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Quaternary groundwater aquifer suitability for drinking in Akhmim, Upper Egypt: an assessment using water quality index and GIS techniques

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Abstract

The Quaternary aquifer has a special significance in Akhmim district, Upper Egypt, especially during the dry seasons, when surface water resources are insufficient and limited. In Akhmim district, the population mainly depends on groundwater for drinking, especially in spontaneous residential areas and inside agricultural lands. Therefore, assessing the groundwater quality is necessary to reduce diseases resulting from using polluted water in drinking. The Weighted Arithmetic Water Quality Index (WAWQI) was used for evaluating the groundwater quality, and it was classified according to the Egyptian and WHO standards and based on fifteen measured physicochemical parameters (TDS, Na, Cl, Ca, pH, Mg, NO_3, SO_4, TH, Cr, Cu, Fe, Pb, Mn, and Zn). To investigate the spatial distribution of WAWQI in Akhmim district, the spatial analyst tools (IDW method) were used. The WAWQI results showed a great diversity in groundwater viability for drinking due to the exposure of groundwater to many sources of degradation, identified through field verification and previous work about the study area. The groundwater of the Quaternary aquifer was divided into excellent, good, poor, very poor, and unsuitable. In addition, about 50% of Akhmim district wells are inappropriate for drinking with classes ranging from unsuitable to poor. To use groundwater for drinking, the sources of degradation to which the groundwater is exposed must first be reduced, and the water should be treated before drinking.

Keywords Akhmim · Egypt · Groundwater quality · GIS · Weighted Arithmetic Water Quality Index (WAWQI)

Introduction

In recent years, the world has faced scarcity of freshwater resources due to the population increase, and urban sprawl, which exposed water resources to deterioration in both quantity and quality (Massoud 2012). Consequently, water quality control in many countries has become among the

highest priorities (Simeonov et al. 2002), especially, in arid and semiarid regions (Sayed et al. 2020). Continuity in evaluation and control of water quality helps in the continuous development of the strategies applied for pollution control (Yao et al. 2010).

There are many concerns about the lack of freshwater resources in Egypt, especially with the rapid population growth and the current threats to the main water resource (Nile River) from some upstream countries. Freshwater resources in Egypt are limited to about 55.5 billion m^3/year from the Nile River and about 6.20 billion m^3/year from the groundwater systems (Allam 1998). This amount of water does not meet Egypt's water needs, which prompted the country, through Egypt Vision 2030, to move forward in the search for nonconventional water resources such as seawater desalination and reuse of agricultural and sanitary drainage water through advanced treatment. Groundwater has become the main source of water for most agricultural reclamation projects in Egypt, especially

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in desert areas, which raises concerns about the sustainability of groundwater resources (El Arabi 2012).

Akhmim district in Upper Egypt is facing high rates of population increase and unplanned expansion of urban and industrial activities. This is accompanied by the ever-increasing water crisis and snowballing production of sewage and other polluted water. Moreover, the desert fringes of the study area are being reclaimed for nonedible woodland using treated wastewater. These hazards worsen the environmental conditions of the whole area and can lead to further deterioration in the groundwater resources (Youssef et al. 2011; Ahmed and Ali 2011).

Generally, the quality of drinking water is evaluated according to several measured parameters (chemical, physical, and microbiological). The water is acceptable for human consumption if parameter values do not exceed the limits set by the WHO and the local health authorities in each country (WHO 2011; EMH 2007).

The effect of overall water quality parameters on the total water quality is expressed through the water quality index (WQI) (Horton 1965). WQI is the most effective method for assessing water quality for drinking purposes (Chowdhury et al. 2012). WQI simplifies a large set of values for many water quality parameters into a single value and simple ratings (e.g., excellent, good, bad, improper, etc.) that can be understood very easily by residents and decision-makers (Nasirian 2007; Chauhan and Singh 2010; Bharti and Katyal 2011).

The first water quality index was developed in 1965 by Horton using the arithmetic weighted average technique (Horton 1965). In 1970, some improvements were made to the Horton index (Brown et al. 1970). After that, many water quality indicators were formulated by many researchers and organizations such as Canadian Water Quality Index (CCMEWQI), National Sanitation Foundation Water Quality Index (NSFWQI), and Florida Stream Water Quality Index (FWQI) (SAFE 1995).

The Weighted Arithmetic Water Quality Index method (WAWQI) developed by (Brown et al. 1972) was used to assess the suitability of groundwater for drinking, where water quality is classified based on the most common water quality parameters and according to its degree of purity (Smith 1989). WAWQI has been used by many scientists (Balogun et al. 2012; Negm and Armanuos 2016; Howladar et al. 2017; Tiwari et al. 2018; Vaiphei et al. 2020; Ahmed et al. 2020) because it has many advantages compared to other methods. One of which is that it has the ability to describe the suitability of both groundwater and surface water for drinking purposes (Tyagi et al. 2013), being free from overestimation or underestimation (Sharma et al. 2016), and it is based on a mathematical equation that includes several water quality parameters

without depending on certain parameters (Chandra et al. 2017; El Zeiny and Elbeih 2019).

Geographic information system (GIS) has essential roles in all aspects related to the management and development of water resources such as assessing groundwater quality, mapping, and assessing groundwater vulnerability and suitability analyses. GIS programs contain spatial analysis tools that have the ability to deal with huge data (Madhloom and Alansari 2018).

Many researchers interested in evaluating groundwater for drinking purposes have used the WQI and inverse distance weighting (IDW) interpolation method in GIS programs. Chabuk et al. (2020) assessed the water quality of the Tigris River, Iraq, using the WQI and the IDW method where the results showed deterioration in the water quality downstream the river. El Zeiny and Elbeih (2019) used the WQI and IDW method to evaluate the groundwater quality in Dakhla Oasis, Egypt, for drinking purposes according to the Egyptian and WHO standards, where the results showed that about 38% of the wells fall into the category of poor water. Ewaid and Abed (2017) used the WQI to assess the water quality of the Gharraf River in southern Iraq through five stations along the river. The WQI rated the river water as good for drinking in station 1, weak in stations 2, 3, and 4, and very weak in station 5. Magesh et al. (2013) assessed groundwater quality in Tamil Nadu region, India, using the WQI and GIS where the results showed that most of the groundwater samples are suitable for drinking.

