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Integrated approach to quality indices and health risk assessment of water in the Bahr Yusuf Canal, Fayoum, Egypt

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Abstract

The Bahr Yusuf Canal is the life artery of the Fayoum Province, which provides the province with two thirds of the freshwater quota from the Nile River. The present work was carried out to assess the suitability of water in the Bahr Yusuf Canal for various purposes and to assess the potential health risk associated with metal content. The results showed that the water quality of Bahr Yusuf was classified as poor and very poor for recreational use according to the Oregon WQI. On the other hand, the Aquatic Toxicity Index indicated the suitability of water for all fish species. The Canadian WQI and the Weighted Arithmetic WQI classified the canal water as good (WQI = 92), fair (WQI = 73) & marginal (WQI = 64) and excellent, poor to good & good to excellent for irrigation, drinking and aquatic life, respectively. Despite the significant contamination of water with heavy metals (as indicated by the Heavy Pollution Index, ranging from 104.44 to 206.32, from 16.81 to 38.48 and from 219.07 to 472.24 µg l^{-1}), the Hazard Quotient (HQ) and the Hazard Index (HI) data indicate that water of Bahr Yusuf does not pose a human health risk through ingestion or dermal contact. In general, the study showed that water in the Bahr Yusuf Canal is characterized by different levels of pollution, which requires rapid and critical intervention by responsible authorities to prevent the discharge of different types of waste and further deterioration of the water quality during the lifetime of the channel and its subsequent rehabilitation.

Key words: Bahr Yusuf Canal, Nile River, Water Quality Indices, heavy metals pollution, health risk assessment, spatial-temporal variations

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Introduction

Water is the most important natural resource in the world, because life cannot exist without it. The presence of a safe and reliable source of water is thus an essential prerequisite for the establishment of a stable community (Hassan & Elhassan 2016).

The contamination of water is one of the real concerns of the whole world. Heavy metals, toxic waste and various effluents from anthropogenic sources as well as industrialization cause the contamination of river water. These pollutants have adverse effects on the health of human and other living beings in terrestrial and aquatic environments, as well as they affect the food chain (Singh & Sao 2015). The quality of the Nile water is a matter of serious concern due to the expansion of industrial, agricultural and entertainment activities in addition to the poorly constructed drainage and sewerage system (Goher et al. 2015; Hassouna et al. 2014a).

Regular monitoring of drinking water at the source of supply and at the consumer end is of primary importance for the creation of a database combining general and chemical characteristics of water, which can help to significantly reduce health hazards (Cieszynska et al. 2012; Faridi et al. 2012). The Water Quality Index is a mathematical tool for summarizing the water quality data in simple terms. It reflects the level of water quality in rivers, streams and lakes (Abdel-Satar et al. 2017; Kükrer & Mutlu 2019). Heavy metals play a major role in water pollution since they are toxic to aquatic animals and may become a threat to humans. The main source of heavy metals in the Nile River is the drainage of domestic sewage, industrial waste and surface runoff of pesticides and herbicides from agricultural land (Ibrahim 2007). Heavy metals (HMs) contamination and accumulation is a critical problem around the world due to their toxicity, abundant sources, non-biodegradable properties and accumulation (Bifeng et al. 2017; Ali 2019).

In ancient times, Bahr Yusuf was a natural branch of the Nile, connected with the Fayoum depression during the Paleolithic period. Without this natural connection, Fayoum would still be a dry desert depression, similar to other depressions existing in the western desert of Egypt (Omar 2013). The natural canal was passing through the natural relief of the mountain bordering the Libyan desert, with a length of 16 km and a width of 1.5 km, and connected the Nile with Moeris Lake (now known as Qarun Lake), which was used as a reservoir for the Nile water during flood periods. During the 12th dynasty, King Amenemhat III constructed an artificial canal (Old Bahr Yusuf Canal) to restore about 13 BCM of flood water in Moeris Lake every year. The artificial canal, 15 km long, 5 m deep and trapezoidal in shape with a width of 600 m at the bottom, was dug along the natural incline of the valley (Chanson 2004). About 230 BC, the old Bahr Yusuf eventually became neglected. Qarun Lake (Moeris Lake) has been converted to a saline lake, which currently receives only drainage water from the Fayoum province via several drains, mainly El-Bats and El-Wadi (Goher et al. 2018).

At present, Bahr Yusuf is an artificial channel that supplies the Nile water to the Fayoum province via the Ibrahimia Canal. The Ibrahimia Canal, which was dug in 1873 in the city of Assiut, 544.8 km downstream from the Aswan High Dam, flows north for about 61 km to the city of Dairut, where it divides into five canals (Sahelyia, Diroutia, Badraman, Abo Gabal, and Irad Delgaw Canals), in addition to two main branches. One branch (the eastern one) is the Ibrahimia Canal proper (Ibrahimia canal downstream), while the other one (the western branch) is the Bahr Yusuf Canal (Chanson 2004; El Quosy & Khalifa 2017).

Despite the great importance of the Bahr Yusuf Canal, which is the main source of freshwater for the Fayoum province, supplying two thirds of the Nile water quota, it has not attracted sufficient interest from scientists and has not been sufficiently researched as an aquatic ecosystem. Very limited research concerned mostly the quality of water in the canal (Mahmoud 2016; Bream 2017) and most research focused on Bahr Yusuf as part of the irrigation system in the Fayoum governorate.

The present work is the first study to assess the suitability of water from the Bahr Yusuf Canal for different purposes. Therefore, this study was carried out to achieve the following objectives: (a) to assess spatial-temporal variations of physicochemical characteristics and trace element levels in the water of the canal; (b) to indicate the suitability of water for various uses such as drinking, irrigation and aquatic life habitat using different indices of water quality and heavy metal pollution load; (c) to assess the possible chemical toxicity and health hazards due to the presence of trace elements in the canal water using the USEPA Model.

Materials and methods

Study area

As mentioned above, Bahr Yusuf connects the Nile River via the Ibrahimia Canal. With a length of about 315 km, the Bahr Yusuf Canal runs north to irrigate the land of western Assiut, western El-Menyia, Beni-suef, Fayoum, and Giza governorates. The Bahr Yusuf Canal takes a zigzag course for about 276 km until it reaches the Fayoum depression through the Hawara Gap where the Lahoon regulator is located.

At Al-Lahoon barrages, the Bahr Yusuf Canal proper branches into many streams, including three main canals, the first one is the Giza Canal (or "Beni-Suef" – Bahr Yusuf segment) that diverts northeast in the northwestern Beni-Suef and Giza districts. Whereas the other two branches, known as Bahr Yusuf and Bahr Hassan Wasef canals, turn west into the Fayoum depression (MWRI 1992; Hewison 2008; Omar 2014).

In the Fayoum province, the section of the Bahr Yusuf Canal extends over a length of about 24 km, 3–5 m depth and 30–50 m width. Numerous canals receive their water from Bahr Yusuf (the main one being the Bahr Wahby Canal that transports water to northern areas) and distribute it over the Fayoum land. The main distribution point is located at the western end of the city of Fayoum, where the Bahr Yusuf Canal splits into eight channels (Hewison 2008). Bahr Yusuf supplies about 1.613–1.707 BCM y^{-1} of the Nile water to the Fayoum province, which corresponds to two thirds of Fayoum's quota (2.42–2.56 BCM y^{-1}) of the Nile water (MWRI/USAID, 2003; Omar 2014). In addition, Bahr Yusuf together with Bahr Hassan Wasef Canals supply water to more than 3.5 million people for various human activities and served about 454700 Feddans (1 Feddan = 4 200 m^2) of the agricultural land in the Fayoum province (Omar 2014). However, Bahr Yusuf in the Fayoum district is exposed to many sources of pollution, including agricultural runoff and domestic sewage effluents from nearby houses along the two banks of the canal. The present study relates to a section of the Bahr Yusuf Canal in the Fayoum province.

