subsidence, including geophysical surveys and updating mathematical models developed during the wellfield design phase based on production data and monitoring well records. Therefore, it is recommended to construct a wireless groundwater monitoring network to overcome issues of remoteness and security. Moreover, the iron and manganese sludge discharged next to wells after water treatment is recommended for recycling and used in various industries. Also, more efforts are required to neutralize the resource from political conflicts and provide protection and necessary financial support for the wellfield management.

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Declarations

Conflict of interest The authors declares that there is no conflict of interest.

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