This study aims to assess the suitability of groundwater quality in Akhmim district for drinking purposes by applying the WQI. Spatial analysis tools in ArcGIS program were used to produce spatial distribution maps of groundwater quality, and the reasons for the unsuitability of groundwater for drinking were determined, based on field verification and published studies.

Methodology

Description of the study area

Akhmim district is located east of the River Nile in Sohag Governorate between longitudes 31° 35` and 31° 55` E and latitudes 26° 30` and 26° 38` N (Fig. 1). The major geomorphological features in Akhmim area include the cultivated Nile flood plain, the Eocene limestone plateau, and the lowland desert areas (Youssef and Abdel Moneim 2006).

In the lowland desert area, south of Akhmim (El-Kola area), treated wastewater is used in the cultivation of woody trees, but this area is insufficient to accommodate the wastewater quantities resulting from the treatment plant. As a result, the wastewater accumulates on the ground surface

Fig. 1 Location and geo-
logical map of Akhmim district
(EGSMA 1983)
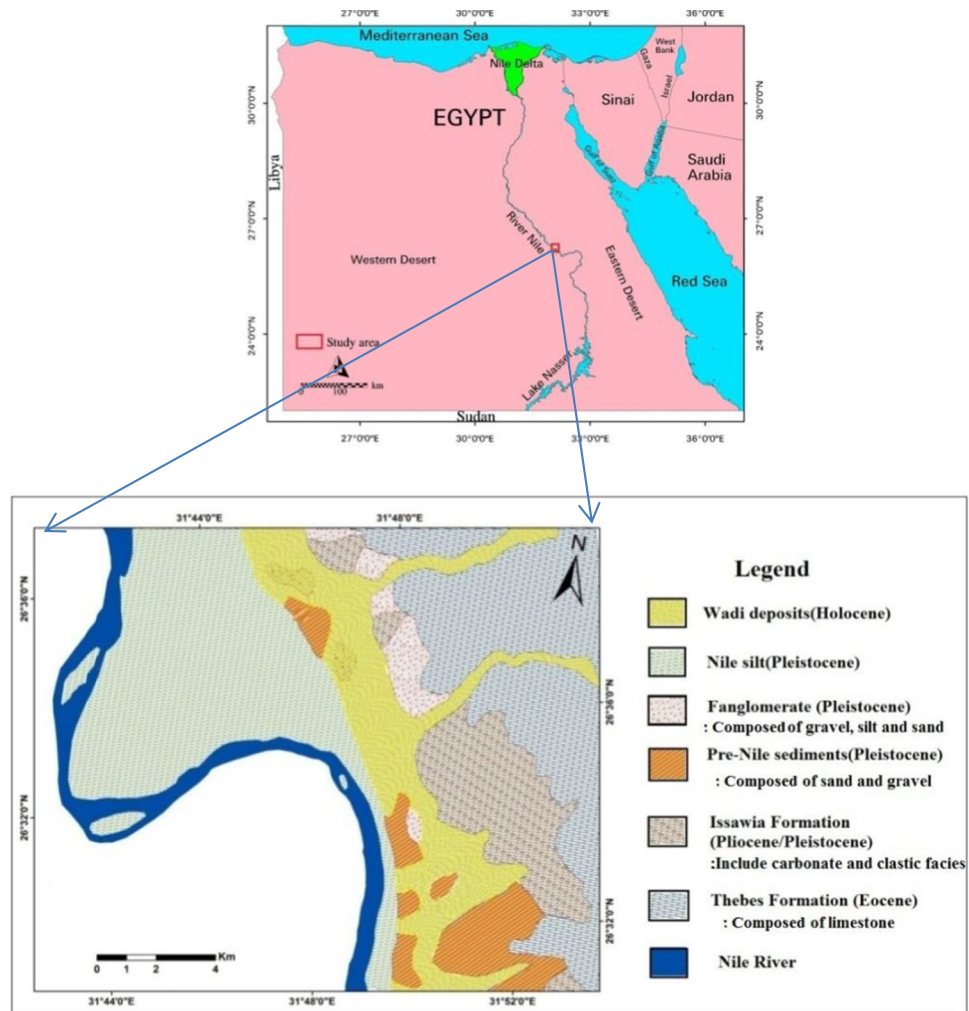
forming large pools (Youssef et al. 2011). In the last few years, many industrial areas were built in Sohag Governorate, where Al-Kawser city is one of these areas and is located north of Akhmim district (Ahmed 2009).

The sedimentary sequence in Akhmim area consists of rock units that extend from Eocene to Recent. The major aquifer in Akhmim area is the Quaternary aquifer system where the Pleistocene deposits are the major water-bearing sediments (Abdel Moneim 1999). On ancient cultivated lands, the Quaternary aquifer is a semi-confined aquifer where the upper member consists of a clay-silt layer, while in the desert fringes, it is an unconfined aquifer, and the clay-silt layer is replaced by desert sands. The groundwater flows towards the River Nile where the groundwater level in Akhmim area ranges from 63 m (masl) at the valley fringes to 53 m (masl) near the River Nile. Return flow from irrigation (excess irrigation water) is the essential source of groundwater recharge, and extraction by pumping wells is the major source of discharge (Ahmed 2007).

The groundwater has a special importance in the study area, as it is used mainly for drinking, especially in random residential areas scattered along the roads and inside agricultural lands. However, it is presently threatened by pollution from urbanization, agricultural activities, and wastewater used in agriculture (Ahmed and Ali 2011). The main pollution source resulting from domestic activities includes leakage from sewage system, septic tanks, and probable release of wastewater from wastewater disposal sites (Ali 2005; Youssef and Abdel Moneim 2006; Elbeih et al. 2021; Hagage 2021). The development projects in the desert zone of Sohag Governorate represent a new source of groundwater contamination for the Quaternary aquifer (Ahmed 2009).

Figure 2 shows the flow chart for the methodology used to determine groundwater suitability for drinking purposes in the study area.

Sampling of groundwater and analysis

Thirty-two groundwater samples representing the Quaternary aquifer system were collected in April 2019. The well coordinates were recorded using Garmin Handheld GPS (Fig. 3).