Collection and analysis of samples

Twelve samples of subsurface water were collected seasonally in 2017 by a 2 l polyvinyl chloride Van Dorn bottle at eleven sites along the Bahr Yusuf Canal in the Fayoum Province (Fig. 1). The samples were collected on the 20th day of February, May, August and November, from 8 a.m. to 2 p.m. Details of surface water sampling locations along with their longitude and latitude are presented in Table 1. The water level followed the following order during the present study:

autumn < winter < spring < summer

Field measurements

Water temperature, EC and pH values were measured in situ, using hydro lab model Orion Research Ion Analyzer 399A. Transparency was measured using a Secchi disk (diameter 30 cm).

Laboratory analysis

Water samples were kept in a polyvinyl chloride Van Dorn bottle in an ice box and analyzed in the laboratory. Physical and chemical parameters of water samples were determined in compliance with standard

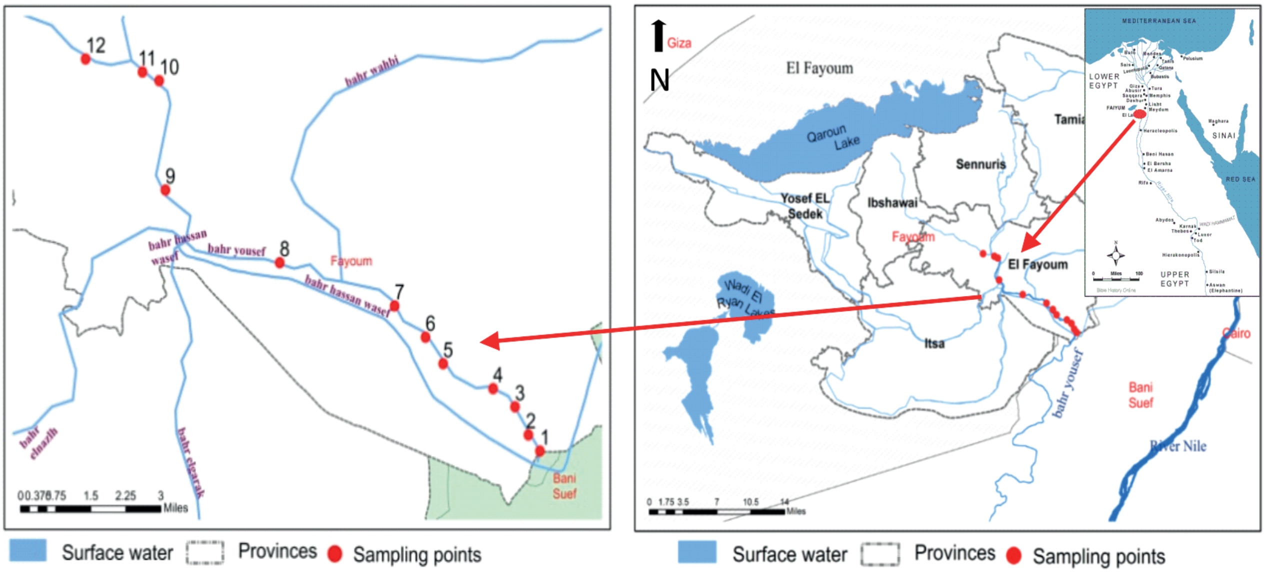

Figure 1

Location of the study area and sampling sites

Table 1

Characteristics, longitude and latitude of the sampling locations

Location	Features of the locations	Latitude (N)	Longitude (E)
1	Hawara before Tafreea (Tema Bridge) (El-Lahon)	30°27′55″	32°32′50.7″
2	Hawarat Adnan	30°27′56″	32°32′50.6″
3	Ezbet Al-Khawaja (Taha)	30°27′58″	32°32′50.5″
4	Ezbet Ameen	30°27′61″	32°32′51.0″
5	Manshiet Kamal	30°27′64″	32°32′52.0″
6	The upper bridge at Dmishqin	30°23′66″	32°33′34.0″
7	Kobry El-Fell	30°02′54″	32°34′74.7″
8	Hawarat Elmaktaa	29°91′16″	32°36′17.6″
9	Village of Snovr	29°24′91″	32°39′45.7″
10	Outlet Qhafa (drinking water plant)	29°16′18″	32°43′56.3″
11	Kobry Baghos	29°15′65″	32°43′58.4″
12	El-Sofi	28°94′18″	32°44′23.6″

methods of the American Public Health Association (APHA 2005). Total solids (TS) were measured by evaporating a known volume of a well-mixed sample at 105°C. TDS were determined by filtrating a known volume of a sample by GF/C filters and evaporating it at 180°C. TSS were directly determined by subtracting TDS from TS (TS – TDS). Dissolved oxygen (DO) was determined by using the modified Winkler method. Biochemical oxygen demand (BOD) was determined by using the 5-day method. Chemical oxygen demand (COD) was determined using the potassium permanganate method. Water alkalinity was determined immediately after sampling, using phenolphthalein and methyl orange as indicators. Chlorides were measured using Mohr's method and sulphates – by turbidimetric methods. Calcium and magnesium were determined by direct titration using EDTA solution; Na^+ and K^+ were determined directly using the Jenway Flame Photometer PFP (U.K.). Concentrations of NO_2-N, NO_3-N, NH_4-N, PO_4^{3-}-P and SiO_4^- were determined using colorimetric techniques with the formation of the corresponding reddish purple azo dye, cadmium reduction, phenate, ascorbic acid molybdate and molybdosilicate methods, respectively. Total phosphorus (TP) and total nitrogen (TN) were measured as reactive phosphates and nitrates, respectively, after alkaline persulfate digestion.

Boron and heavy metals (Zn, Cd, Cu, Fe, Mn, Ni, Pb, Cr, B, and Al) were measured using an atomic absorption reader (SavantAA AAS with GF 5000 Graphite Furnace) according to Geugten (1981) and APHA (2005), respectively. Chlorophyll-*a* was calculated according to the equation of Jeffrey & Humphrey (1975):

$$Chlorophyll\ a = \frac{[11.85(E664 - E750) - 1.54(E647 - E750) - 0.08(E630 - E750)] \times Ve}{L \times Vf} \qquad (1)$$

where E – absorbance at wavelength indicated, L – cuvette light path in centimeter; V_e – volume of extraction solvent in ml; V_f – volume of a sample filtered in l and concentrations in μg l^{-1}.

Statistical analysis

The one-way ANOVA test was used to determine spatial and temporal significant differences for the obtained data (Leščešen et al. 2015) using Excel-Stat software (2013). In addition, standard deviation and pair coefficients of correlations (r) were calculated.

Water quality indices

Four integrated water quality indices were used to examine the suitability of water in the Bahr Yusuf Canal for different uses. Table 2 shows the values and ratings of each index.

Aquatic Toxicity Index (ATI)

The index was developed by Wepener et al. (1992) to assess the health of aquatic ecosystems. Since an extensive toxicity database is available for fish, toxic effects of varying water quality on fish have been employed as health indicators of the aquatic ecosystem. In the present study, the following water quality parameters were used: pH, DO, ammonium, TDS, potassium, orthophosphates, Zn, Mn, Cr, Cu, Pb, and Ni. In the case of the ATI, the Solway Modified Unweighted Additive Aggregation function (Wepener et al. 1992; Sarkar & Abbasi 2006) was employed as an aggregation technique:

$$ATI = \frac{1}{100}\left(\frac{1}{n}\sum_{i=1}^{n} q_i\right) \qquad (2)$$

Table 2

Water rating according to different Water Quality Index methods

ATI		OWQI		WAWQI		CWQI)	
WQI	Rating	WQI	Rating	WQI	Rating	WQI	Rating
60–100	Suitable for all fish species	90–100	Excellent	0–25	Excellent	95–100	Excellent
51–59	Suitable only for hardy fish species	85–89	Good	26–50	Good	80–94	Good
0–50	Totally unsuitable for normal fish life	80–84	Fair	51–75	Poor	65–79	Fair
		60–79	Poor	76–100	Very poor	45–64	Marginal
		0–59	Very Poor	<100	Unsuitable	0–44	Poor

where q_i is the quality of the ith parameter (between 0 and 100), n is the number of determinants in the indexing system and ATI is the final index score value between 0 and 100. Details of q_i calculation are presented in Wepener et al. (1992).