Fig. 2 Flowchart of materials and method steps
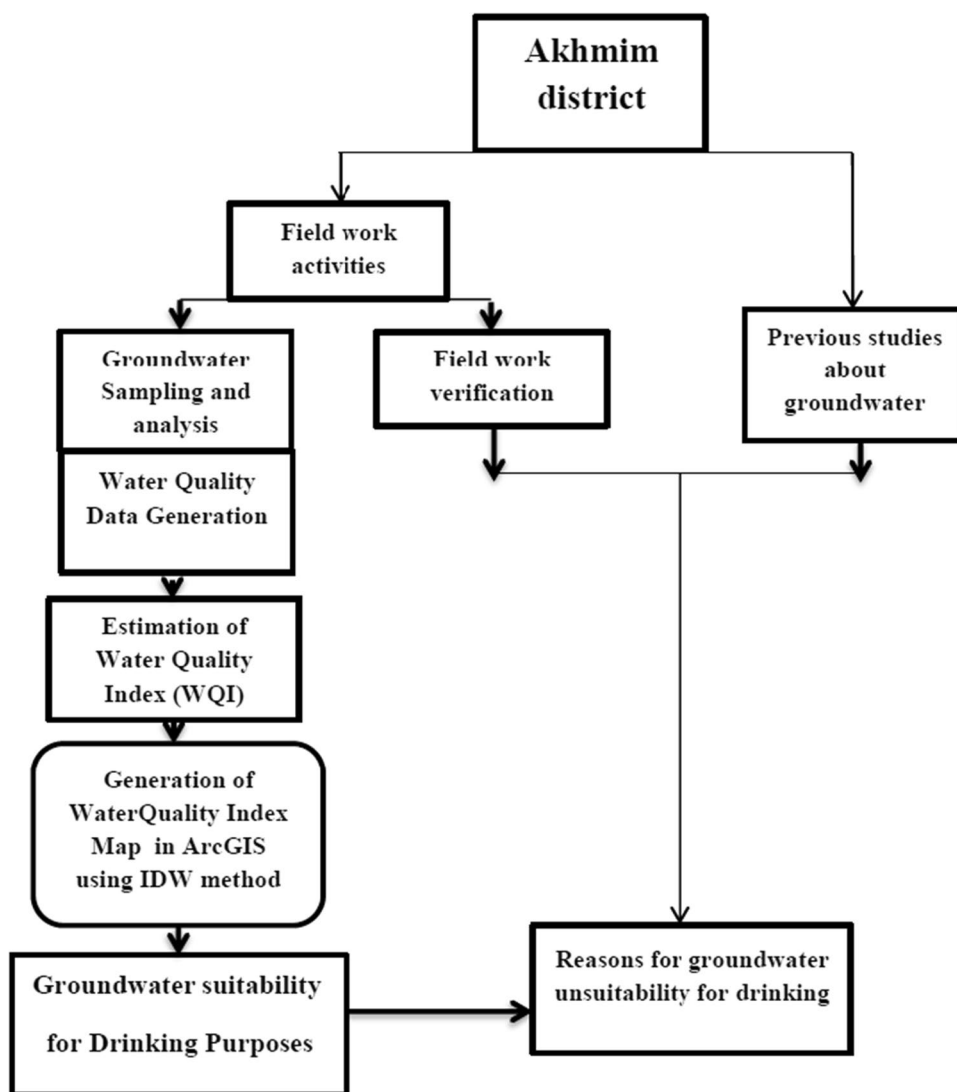
The wells were pumped for 10 min prior to sample collection to avoid stagnant water from the boreholes and rinsing the bottles several times with the groundwater prior filling with water to minimize any contamination. Two bottles were collected from each well, 1 l bottle and another bottle of 100 ml acidified with nitric acid (1%) for heavy metals analysis and preserved separately, and all water samples were closed carefully and labeled after collection and preserved in an icebox until analysis. In the central laboratory of the National Water Research Center, analysis was carried out, where cations, anions, nutrients, and soluble heavy metals were determined.

Water quality index calculation

In this study, the Weighted Arithmetic Water Quality Index (WAWQI) method was used. The water quality was classified according to the Egyptian Ministry of Health and Population (EMH 2007) and World Health Organization (WHO) standards (WHO 2011) based on fifteen measured parameters (TDS, Cl, Ca, Na, Mg, pH, NO_3, SO_4, TH, Cr, Cu, Fe, Pb, Mn, and Zn).

Weighted arithmetic water quality index

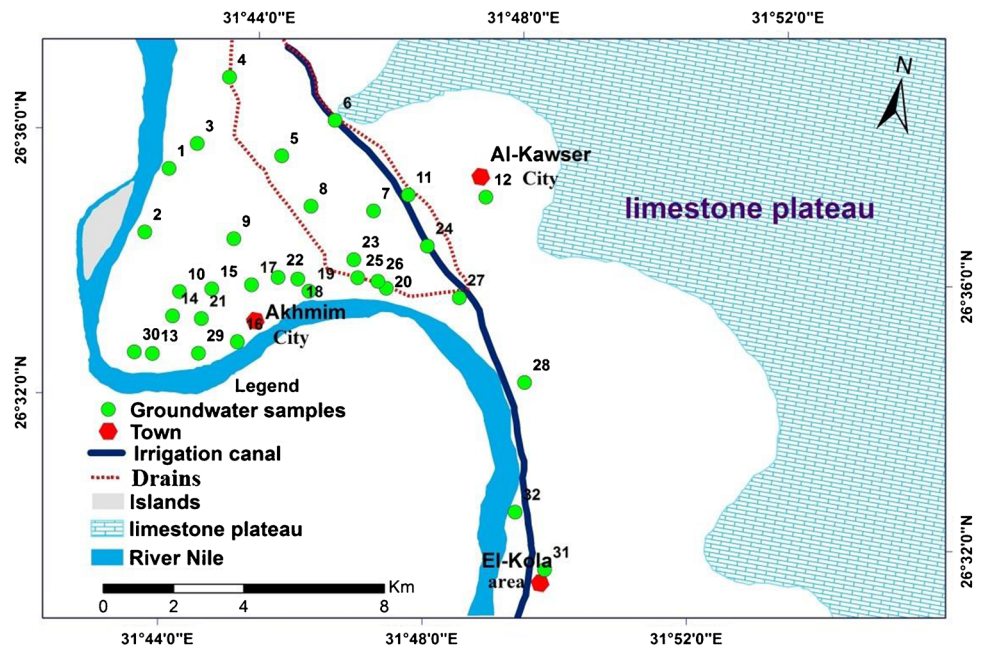The WAWQI was developed by Brown et al. (1972), and it is determined using the next equations:

$$WAWQI = \frac{\sum Q_i W_i}{\sum W_i} \tag{1}$$

where,

(W_i) is the relative weight of ith parameter.
(Q_i) is a quality rating scale for the ith parameter.

Fig. 3 Groundwater sampling locations in Akhmim district

Table 1 Water quality classification according to WAWQI (Brown et al. 1972)

WAWQI rating	Water quality
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
Above 100	Unsuitable for drinking purpose

The water quality classification based on the above calculated WAWQI using Eq. 1 is given in Table 1.

The following steps were used to determine the WAWQI.

1- Calculation of quality rating scale (Q_i)

Q_i is a number that reflects the ratio of the concentrations of different water quality parameters in relation to its standard value and is calculated by Eq. 2:

$$Q_i = \frac{V_i - V_0}{S_i - V_0} * 100 \qquad (2)$$

where,

(V_i) estimated concentration of ith parameter in the analyzed water sample.

(V_0) the ideal value of this parameter in pure water, $V_0 = 0$ (except for dissolve oxygen $= 14.6$ and pH $= 7.0$).

(S_i) the recommended standard value of ith parameter (WHO 2011; EMH 2007).

The World Health Organization (WHO 2011) and the Egyptian Ministry of Health (EMH 2007) have standard values of maximum allowable limits for the parameters measured in drinking water as shown in Table 2.

2- Calculation of relative weight (W_i)

To calculate the relative weight, different weights were assigned to the measured parameters according to their impact on water quality used for drinking purposes, potential health effects, and according to researchers opinions (Balogun et al. 2012; Ambiga and Durai 2013; Anbazhagan and Jothibasu 2014; Negm and Armanuos 2016; Howladar et al. 2017; Tiwari et al. 2018; Vaiphei et al. 2020; Ahmed et al. 2020). Researchers have assigned the weights of parameters in the range from 1 to 5. The highest weights (5 and 4) have been assigned to parameters such as TDS, NO_3, SO_4, Cr, Fe, and Pb due to their major importance in water quality assessment for drinking. On the other hand, weights of 3 and 2 were assigned to other parameters such as pH, Ca, Mg, Cl, and Na depending on their importance in the overall water quality. The lowest weight (1) has been assigned to parameters (HCO_3) which is considered of less impact on the water quality.

The relative weight (W_i) is calculated using the next formula (Singh 1992):

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad (3)$$

where,

Table 2 Maximum allowable limits for the parameters measured in drinking water

Parameters	Egyptian maximum allowable limit (EMH 2007)	WHO maximum allowable limit (WHO 2011)
pH	6.5–8.5	6.5–8.5
Total dissolved solids (TDS) mg/l	1000	1000
Calcium (Ca) mg/l	200	200
Magnesium (Mg) mg/l	150	130
Sodium (Na) mg/l	200	200
Chloride (Cl) mg/l	250	200
Nitrate (No$_3$) mg/l	45	50
Sulfate (SO$_4$) mg/l	250	200
Total hardness (TH)	500	500
Chromium (Cr) mg/l	0.05	0.05
Copper (Cu) mg/l	1	1.5
Iron (Fe) mg/l	0.3	0.3
Lead (Pb) mg/l	0.05	0.01
Manganese (Mn) mg/l	0.1	0.1
Zinc (Zn) mg/l	5	5

Table 3 Weight and relative weight of parameters

Parameters	Weight (w_i)	Relative weight (W_i) $= w_i/\sum_{i=1}^{n} w_i$
TDS	5	0.098
pH	3	0.059
Ca	2	0.039
Mg	2	0.039
Na	3	0.059
Cl	3	0.059
NO$_3$	5	0.098
SO$_4$	4	0.078
TH	2	0.039
Cr	4	0.078
Cu	3	0.059
Fe	4	0.078
Pb	4	0.078
Mn	4	0.078
Zn	3	0.059
Sum	51	1

wi is the weight of the ith parameter.

The weights assigned to the different parameters, as well as the relative weights calculated, are presented in Table 3.

GIS analyses

The inverse distance weighting (IDW) interpolation method in ArcGIS V.10.2 software was used to investigate the spatial distribution of WAWQI in Akhmim district. This method is the most widely used by earth and water scientists compared with other spatial analysis tools because of its high accuracy (Madhloom and Alansari 2018). The assumption that IDW interpolation method relied upon is that sites close to each other are more similar than those far away from each other (Lu and Wong 2008).

Field verification

After calculating the water quality index and identifying the areas that suffer from unsuitability of groundwater for drinking, the results were confirmed through:

(1) Field verification to identify the reasons for the unsuitability of groundwater for drinking in these areas.

(2) Published studies on groundwater quality in Sohag Governorate (Youssef and Abdel Moneim 2006; Youssef et al. 2011; Ahmed and Ali 2011; Elbeih et al. 2021; Hagage 2021).

Results and discussion

Groundwater quality using WQI

The WQI was calculated, in order to estimate the suitability of groundwater in Akhmim area for drinking. Statistical analysis of the physical and chemical properties of the groundwater samples that were applied in the calculation of the WQI is shown in Table 4.

WAWQI results showed a great diversity in groundwater viability for drinking where the groundwater in Akhmim district was divided into categories: unsuitable, very poor, poor, good, and excellent. The results of applying WAWQI for drinking purposes are shown in Table 5. The percentages of WAWQI according to the Egyptian standards and WHO standards are shown in Fig. 4.