Oregon Water Quality Index (OWQI)

The OWQI is a single number that expresses water quality by taking eight water quality parameters (temperature, DO, pH, BOD, TP, TS, fecal coliform, ammonia, and nitrate nitrogen) into account. The OWQI was computed according to Cude (2001):

$$OWQI = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{S_i^2}}} \tag{3}$$

where n is the number of sub-indices and S_i is the sub-index of each parameter. Details of how to calculate the sub-index for each parameter are provided in Cude (2001).

Weighted Arithmetic Water Quality Index

The weighted arithmetic water quality index (WAWQI) classifies the water quality according to the degree of purity by using the most commonly measured water quality parameters. The WQI was calculated using the equation provided by Rown et al. (1972):

$$WAWQI = \frac{\sum_{i=1}^{n} Q_i W_i}{\sum_{i=1}^{n} W_I} \tag{4}$$

Details of the calculation of the quality rating scale (Q_i) and the unit weight (Wi) for each parameter are presented in Goher et al. (2014a).

Canadian Water Quality Index (CWQI)

To simplify complex and technical water quality data, the Canadian Council of Ministers of the Environment developed a water quality index (CCME 2001). CWQI was calculated using the following equation:

$$CWQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \tag{5}$$

where 1.732 is the corrected factor; F_1 (Scope) represents the percentage of failed variables relative to the total number of variables measured; F_2 (Frequency) represents the percentage of individual failed tests relative to the total number of tests; F_3 (Amplitude) represents the excursion of failed tests relative to their objectives. Details of the calculation are provided in CCME (2001).

Heavy Metal Pollution Index (HPI)

The HPI describes the quality of water with reference to metals and its suitability for drinking (Prasad & Bose 2001). It is based on the weighted arithmetic quality mean method (Mohan et al. 1996):

$$HPI = \frac{\sum_{i=1}^{n} Q_i W_i}{\sum_{i=1}^{n} W_i} \tag{6}$$

where W_i is the weight unit of the ith metal (between 0 and 1), n is the number of measured metals and Q_i is the sub-index of the ith metal.

$$W_i = \frac{K}{S_i} = \frac{1}{S_i} \tag{7}$$

K is the proportionality constant

$$Q_i = \frac{C_i - I_i}{S_i - I_i} \times 100 \tag{8}$$

where C_i is the measured value of the ith metal; S_i is the standard permissible value of the ith parameter and I_i is the ideal value of the ith metal; in pure water I_i = zero.

Thus equation 8 converts to

$$Q_i = \frac{C_i}{S_i} \times 100 \tag{9}$$

Finally, the critical pollution index score for drinking water is 100 (Prasad & Bose 2001).

Human Health Risk

The human health risk associated with the use of water contaminated with various metals, i.e. the non-carcinogenic risk was assessed using the Hazard Quotient (HQ) and the Hazard Index (HI), which are based on the USEPA module (USEPA 1989):

$$HI = \sum_{i=1}^{n} HQ_i \tag{10}$$

where HQ_i is the Hazard Quotient (HQ) for the ith metal.

Where

$$HQ_i = HQ_{oral} + HQ_{dermal} \tag{11}$$

and

$$HQ_{oral} = \frac{C_i \times IR \times EF \times ED}{RFD_o \times BW \times AT} \tag{12}$$

where HQ_{oral} is the quotient of hazard via ingestion (unitless); C_i is the concentration of a heavy metal in water (mg l^{-1}); IR is the ingestion rate (l day^{-1}); EF is the exposure frequency (days $year^{-1}$); ED is the exposure duration (years), BW is the body weight in (kg); AT is the average time (days) and RFD_0 is the oral reference dose (mg kg^{-1} day^{-1}). In the present study, EF = 365 days; ED = 70 years, BW = 70 kg and AT = 25 550 days (USEPA 2001).

$$HQ_{dermal} = \frac{C_i \times SA \times EF \times ED \times EV \times t_{event} \times K_p}{RFD_{ABS} \times BW \times AT} \tag{13}$$

where

$$RfD_{ABS} = RfD_0 \times ABS_{Gi} \tag{14}$$

where HQ_{dermal} is the quotient of hazard via dermal contact (unitless); C_i is the heavy metal concentration in water (mg cm^{-3}); SA is the skin surface area available for contact (cm^2); ED is the exposure duration (years); t_{event} is the event duration (h $event^{-1}$); K_p is the dermal permeability coefficient of the target compound in water (cm h^{-1}); EV is the event frequency (event day^{-1}); EF is the exposure frequency (days $year^{-1}$); BW is the body weight (kg); AT is the average time (days) and RfD_o is the oral reference dose (mg kg^{-1} day^{-1}); RfD_{ABS} is the absorbed reference dose (mg kg^{-1} day^{-1}) and ABS_{Gi} is the fraction of a contaminant absorbed in the gastrointestinal tract (dimensionless) in the critical toxicity study. According to USEPA (2004): EF = 350 days, ED = 70 years, SA = 18 000 cm^2, EV = 1.0 event day^{-1}, t_{event} = 0.58 h $event^{-1}$, BW = 70 kg and AT = 10 950 days. The oral reference dose (RfD_0), the gastrointestinal absorption factor and the dermal permeability coefficient (K_p) are presented in Table 3.

Results and discussion

The seasonal distribution of the physicochemical characteristics of water in the Bahr Yusuf Canal is presented in Table 4, while Table 5 shows the guidelines for drinking water developed by WHO (2017), USEPA (2018a,b) and EWQS (2007), and for irrigation water according to Ayers & Westcot (1985), in addition to aquatic life criteria defined by CCME (2007).

Physical characteristics

The results showed that the water temperature was within ordinary values suitable for fish and aquatic organisms (8–28) throughout the year with a slight elevation in summer with a large significant temporal difference ($p < 0.01$). Transparency ranged from 34 to 94 cm and was affected by domestic sewage effluents

Table 3

The reference dose level (RfD0; mg kg^{-1} day^{-1}), the absorbed factor (ABS) and the dermal permeability coefficient (Kp; cm h^{-1}) for boron and the measured heavy metals

Chemicals	RfD_0 [a]	ABS_{Gi} [ab]	K_p [ab]	Chemicals	RfD_0 [a]	ABS_{Gi} [ab]	K_p [ab]
Al	1	1	0.001	Fe	0.7	1	0.001
B	0.2	1	0.001	Mn	0.024	0.04	0.001
Cd	0.0005	0.05	0.001	Ni	0.02	0.04	0.0002
Cr	0.003	0.013	0.001	Pb	0.015	1	0.0001
Cu	0.04	1	0.001	Zn	0.3	1	0.0006

a: USEPA (2018a); b: USEPA (2004)