Table 4 Statistical analysis of the measured parameters of the groundwater samples

Parameters	Units	Minimum	Maximum	Mean
TDS	mg/l	228	3088	756
pH	–	7.2	7.8	7.52
TH	mg/l	156	894	251
Na	mg/l	17	750	130
Ca	mg/l	52	176	81
Mg	mg/l	10	35	26
NO_3	mg/l	0.2	125	16
CL	mg/l	21	1087	124
SO_4	mg/l	27	493	93
Pb	mg/l	0.004	0.05	0.025
Mn	mg/l	0.004	1.3	0.168
Cr	mg/l	0.002	0.02	0.011
Cu	mg/l	0.011	0.23	0.03
Fe	mg/l	0.006	0.14	0.030
Zn	mg/l	0.01	1.81	0.177

Table 5 WQI values and groundwater viability for drinking in Akhmim district

Well no	Egypt standards (2007)		WHO standards (2011)	
	WQI	Water type	WQI	Water type
1	36.6	Good	51.7	Poor
2	28.2	Good	31	Good
3	19.1	Excellent	22	Excellent
4	24.1	Excellent	37.7	Good
5	35.9	Good	40	Good
6	25.5	Good	27.8	Good
7	30	Good	34.4	Good
8	50.9	Poor	61.4	Poor
9	60.1	Poor	63.3	Poor
10	25.9	Good	31.3	Good
11	35.5	Good	41.5	Good
12	86.9	Very poor	98	Very poor
13	30.8	Good	58.5	Poor
14	32.3	Good	42.8	Good
15	38	Good	48	Poor
16	61.4	Poor	84.5	Very poor
17	34.5	Good	53	Poor
18	34.1	Good	44.2	Good
19	123	Unsuitable	136	Unsuitable
20	58.5	Poor	75.5	Very poor
21	32.5	Good	50.5	Poor
22	35.5	Good	65.2	Poor
23	56.4	Poor	63.7	Poor
24	50.1	Poor	82.4	Very poor
25	35.1	Good	67.1	Poor
26	62.9	Poor	79.1	Very poor
27	39.8	Good	59.5	Poor
28	36.5	Good	51	Poor
29	57.4	Poor	62.5	Poor
30	57.5	Poor	69.5	Poor
31	119	Unsuitable	138	Unsuitable
32	17.5	Excellent	27.3	Good

Spatial distribution maps of WQI according to the Egyptian and WHO standards were created for study area as shown in Figs. 5 and 6. According to WHO standards, the groundwater in Akhmim district is divided into four categories: good, poor, very poor, and unsuitable for drinking. The unsuitable groundwater in Akhmim district is about 4% of the total area (Akhmim city, El-Kola area), while 11.5% is located in very poor groundwater quality (as Al-Kawser city). The good groundwater area is about 35.5%, while most parts of Akhmim district (49%) have poor groundwater quality.

According to the Egyptian standards, the groundwater in Akhmim district is divided into categories: excellent, good, poor, very poor, and unsuitable for drinking. The unsuitable groundwater for drinking in Akhmim district is about 2% of the total area (Akhmim city, El-Kola area), while 5% is located in very poor groundwater quality (as Al-Kawser city). The excellent groundwater area is about 0.5% and the poor groundwater quality is about 35.5% of the study area. In most parts of Akhmim district (57%), groundwater is good.

The results obtained after applying both standards are very close to each other, as the very poor quality of water and unsuitable for drinking are concentrated in Akhmim city, Al-Kawser city, and El-Kola area. Both guidelines are applicable for such types of study.

Reasons for groundwater unsuitability for drinking in the study area

In Akhmim area, it is assumed that water in canals and drains is the main source for groundwater recharge and the main factor contro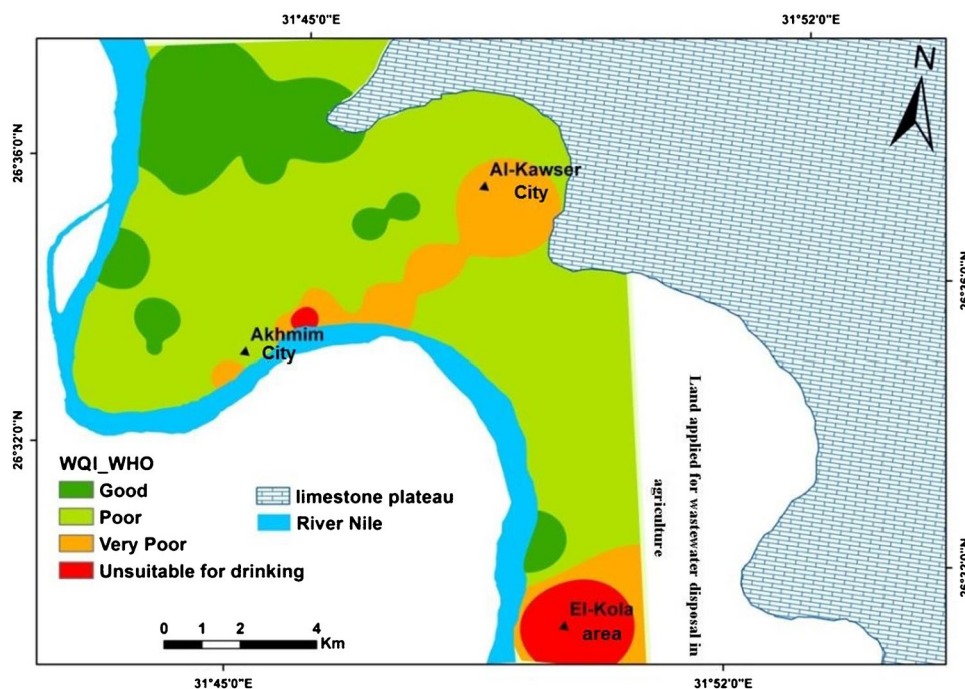lling its quality. Recently, other sources have emerged that contribute to the groundwater recharge and accordingly to the quality of groundwater and led to further degradation. These other sources include urbanization, agricultural activities, and using wastewater in agriculture indiscriminately and without proper control (Ali 2005; Ahmed 2009).

The spatial distribution maps of WQI in Akhmim district show that the entire study area suffers from groundwater quality deterioration. The areas that suffer severely from such deterioration and the unsuitability of groundwater for drinking are Akhmim city, Al-Kawser city, and El-Kola area. The reasons for groundwater deterioration and its unsuitability for drinking were determined through field verification and published studies (Omer et al. 2005; Youssef and Abdel Moneim 2006; Ahmed 2009; Youssef et al. 2011;

Fig. 4 The percentages of WQI categories according to Egyptian and WHO standards

	Unsuitable	Very Poor	Poor	Good	Excellent
Egypt(2007)	2	5	35.5	57	0.5
WHO(2011)	4	11.5	49	35.5	0
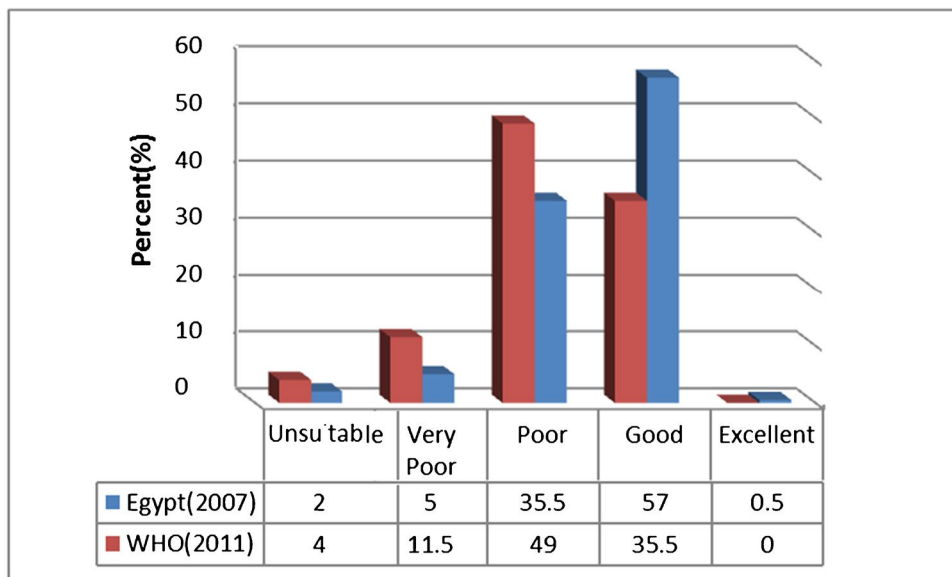
Fig. 5 Spatial distribution of WQI according to the WHO standards

Elbeih et al. 2021; Hagage 2021), which can be clarified in the following points:

1- Using septic tanks (sewage rooms) and injection wells to get rid of sewage

In Akhmim district, built-up areas expanded from 9189.9 km^2 in 1990 to 13,696.2 km^2 in 2019 (Elbeih et al. 2021). Population growth and urbanization without proper urban planning in the study area generated random sewage systems as the only way to get rid of sewage, especially in rural areas and scattered settlements (Fig. 7).

Sewage rooms are the popular disposal facility used in the study area. These rooms are built in a way that sewage water percolates from the walls and bottoms leading to further groundwater deterioration (Ahmed and Ali 2011). The second form of random sewage systems is the use of injection wells in some areas for sewage disposal. The amount of sewage pumped into the groundwater aquifer depends on the population density and the amount of water consumed for domestic purposes (EEAA 1997).
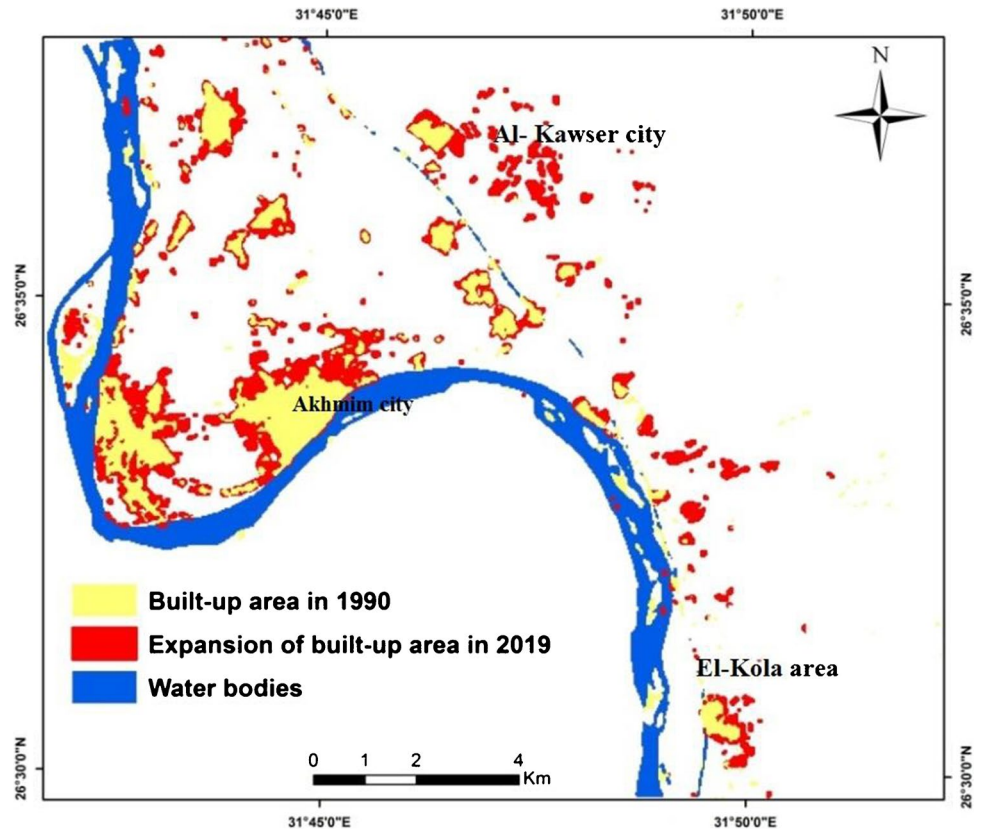
2- Discharging liquid industrial wastes into the ground without proper treatment