Table 4

Physical and chemical characteristics of water in the Bahr Yusuf Canal in 2017

Parameter	Winter Range	Spring Range	Summer Range	Autumn Range	Annual Average
Temperature (°C)	19.0–21.0	25.6–26.3	29.4–30.5	24.5–26.0	25.2 ± 3.61
Transparency (cm)	34.0–78.0	66.0–94.0	67.0–94.0	53.0–80.0	73.92 ± 10.53
EC (μS cm^{-1})	406–495	353–505	313–446	518–592	458.13 ± 69.4
TDS (mg l^{-1})	243.6–297	211.8–303	187.8–267.6	310.8–355.2	274.9 ± 41.65
TSS (mg l^{-1})	21.8–78.8	10.0–35.0	7.2–19.40	21.2–50.8	24.7 ± 13.06
TS (mg l^{-1})	273.6–375.8	227.8–327	204.6–287	337.6–381.6	300 ± 49.75
pH	7.7–7.86	8.17-8.38	8.01-8.25	7.49–7.92	7.95 ± 0.24
DO (mg l^{-1})	8.19–9.3	7.89–9.23	7.01–8.69	6.52–7.67	8.58 ± 0.64
COD (mg l^{-1})	5.2–8.88	5.0–7.8	6.18–9.6	6.82–10.2	7.59 ± 1.31
BOD (mg l^{-1})	2.93–4.27	4.2–6.19	4.8–6.32	3.76–4.89	6.32 ± 0.91
NO_2-N (μg l^{-1})	18.8–45.2	4.8–40.2	14.2–23.0	27.2–38.2	23.35 ± 11.06
NO_3-N (μg l^{-1})	162–410	52.9–172.1	148–315	449–707	285.8 ± 177.2
NH_4-N (μg l^{-1})	231.6–299.2	137.6–192.6	11.4–142.4	239.16–331	209.9 ±72.68
TN (μg l^{-1})	500–945	365–517	436–665	1060–1393	725 ± 305
PO4-P (μg l^{-1})	13.6–19.2	7.22–12.4	8.48–18.82	18.67–25.33	15.49 ± 5.36
TP (μg l^{-1})	71–115	45.6–95.2	45.6–97.8	74.2–167	83.7 ± 22.57
Silicate (mg l^{-1})	2.2–2.9	3.71–5.94	5.73–7.86	2.84–6.52	4.75 ± 1.67
TA (mg l^{-1})	122.3–145.7	143.4–159.52	99.7–126.9	105.6–138.8	130.2 ± 16.08
CO_3^{2-} (mg l^{-1})	3.6–9.6	2.4–4.8	2.16–4.92	2.4–7.2	4.29 ± 1.88
HCO_3^- (mg l^{-1})	132.1–161.7	166.5–187.3	114.4–148	122.8–161.8	150.1 ± 19.18
Cl (mg l^{-1})	18.96–27.62	20.39–24.36	15.22–22.29	28.73–31.94	24.24 ± 4.7
SO_4^{2-} (mg l^{-1})	16.9–19.17	11.62–16.74	9.88–13.66	14.89–17.54	15.2 ± 2.56
Na (mg l^{-1})	20.16–22.38	18.26–19.68	17.73–18.96	22.18–23.28	20.32 ± 1.89
K (mg l^{-1})	5.8–6.41	4.8–5.44	4.3–4.89	5.4–6.55	6.1 ± 0.73
TH	107.7–129.5	97.48–126.58	84.29–112.55	129.42–143.44	118.51 ± 14.97
Ca (mg l^{-1})	18.52–22.7	16.47–21.78	14.65–20.45	23.07–26.03	20.96 ± 2.86
Mg (mg l^{-1})	14.7–17.46	13.5–17.34	11.4–14.74	17.2–18.92	15.9 ± 1.92
B (μg l^{-1})	25.28–47.22	26.39–49.44	28.61–48.89	45.28–77.22	44.07 ± 12.91
Chlorophyll-*a* (μg l^{-1})	14.38–22.95	21.36–38.2	31.69–44.47	13.96–33.28	26.59 ± 8.62

TA: total alkalinity; TH: total hardness

Table 5

Guidelines for the measured parameters in mg l^{-1} (except Temp., EC and pH) according to national and international permissible levels

Parameter	Drinking Water			Irrigation	Aquatic life	Parameter	Drinking Water			Irrigation	Aquatic life
	EWQS	WHO	EPA				EWQS	WHO	EPA		
Temp. (°C)				< 35	8–28	$SO_4^{2-a,b}$	250	250	250	960	
EC(μS cm^{-1})^{a,b}	2000			3000		Na^{a,b}	200			919	
pH^{a,b,c}	6.5–8.5	8.5	6.5–8.5	8.5	6.5–9	K^{b}				2	
TDS^{a,b,c}	1000	500	500	2000	500	TH^{a}	500	500			
DO^{ac}	6			> 4	> 5.5	Ca^{a,b}	75	75		60	
BOD^{a}	3	3*				Mg^{a,b}	50	50		400	
COD^{a}	10	10				Al^{a,b,c}	0.2	0.2	0.2	5	0.1
NO_2-N^{a,c}	0.06	0.9	1		0.06	B^{abc}	0.5	2.4	0.5–2		1.5
NO_3-N^{a,b,c}	10	11	10	10	2.93	Cd^{a,b,c}	0.003	0.003	0.005	0.01	0.001
NH_4-N^{a,b,c}	0.41	0.2		5	1.27–0.077**	Cr^{a,b,c}	0.05	0.05	0.1	0.1	0.01
PO_4-P^{b}				2		Cu^{a,b,c}	2	2	1.3	0.2	0.004
TP^{a}	1					Fe^{a,b,c}	0.3		0.3	5	0.3
TA		250			> 20	Mn^{a,b,c}	0.4	0.1	0.05	0.2	0.05
$CO_3^{\ b}$				3		Ni^{a,b,c}	0.02	0.07	0.1	0.2	0.025
$HCO_3^{\ b}$				610		Pb^{a,b,c}	0.01	0.01	0.015	0.2	0.007
Cl^{a,b,c}	250	200	250	1036	120	Zn^{a,b,c}	3	4	5	5	0.05
Reference	EWQS 2007	WHO 2017	EPA 2018a,b	Ayers & Westcot 1985	CCME 2007		EWQS 2007	WHO 2017	EPA 2018a,b	Ayers & Westcot 1985	CCME 2007

^{abc} The parameter used to calculate CWQI and WAWQI for (a) drinking, (b) irrigation and (c) aquatic life purposes. TA: Total alkalinity; TH: Hardness, * BOD according to EU (1975) **Ammonia permissible level dependent on Temperature (20–30°C) and pH value (7.5–8.5) and flow levels. This result was consistent with Goher et al. (2014a), who reported that transparency ranged from 35 to 120 in the Ismailia Canal of the Nile River. The lowest transparency values were recorded in autumn, which corresponds to the low flow level, while an increase in the intensity of solar radiation penetrating the water during summer increases the transparency (Abdel-Satar et al. 2017). ANOVA results show a large significant temporal difference ($p < 0.01$) for the transparency value. In general, low transparency values (34-94 cm) compared to the reference point of the Nile River in the Aswan Governorate (400–950 cm; Abdel-Satar et al. 2017) reflect the negative anthropogenic effect on the Nile River and its branches.

The decrease in the flow level in the Bahr Yusuf Canal in autumn leads to the concentration of ions, which results in an increase in the EC levels, where EC and the water level are inversely related (Islam et al. 2015). EC varied in the ranges of 406–495, 353–505, 313–446 and 518–592 µs cm^{-1} in winter, spring, summer, and autumn, respectively, with a large significant temporal difference ($p < 0.01$). These results were lower compared to the previous study on Bahr Wahby (originating in the Bahr Yusuf Canal) obtained by Mahmoud et al. (2016), who reported that EC fluctuated between 424.6 and 797.7 µs cm^{-1}. EC is positively correlated (n = 48, $p < 0.01$) with TS, TSS, TDS, COD, the main anions and the main cations. Whereas EC is negatively correlated with pH, DO and BOD.

TS, TDS, and TSS were varied in the ranges of 204.6–375.8, 187.8–355.2 and 7.20–78.80 mg l^{-1}, respectively. TSS showed an opposite trend compared to transparency values, with the highest values recorded in autumn, while the lowest TSS content was recorded in summer.

Chemical characteristics

The pH values were within the acceptable ranges for different applications (Tables 4 and 5). They were in the alkaline range (7.49–8.38), reflecting an increase in the photosynthetic activity of planktonic algae, with a large significant temporal difference ($p < 0.01$). The relative increase in pH values in hot seasons (spring and summer) may be attributed to the photosynthesis and growth of aquatic plants, when photosynthesis uses CO_2 leading to an increase in pH values (Yousry et al. 2009; Ezzat et al. 2012). The high positive correlation between pH and DO (r = 0.48, n = 48, $p < 0.01$) confirms the effect of photosynthetic activity on the increase in pH values (Goher et al. 2014a).