Fig. 6 Spatial distribution of WQI according to the Egyptian standards
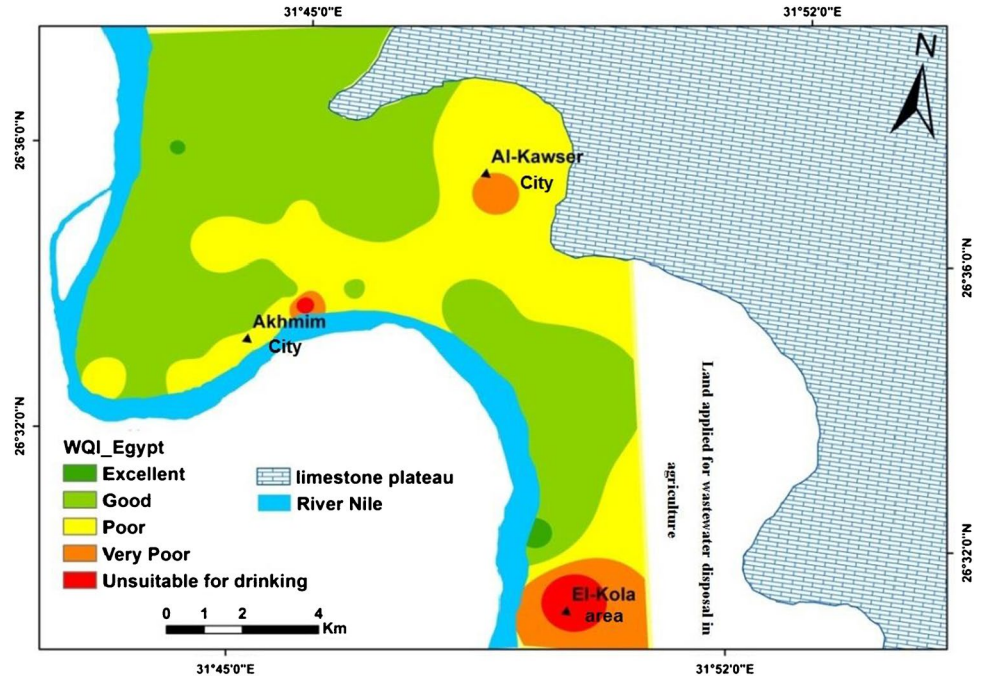

Fig. 7 Expansion in built-up areas based on two multispectral Landsat images (L.S 5 TM and L.S 8 OLI), dated 2nd of February 1990 and 23rd of April 2019 (Elbeih et al. 2021)

Al-Kawser city is the main source of industrial pollution of groundwater in Akhmim district, where the factories there lack proper treatment and sewage systems. There are major factories in the area for sugar, soft drinks, garment industries, and oil dehydration industries. One of the major problems facing these industrial communities is the potential health and environmental hazard posed by industrial wastewater. Untreated wastewater discharged by industrial
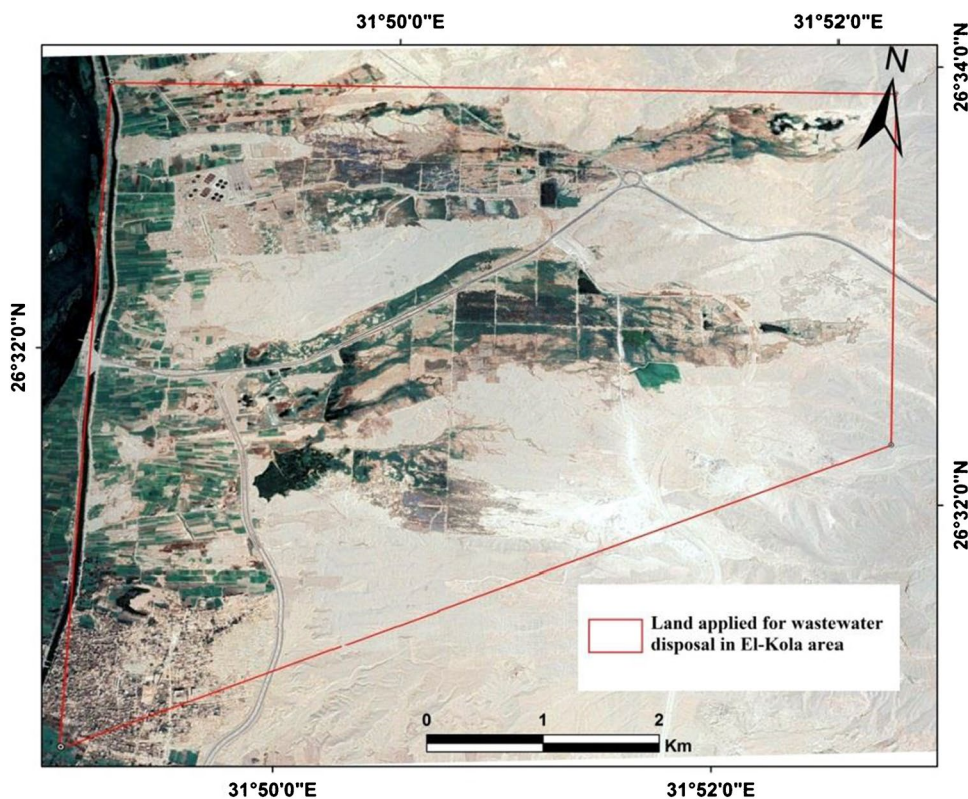
activities is often contaminated by a variety of toxic or harm-
ful substances (El-Gohary et al. 2002). Most factories dis-
charge their liquid wastes into subsurface tanks. Pollutants
seep into the groundwater, especially west of Al-Kawthar
area, where the water level is relatively shallow, and the
rate of infiltration of soil sand and silt is considerably high
(Youssef and Abdel Moneim 2006).

3-   Using treated wastewater in irrigation

Secondary treated wastewater is used for irrigation of
woody farmlands in the desert area east of El-Kola area in
a random manner. Irrigation in this area takes place without

applying the conditions and rules established by the Food
and Agriculture Organization (FAO 2003) regarding using
treated wastewater in agriculture (Fig. 8). More than 28,000
m^3/day of treated wastewater from the El-Kola treatment
plant is used in irrigating the woody farmlands (Egyptian
Ministry of Environment 2019).

The random use of wastewater in agriculture led to its
accumulation on the earth's surface, creating large ponds at
the site as shown in Fig. 9. The geology of the region may
have a role in the formation of these ponds. Youssef et al.
(2011) mentioned that El-Kola site has a unique geological
advantage, the presence of a dense Pliocene clay layer very
close to the surface, which greatly enhances the formation