DO, BOD and COD were varied in the ranges of 6.52–9.30, 2.93–6.32 and 5.0– 10.2 mg l^{-1}, respectively, with significant seasonal variations ($p < 0.01$). These results are consistent with the results on DO (3–13.2 mg l^{-1}) and BOD (1.2–8.0 mg l^{-1}) in the Nile River obtained by Abdel-Satar et al. (2017). The highest values of DO recorded in spring can be attributed to the increased photosynthesis activity, which releases a significant amount of oxygen to the surrounding aquatic ecosystem (Goher et al. 2014a). DO is an important parameter in assessing the suitability of water for aquatic life and drinking. The average values of DO at all monitoring sites were within the water quality criteria specified by WHO (2017), USEPA (2018a,b) and EWQS (2007) for drinking water and CCME (2007) for aquatic life. The maximum value of BOD was observed in summer and this may due to the activity of microorganisms and a higher rate of organic matter decomposition at high temperatures (Sanap et al. 2006). The highest content of COD was recorded in autumn at a low water level.

Nutrient salts and chlorophyll-*a*

Nutrient salts play an important role in the productivity of aquatic ecosystems by supporting the food chain of phytoplankton and zooplankton as well as fish**.** The basic nutrient salts show large significant temporal differences ($p < 0.01$). They fluctuated in the following ranges: 111.4–331.0, 52.92–707, 4.8–45.2, 436–1393, 7.22–25.33, 45.6–167.0 µg l^{-1} and 2.20–7.86 mg l^{-1} for ammonia, nitrate, nitrite, total nitrogen orthophosphate, total phosphorus and silicate, respectively.

In the case of inorganic nitrogen forms, nitrate dominated, followed by ammonia and nitrite. The increase in NO_2^- and NO_3^- concentrations in winter may be due to the decomposition of organic matter present in wastewater, where *Nitrosomonas* bacteria oxidize ammonia to nitrite by denitrification (Saad et al. 2011), and due to rapid conversion of NO_2^- to NO_3^- by nitrobacteria (Ashry et al. 2013). The increase in ammonia levels in autumn can be attributed to the denitrification process by reducing NO_2^- and NO_3^- to NH_4^+ at low DO, in addition to the effect of drainage waste at the low water level in the canal. Similarly, the highest content of TN was recorded during the cold seasons (autumn and winter), revealing the impact of different types of waste at the low water level (drought period).

Orthophosphate and total phosphorus showed a significant increase during the drought period. The results were consistent with those obtained by Goher et al. (2014a) and El Degway (2016). Nitrogen and phosphorus are important components of a healthy aquatic ecosystem, but elevated levels may have a negative impact on water bodies, as an increase in algal blooms due to nutrient abundance can cause "hypertrophication" of aquatic systems (Anonymous 2015). The determined content of nitrogen and phosphorus indicates that the water in the Bahr Yusuf Canal is between mesotrophic and eutrophic (Dodds & Smith 2016).

The fluctuation in the concentration of silicates did not follow the distribution pattern of other nutrients, with a high content during the hot season (high water level). These results indicate that the discharged wastewater did not play a major role in the distribution of silica in the Nile water (Abdel-Satar et al. 2017). The main factors affecting the reactive silicate distribution are the uptake by diatoms, silicate rock weathering, as well as water movement, turbulence, temperature, pH and salinity, especially during floods (Ahlers et al. 1991).

Chlorophyll-*a* can be used as an indicator parameter for the quality and health of water bodies. It is essential to the phytoplankton growth and is a measure of productivity of a water body. Chlorophyll-*a* values in the water of the Bahr Yusuf Canal varied in the following ranges: 14.38–22.95, 31.69–44.47, 13.96–33.28 and 21.36–38.20 μg l^{-1} in winter, spring, summer and autumn, respectively. The low level of phytoplankton chlorophyll-*a* observed in winter may be due to light limitation (Al-Hashmi et al. 2010). The high positive correlation between chlorophyll-*a* and temperature ($r = 0.48$, $n = 48$, $p < 0.01$) is consistent with the findings of Jarvie et al. (2003), who confirmed clear correlations between chlorophyll concentrations, water temperature, light and primary productivity in canals and rivers.

On the basis of chlorophyll-*a* concentration, the trophic status of streams and rivers can be classified as oligotrophic (Chl-*a* < 10 μg l^{-1}), mesotrophic (Chl-*a* 10-30 μg l^{-1}) and eutrophic (Chl-*a* > 30 μg l^{-1}; Dodds & Smith 2016). Based on the levels of chlorophyll-*a* (13.96–44.47 μg l^{-1}), the Bahr Yusuf Canal can be classified as a mesotrophic/eutrophic water body. In general, the eutrophication status of the Bahr Yusuf Canal indicates its poor water quality.

Main cations and anions

The main components of alkalinity of surface water are carbonates and bicarbonates (Muhammad et al. 2000). CO_3^{2-} and HCO_3^- concentrations were varied in the range of 2.16–9.60 and 114.35–187.29 mg l^{-1}, respectively, with significant seasonal variations ($p < 0.01$). Bicarbonates are the most abundant anions in stream water. The highest values were recorded in the spring season. Chlorides and sulfates were in the range of 15.22–27.62 and 9.88–19.17 mg l^{-1}, respectively, showing a high significant temporal difference ($p < 0.01$), with a clear increase in the drought period, which is consistent with the result obtained by El-Degwy (2016). Chlorides and sulfates are positively correlated with the main cations, reflecting the occurrence of main cations in the Bahr Yusuf Canal water as sulfates and chlorides.

Calcium and magnesium values were in the range of 14.65–26.03 and 11.4–18.9 mg l^{-1}, respectively, with large seasonal variations ($p < 0.01$), which are consistent with those observed by Mahmoud et al. (2016). The decrease in Ca and Mg concentrations in hot seasons (summer and spring) may be due to the precipitation of $CaCO_3$ resulting from an increase in temperature (Madbouly 2015) and adsorption of $MgCO_3$ onto clay minerals and bottom deposition due to water temperature rise as reported by Chiu et al. (2010). Sodium and potassium show high significant seasonal variations ($p < 0.01$) and varied in the range of 17.73–23.28 and 4.3–6.55 mg l^{-1}, respectively. The distribution levels of Na and K followed the same pattern as Ca and Mg, i.e. their increase was greater during the cold seasons than in the hot seasons. The abundance of the main cations in the water of the Bahr Yusuf Canal was as follows Ca > Na > Mg > K with a similar order of their presence in the Nile water according to Abdel-Satar et al. (2017).

Boron and Heavy Metals

The mean levels of Ba, Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn in the water of the Bahr Yusuf Canal were as follows: 44.07 ± 12.91, 72.22 ± 23.7, 4.872 ± 1.351, 14.06 ± 3.3, 8.67 ± 2.56, 268.13 ± 71.59, 37.53 ± 9.97, 32.63 ± 7.19, 31.85 ± 6.55 and 27.99 ± 4.91 μg l^{-1}, respectively (Fig. 2). The concentrations of boron and most heavy metals showed highly significant differences ($p < 0.01$) between different seasons, where the lowest values were measured in summer, coinciding with a high flow level in the Bahr Yusuf Canal, while the highest values were recorded in autumn.