Fig. 9 Wastewater pools in the
land applied for wastewater
disposal

Fig. 10 A Aster Global Digital Elevation Model (AS TGDEM) showing the topography of the study area (Hagage 2021). **B** Detailed cross section in El-Kola disposal site showing the subsurface succession in the area and the expected flow direction of water (Youssef and Abdel Moneim 2006)
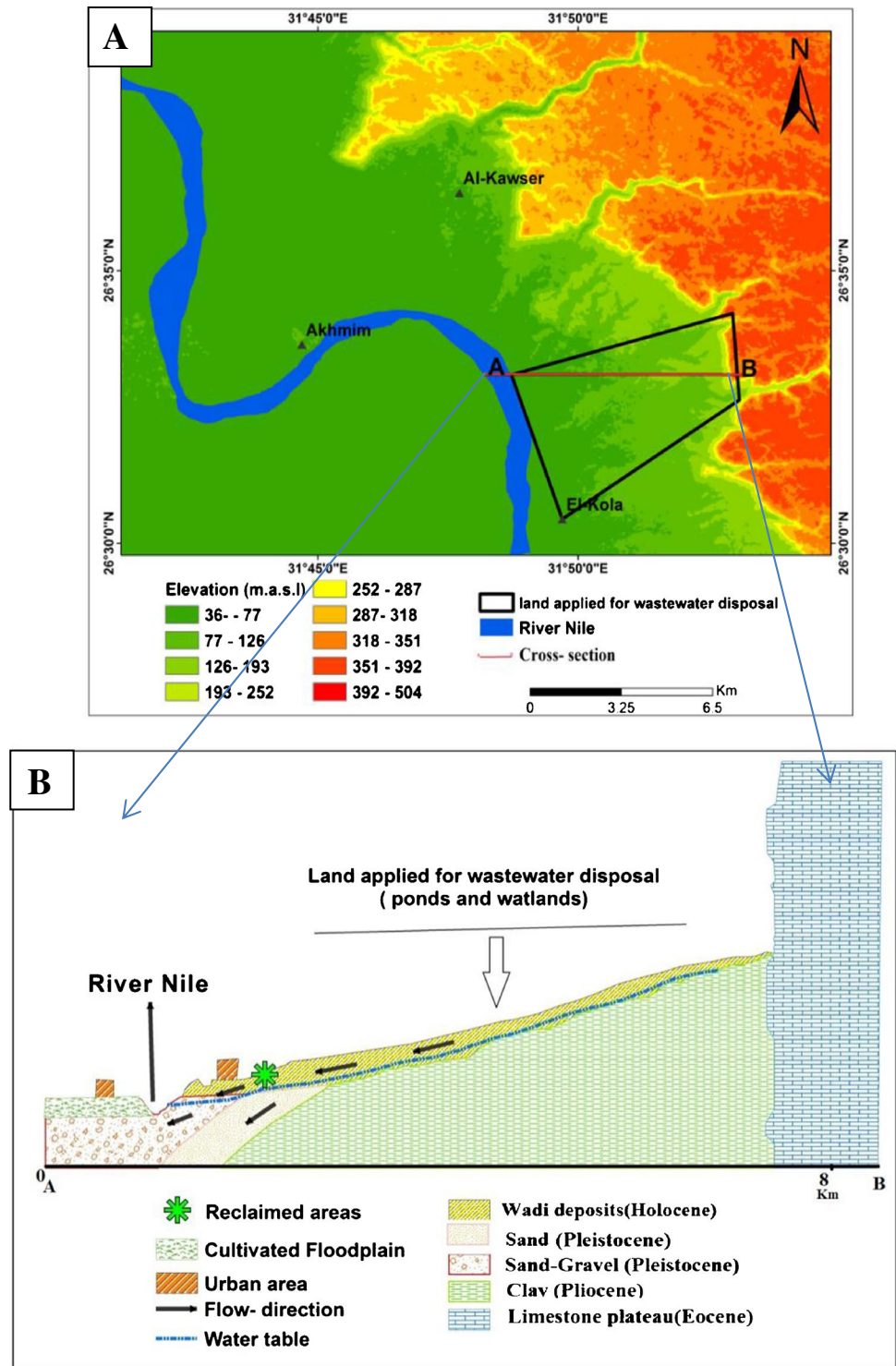
of these ponds (Fig. 10). This Pliocene clay represents a barrier against water to penetrate downwards to the subsurface layers, and hence several ponds are formed.

There are different types of seepage of treated wastewater at this area including seepage due to irrigation method, seepage from the pipelines, and seepage from the ponds (Youssef and Abdel Moneim, 2006). Wastewater accumulated in the land applied for wastewater disposal can be infiltrate down and reach the groundwater where the sediments in this area are classified as coarse textured sediments where the sand fraction is predominant, the hydraulic conductivity ranges from 1.5 to 26 cm/h, which reflects good permeability of these deposits (Omer et al., 2005).

As a result of the ground surface slope to the west and the presence of a layer of dense Pliocene clay very close to the surface in the land applied for wastewater disposal (Fig. 10), water accumulating moves towards the groundwater aquifer (Elbeih et al. 2021), which pollutes the groundwater in the area (Ali 2005; Ahmed 2009).

Conclusion and recommendations

Akhmim district is located east of Sohag Governorate, Upper Egypt, and is facing a high rate of population increase and unplanned expansion of urban and industrial activities that could lead to further deterioration in the groundwater quality. Akhmim district depends mainly on groundwater for drinking, especially in the summer where the surface water is insufficient and limited. Therefore, assessing groundwater quality is necessary to reduce diseases resulting from the use of polluted water in drinking.

The suitability of groundwater for drinking was assessed using the WAWQI method developed by Brown et al. (1972), according to the Egyptian and WHO standards, and based on thirty-two groundwater samples collected from Akhmim district. The spatial distribution of groundwater suitability for drinking was shown using the spatial analysis tools in ArcGIS software.

WAWQI results showed a great diversity in groundwater viability for drinking as the groundwater was divided into excellent, good, poor, very poor, and unsuitable for drinking. About 50% of the wells of Akhmim district are inappropriate for drinking in categories from unsuitable to poor.

The areas that suffer severely from the deterioration of groundwater and its unsuitability for drinking are Akhmim city, Al-Kawser city, and El-Kola area. Field investigations were conducted to confirm the reasons of groundwater unsuitability for drinking in these areas. These reasons are using septic tanks (sewage rooms) and injection wells to get rid of sewage in most of the study area, discharging liquid industrial wastes into the ground without proper treatment in Al-Kawser city, and using of treated wastewater in agriculture east of El-Kola area in a random and unplanned manner.

To use groundwater for drinking, the following recommendations should be taken into account:

- Treating groundwater before drinking so that water quality will fall within acceptable standard limits.
- Establishing sewerage networks in all residential areas, especially rural areas to prevent the seepage of wastewater to groundwater
- Forcing factories to treat their wastewater to be within the standard limits for liquid waste before discharging it

- Introducing restrictions on the use of untreated or partially treated sewage water for irrigation

Declarations

Conflict of interest The authors declare no competing interests.

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