Boron is a mobile trace element, an essential micronutrient for plants, animals and aquatic life, but it becomes toxic in higher concentrations (Zhang et al. 2018; CCME 2009). Rock weathering is the main source of B, but anthropogenic activities also contribute, though to a lesser extent, as a source of B in water bodies (Emiroğlu et al. 2010; Gaillardet et al. 2003). Its compounds are used in the manufacture of glass, soap and detergents and as flame retardants. The borate content in surface water may increase as a result of wastewater discharges (WHO 2017). Boron is present in freshwater as nonionized boric acid and negatively

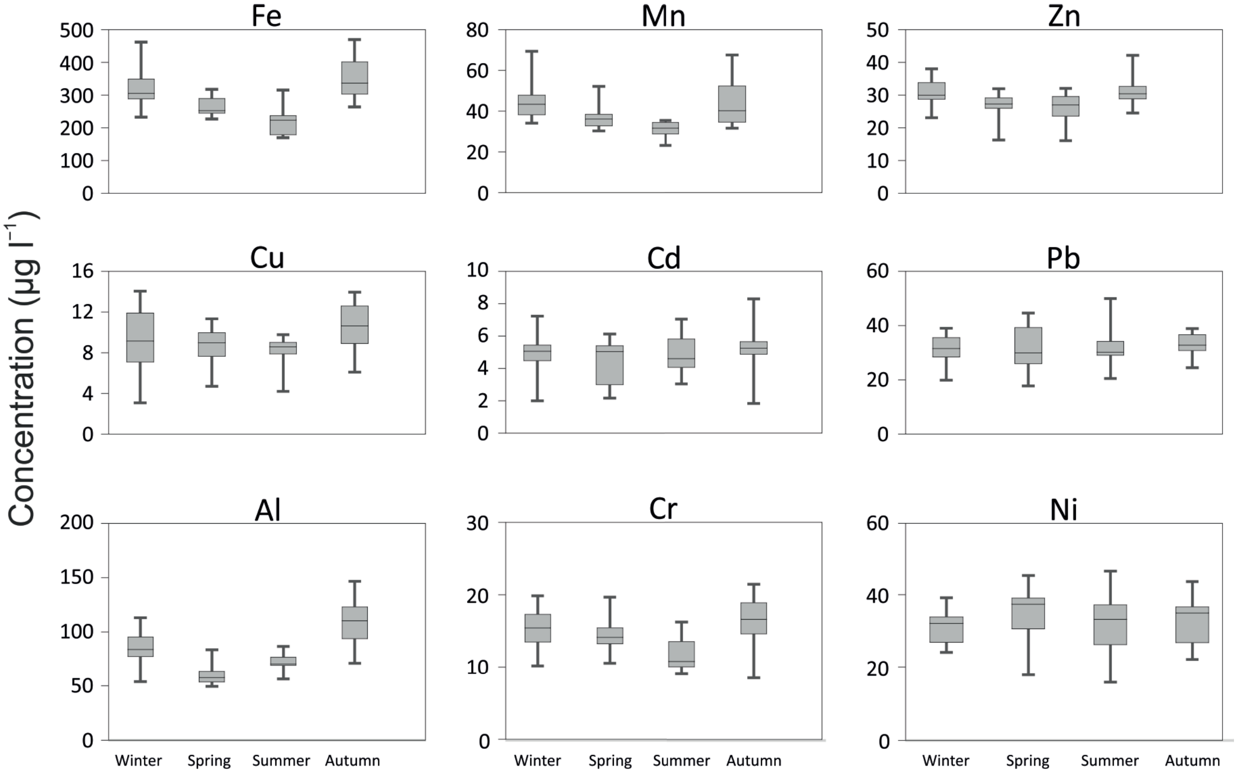

Figure 2

Multiple box and whisker plots of measured heavy metal concentrations (μg l⁻¹) in the water of the Bahr Yusuf Canal in 2017

charged borate ion $B(OH)_4^-$ (Gaillardet et al. 2003). The content of boron in the Bahr Yusuf Canal was much lower than the national and international acceptable levels for water intended for different uses, ranging from 25.38 to 77.22 μg l^{-1} with a high significant temporal difference ($p < 0.01$). Gaillardet et al. (2003) found that the level of boron in 60 rivers around the world ranged from 0.002 to 0.15 mg l^{-1} with a mean value of 0.01 mg l^{-1}. Based on this observation, the presented results were similar to those for rivers and freshwater worldwide, which is consistent with those obtained by Zhang et al. (2018). The high positive correlation between boron and chloride ($r = 0.69$, $n = 48$, $p < 0.01$) is in line with the results obtained by Johannesson et al. (1996), which reveals a strong contribution of evaporation, weathering and the same origin and behavior of these elements in a watershed (Gaillardet et al. 2003). The good correlation between B and Na ($r = 0.58$, $n = 48$, $p < 0.01$) may be related to the presence of boron mainly as sodium borate in water.

Both Fe and Mn are commonly found in water and are essential elements required in small amounts by all living organisms. The presence of iron or manganese in drinking water can affect the smell, taste or color of the water (NSF 2018). Fe and Mn levels fluctuated in the range of 169.55–568.4 and 34.27–69.35 μg l^{-1} with high significant temporal variations ($p < 0.01$). The current results in several cases exceed the permissible national and international limits (300 μg l^{-1} of Fe) and the permissible international limits (0.05 of Mn) for drinking water and aquatic life, which is an indication of poor water quality in the Bahr Yusuf Canal. It has been reported that the concentrations above 0.3 mg l^{-1} of Fe may lead to pollution of the aquatic environment (Ramadan 2015), which has resulted in the development of several methods to remove it from aquatic environments or to reduce its concentrations (Hassouna et al. 2014b; 2017; 2018).

The level of aluminum was generally within the allowable national and international standard levels for drinking and irrigation water (200 and 5000 μg l^{-1}, respectively). Whereas it was higher than the permissible national level for aquatic life (100 μg l^{-1}) in autumn and winter, which may be related to the effect of wastes discharged into the canal during the drought period. It ranged from 49.27 to 145.77 μg l^{-1} with highly significant differences between the sites ($p < 0.01$). According to Madbouly (2015), the Al^{3+}

cation dominates at pH below 4. Above neutral pH, the dominant dissolved form is Al $(OH)_4^-$. Aluminum is not essential for plants and animals. Similarly to Fe and Mn, the level of Al increases in the drought period as a result of anthropogenic activities.

Nickel at many sites exceeded the acceptable limits for drinking water (20 μg l^{-1}) and aquatic life (25 μg l^{-1}); it was in the range of 16.07–47.56 μg l^{-1}, with a highly significant temporal difference ($p < 0.01$). The major source of Ni pollution in aquatic ecosystems is domestic wastewater effluents, where Ni is released from pipes under the influence of drinking water and acidic beverages. In addition, nickel is introduced in industrial and commercial uses, which increases its release into water bodies (Cempel & Nikel 2006). The highest Ni value recorded during the spring season may be due to the release of heavy metals from sediment into the water during the decomposition of organic matter as a result of high temperature and the fermentation process (Goher et al. 2014b), as well as due to the contamination of phytoplankton with nickel that occurs in a large quantity during the spring season, which is consistent with the results obtained by Masoud et al. (2004).

The concentrations of Cu, Zn and Cr were below the guidelines for drinking and irrigation water, while Cu and Cr exceeded the allowable limits for the aquatic life (Tables 4 and 5). Cu, Zn, and Cr were in the ranges of 3.04–13.94, 16.03–42.18 and 8.62–21.44 μg l^{-1}, respectively, with highly significant temporal variations ($p < 0.01$). On the other hand, Cd and Pb concentrations fluctuated between 1.86–8.25 and 17.62–49.62 μg l^{-1}, which exceeded the guidelines for drinking water and water suitable for aquatic life (for most samples in the case of Pb and some samples in the case of Cd, especially during the drought period). The high positive correlation between most trace elements ($r = 0.41–0.71$, $n = 48$ and $p < 0.01$) confirmed that they have the same origin and source.

The above results show that most of the water parameters in the Bahr Yusuf Canal increase in the cold (drought) period, particularly in autumn at the lowest water level. On the other hand, the results obtained for the Bahr Yusuf Canal are consistent with the previous studies on the Nile River and its branches. Table 6 shows the obtained results in relation to the Nile River and Nile canals in Egypt.

Water quality indices (WQIs)

Several indices were used to assess the water quality in the Bahr Yusuf Canal, including the Aquatic Toxicity Index (ATI), the Canadian Water Quality Index (CWQI), the Oregon Water Quality Index (OWQI) and the Weighted Arithmetic Water Quality Index (WAWQI). In the present study, seven water parameters were selected to compute the OWQI (temperature, DO, pH, BOD, TP, TS, ammonia and nitrate nitrogen), which is used to assess the quality of water with respect to general recreational use, including fishing and swimming (Sarkar & Abbasi 2006). To calculate the Aquatic Toxicity Index (ATI), 12 water parameters (DO, TDS, pH, NH_4-N, PO_4^{3-}-P, K, Cr, Cu, Mn, Ni, Pb, and Zn) were used. The ATI was developed to evaluate the aquatic ecosystem health and to determine the suitability of aquatic environments for different fish species. A total of 27, 25 and 17 variables (presented in Table 5) were selected to assess the suitability of water in the Bahr Yusuf Canal for drinking, irrigation and aquatic life, respectively, according to CWQI and WAWQI modules. Egyptian standards were used for drinking water assessment.

Table 7 shows the values of WQIs and the water grades of the Bahr Yusuf Canal for different modules. The OWQI score ranged from 58.82 to 64.77, with a mean value of 61.6 for the whole canal. These results indicate the unsuitability of the canal's water for recreational use, with water quality classified between poor and very poor for all sampling sites. On the other hand, the ATI results give an indication about the suitability of water quality for all fish species, where ATI ranged from 87.77 to 90.26. According to Poonam (2013), the water quality varies according to the type of use. Based on the CWQI results, the canal water was classified as fair (WQI = 73), good (WQI = 92) and marginal (WQI = 64) for drinking, irrigation and aquatic life, respectively. The CWQI indicated that the water in the Bahr Yusuf Canal may be suitable to some extent for drinking and irrigation, but it is an unsuitable habitat for aquatic life. The WAWQI classified the water quality according to the degree of purity using the most commonly measured water quality parameters (Tyagi et al. 2013). It also describes the suitability of surface water sources for human consumption (Chandra et al. 2017). According to WAWQI, the water in the Bahr Yusuf Canal is classified as excellent, from good to poor, and from good to excellent for irrigation, drinking and aquatic life, respectively. The corresponding values of WAWQI were in the range of 0.87–2.02, 36.09–65.36 and 17.16–39.03, respectively.

It is worth mentioning that different water quality results and water quality categories are related to the type of consumption and the use as drinking water, industrial water and ecosystem preservation (Poonam 2013), as well as to the number and type of water parameters used and the arithmetic and statistical approach of the index used.

Table 6

Water parameters of the Bahr Yusuf Canal compared to the Nile River and other Egyptian Nile canals

Parameters	Units	Water resource						
		Nile River	Nile River	Bahr Yusuf Canal	El-Sharkawia Canal	Ismailia Canal	Beni-Suef Water Resources	Bahr Yusuf Canal
Temp.	°C		17.8–30.7	24.5–25.16	14.50–33.10	16–33		19–30.5
Transparency	cm		15–950		50–150	35–120		34–94
EC	ms cm^{-1}		210–1014	424.6–797.7	313–531	350–544	319–1473	313–592
TDS	mg l^{-1}	128.8–409.9	137–659	260.6–518.6	212.5–348.2	210–365	204–943	187.8–355.2
TSS					10.67–46.00	39–176		7.2–78.8
TS					230.5–358.8	286–528		204.6–381.6
pH		7.43–8.68	7.3–9.0		7.89–8.59	7.09–8.46	7–7.93	7.49–8.38
DO	mg l^{-1}		3–13.2		1.60–9.68	5.78–9.98		7.01–9.3
BOD			1.2–8.0		1.40–6.84	0.3–7.18		2.93–6.32
COD					3.78–14.04	3.68–15.08		5–10.2
CO_3					5.20–20.09	0.0–22.2		2.16–9.6
HCO_3		122–517.4	94.1–324.6		110.4–186.1	105.9–162.4	128–297	114.35–187.2
Cl			6.18–96.80	23.46-84.47	15.10–23.11	14.25–33.16	21–274	15.22–31.94
SO_4		5–50	3.83–58.94	31.7 -86.19	14.60–34.46	8.71–98.8	20–118	9.88–19.17
Ca		18.4–59.6	9.43–41.16	29.58 to 53.75	16.33–30.54	24.17–38.82	34–79	14.65–26.03
Mg		18.5–52.6	6.08–44.93	10.04–15.09	11.05–22.40	9.78–17.62	9–24	11.4–18.9
TH						102–169.34		84.29–143.44
Na		14.4–99.5	11.25–72.7	20.86–57.58	19.73–41.18	15.14–39.7	18–204	17.73–23.28
K		1.4–6.9	3.67–12.08	1.51–5.09	8.06–12.35	5.77–8.89	2.5–16	4.3–6.4
NO_3-N	µg l^{-1}	0–23.8	3–1878	1320–4930	24.37–177.3	31–584	300–16000	52.92–707
NO_2-N			0.5–6943	UDL–460	3.55–19.64	2–27		4.8–45.2
NH_4-N			21–17928		119.0–1793.6	88–569		111.4–331
TN	mg l^{-1}							0.52–139
PO_4-P	µg l^{-1}		4–383		5.69–52.43	8–399		7.22–25.33
TP			15–998		35.43–251.8	38–480		44.1–167
SiO_3			0.39–14.62		1.50–10.95	0.37–8.78		2.2–7.86
Ba				UDL			20–225	25.83–77.22
Fe			199–2211	490–2900	125.8–1478.5	109–223.9	13–1415	169.55–460.5
Mn			30–298	104–850	1.80–119.00	20–483	37–713	23.29–69.35
Zn		50–700	10–115	UDL	1.60–40.40	2–127	< 1–1700	16.03–42.18
Cu		UDL–170	10–51	UDL	0.60– 4.12	3–21	< 1–1080	3.04–13.94
Ni			1–33	UDL	1.75–20.20	0.0–25		16.07–47.56
Cr		1.7–467			5.20–25.20			8.62–21.44
Cd		UDL–5	0.2–8.1	UDL	0.00–1.21	0–3	< 1–400	1.86–8.25
Pb		163–402	5–51	UDL	3.40–32.60	11–34		17.62–49.62
Al				370–2800		55–45400	1608–2545	49.27–145.77
Reference		Elnazer et al. (2018)	Abdel-Satar et al. (2017)	Mahmoud et al. (2016)	El-Degwy (2016)	Goher et al. (2014a)	Melegy et al. (2014)	Present study

UDL = under detection limit

Heavy Pollution Index (HPI)

Nine heavy metals (Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) were selected to assess the contamination of water in the Bahr Yusuf Canal with metals, based on the Heavy Pollution Index (HPI). The HPI is a comprehensive tool or a rating model that assesses the overall water quality according to the composite effects of individual heavy metals (Herojeet et al. 2015; Vetrimurugan et al. 2017). Table 8 shows that the Heavy Pollution Index for water in the Bahr Yusuf Canal ranged from 104.44 to 206.32, from 16.81 to 38.48 and from 219.07 to 472.24 for drinking water, irrigation water and aquatic life, respectively. These results demonstrate that all the studied metals did not have a polluting effect for irrigation use, but the Bahr Yusuf Canal suffers from different levels of contamination with the studied metals, posing a threat to aquatic life and drinking use. Spatial distributions of the HPI indicate an increase in the potential contamination

Table 7

WQI and their categorization of Bahr Yusuf water in 2017 for different purposes

Location	OWQI	ATI	CWQI			WAWQI		
			Drinking	Irrigation	Aquatic life	Drinking	Irrigation	Aquatic life
1	62.46 Poor	90.26 Suitable	78 Fair	92 Good	73 Fair	30.09 Good	0.87 Excellent	17.16 Excellent
2	63.82 Poor	89.49 Suitable	74 Fair	92 Good	65 Fair	50.34 Poor	1.46 Excellent	28.51 Good
3	58.82 Very poor	88.86 Suitable	73 Fair	91 Good	65 Fair	52.35 Poor	1.93 Excellent	37.77 Good
4	59.38 Very poor	89.23 Suitable	76 Fair	92 Good	69 Fair	54.94 Poor	1.99 Excellent	38.59 Good
5	62.72 Poor	88.7 Suitable	72 Fair	92 Good	63 Marginal	51.75 Poor	2.00 Excellent	38.84 Good
6	64.77 Poor	88.34 Suitable	75 Fair	91 Good	67 Fair	44.67 Good	1.89 Excellent	37.04 Good
7	62.15 Poor	88.63 Suitable	73 Fair	91 Good	63 Marginal	51.90 Poor	1.81 Excellent	35.44 Good
8	60.9 Poor	89.14 Suitable	73 Fair	92 Good	65 Fair	59.11 Poor	1.74 Excellent	34.28 Good
9	60.27 Poor	88.45 Suitable	72 Fair	92 Good	65 Fair	65.36 Poor	1.83 Excellent	35.85 Good
10	61.11 Poor	87.77 Suitable	71 Fair	93 Good	65 Fair	57.02 Poor	2.02 Excellent	39.03 Good
11	60.85 Poor	87.93 Suitable	73 Fair	92 Good	66 Fair	53.72 Poor	1.66 Excellent	32.67 Good
12	59.53 Very poor	87.8 Suitable	71 Fair	91 Good	60 Marginal	45.34 Good	1.86 Excellent	35.90 Good
Overall	61.6 Poor	88.34 Suitable	73 Fair	92 Good	64 Marginal	52.31 Poor	1.76 Excellent	34.26 Good

downstream, with the lowest values of HPI for different uses of water recorded at site 1 (the mouth or the beginning of the canal). According to the critical HPI value of 100, the data indicate that aquatic organisms living in the Bahr Yusuf Canal may be exposed to greater risks (Table 8). Nadmitov et al. (2015) reported that at HPI > 100, the overall pollution level must be assessed as undesirable for an aquatic ecosystem.

Human Health Risk

Based on the content of trace elements in the water of the Bahr Yusuf Canal, the non-carcinogenic risk was calculated using the Hazard Quotient (HQ) and the Hazard Index (HI) at 12 locations along the canal. The obtained results showed that HQ_{oral} was much higher than HQ_{dermal}, ranging from 2.98×10^{-3} to 3.22×10^{-1}

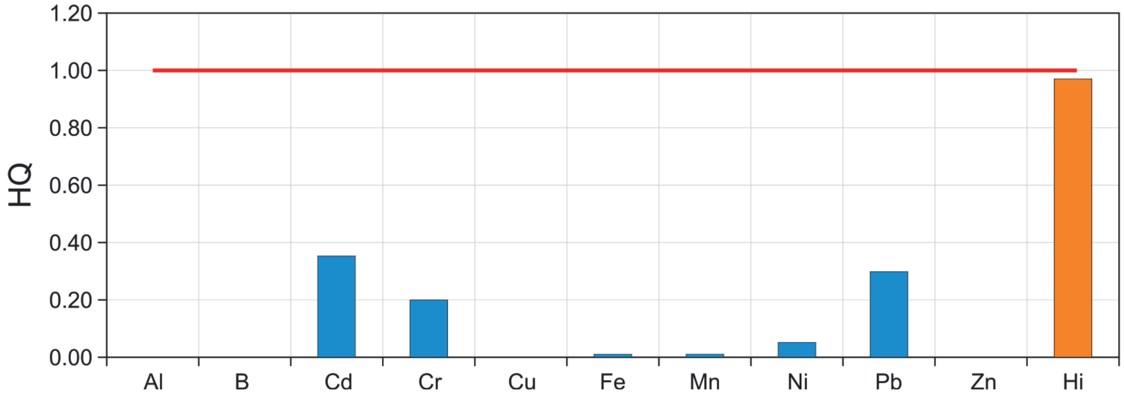

Figure 3

Hazard Quotient (HQ) and Hazard Index (HI) in relation to the human population and contamination of water in the Bahr Yusuf Canal with metals in 2017

Table 8

Heavy Pollution Index of the measured metals in water of the Bahr Yusuf Canal in 2017 according to guideline levels for drinking, irrigation, and aquatic life

Station	Drinking		Irrigation		Aquatic	
	HPI	Category	HPI	Category	HPI	Category
1	104.44	Polluted	16.81	Unpolluted	219.07	Polluted
2	153.66	Polluted	27.88	Unpolluted	347.70	Polluted
3	198.93	Polluted	36.66	Unpolluted	461.37	Polluted
4	206.32	Polluted	37.96	Unpolluted	472.24	Polluted
5	200.49	Polluted	38.25	Unpolluted	468.55	Polluted
6	193.40	Polluted	36.01	Unpolluted	444.86	Polluted
7	187.96	Polluted	34.42	Unpolluted	427.57	Polluted
8	187.49	Polluted	33.08	Unpolluted	415.61	Polluted
9	187.89	Polluted	34.81	Unpolluted	430.82	Polluted
10	201.31	Polluted	38.48	Unpolluted	469.04	Polluted
11	175.02	Polluted	31.52	Unpolluted	393.04	Polluted
12	191.44	Polluted	35.04	Unpolluted	434.95	Polluted
Overall	182.36	Polluted	33.62	Unpolluted	417.46	Polluted

and 3.3×10^{-2} to 9.16×10^{-6}, respectively, where Cd and Zn recorded the highest and lowest HQ_{oral} and HQ_{dermal} values, respectively. In general, HQ and HI values ≤ 1 are expected to be safe and HI values ≥ 1 indicate the non-carcinogenic risk. The graphical presentation of HQ and HI values indicates that the entire study area is not exposed to a carcinogenic risk through the consumption and other uses of water from the Bahr Yusuf Canal (Fig. 3). It is worth mentioning that HQ and HI are not a measure of risk but indicate the level of concern (Goher et al. 2015). In fact, the USEPA model of HQ and HI shows a limitation in the Health Risk Assessment. The HQ represents the single effect of one element and the HI represents the sum of these effects. They do not represent the combined or integrated effects of different pollutants (Ma et al. 2014). According to Graf et al. (2007), the combined effect causes the toxicity of pollutants to be additive (synergic) or antagonistic.

Conclusion

The Bahr Yusuf canal is the main source of freshwater for the Fayoum governorate. It is exposed to the deterioration in water quality due to different types of waste that are discharged into this water body, including mainly agricultural runoff and municipal wastes.

The present study was carried out to assess the quality of water in the canal and its suitability for different uses. The study also focused on the determination of the magnitude of pollution, as well as the potential health risk associated with the metal content. Four water quality indices were used to determine the suitability of the canal water for fishing, drinking, irrigation, as well as aquatic life habitat. The water quality varied according to the type of use, the number and type of water parameters used, and the arithmetic and statistical approach of the index applied.

The OWQI indicated the unsuitability of the canal water for recreational use, as the water quality was determined as poor and very poor. Whereas the ATI rated the quality of water in Bahr Yusuf as excellent and suitable for all fish species. CWQI and WAWQI showed that the quality of water in Bahr Yusuf was good, fair & marginal and excellent, from good to poor & from good to excellent for irrigation, drinking and aquatic life, respectively. On the other hand, the HPI results demonstrated that all the studied metals did not have a polluting effect for irrigation use, but the Bahr Yusuf Canal suffers from different levels of contamination with the studied metals, which poses a threat to aquatic life and human health when water is used for drinking. The USEPA module for the human health risk assessment indicates that the entire study area is not exposed to the carcinogenic risk as a result of consumption and other uses of water from the canal.

Last but not least, since the results of the present study showed that the water in the Bahr Yusuf Canal suffers from different levels of pollution, we urge the responsible authorities to prevent the discharge of different types of waste without ensuring an effective pretreatment, to achieve the internationally recommended safe parameters before the waste is discharged into the canal, and to avert further deterioration of the quality of water and, consequently, to carry out its rehabilitation.

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