Sustainable Water Resources Management (2021) 7:86
https://doi.org/10.1007/s40899-021-00569-x

ORIGINAL ARTICLE

Nature-based management scenarios for the Khojasan Lake

Rovshan K. Abbasov[1] · Chelsea L. Cervantes de Blois[2]

Received: 28 November 2020 / Accepted: 27 September 2021

Abstract
What is an effective approach to address wastewater treatment within low- and middle-income countries (LMICs)? To answer this question, we developed an integrated lake management (ILM) model which proves to reduce the pollution levels in our study site, Lake Khojasan basin, located in LMIC Azerbaijan. We found that the inflow of the treated wastewater into the lake can be a reliable approach to effectively restore the lake's ecosystem. Our model suggests that treated wastewater may gradually replace polluted water from the lake and support its full rehabilitation while at the same time restoring neighboring water systems. Our ILM is based on our calculated water and pollutant balance equations. According to our model, the increased investment around the lake will lead to an improvement of the treated water. From the results of this work, future studies may expand upon our cost-effective integrated lake management (ILM) model when using natural inflow patterns into wetlands to purify the water basin. Our study provides a model for researchers to use or expand upon when implementing sustainable and eco-friendly methods that can control highly polluted and mismanaged lakes within LMICs.

Keywords Integrated lake management · Pollution · Water restoration · Water budget · Nutrient loads

Introduction

Low- and middle-income countries (LMICs) compared to high-income countries are more often challenged with pollution management (Abbasov and Smakhtin 2012; Khan et al. 2017; Zurbrügg 2002). Specifically, pollution control of inland bodies of water within LMICs has shown to be a significant challenge due to limited financial support and resources (Jirka and Weitbrecht 2005; Mrdjen et al. 2018; Effler and Hennigan 1996; Kayani et al. 2020; Liu et al. 2008; Rahman et al. 2017). It is important to investigate cost-effective methods to address surface water pollution (i.e., urban lakes) because surface water is one of the most susceptible natural resources that is sensitive to being polluted due to its high mobility and universal solvent nature. Additionally, urbanization and rapid industrialization has caused deterioration of surface water quality, which makes it one of the most severe environmental problems for communities to address within LMICs (Khan et al. 2020). The expansion of urban areas or industrial sites (i.e., mining or oil extraction; see Santana et al. 2014) near surface water makes the challenge of mitigating pollutants from urban water sources an increasingly difficult task for urban planners and environmental scientists to address, specifically within LMICs.

To manage surface water pollution is critical for economic, ecological, and human health focused studies (Kertész et al. 2019; Reynaud and Lanzanova 2017). However, numerous studies identify the process of restoring polluted urban lakes as a difficult task (Carpenter and Lathrop 1999; Salonen et al. 1993). Specifically, the limitations of resources and funding to invest in urban remediation cleanup projects, for surface water, are often unsuccessful and do not fully restore the water quality, resulting in a failed rehabilitation project (Kagalou et al. 2008; Le et al. 2010; Søndergaard et al. 2007). In this sense, the difficulties and problems that arise during the cleaning of Lake Boyukshor in Azerbaijan can be cited as an example (Abbasov et al. 2019). Thus, to effectively tackle challenges of surface water pollution within LMICs, it is important to establish an economical

✉ Rovshan K. Abbasov
rabbasov@khazar.org

Chelsea L. Cervantes de Blois
Cerv0036@umn.edu

1 Department of Geography and Environment, Khazar University, 41 Mehseti Str, AZ1006 Baku, Azerbaijan

2 Department of Geography, Environment and Society, University of Minnesota Twin Cities, 414 Social Sciences, 267 19th Ave S, Minneapolis, MN 55455, USA

Published online: 06 October 2021

method that is sustainable. Therefore, recent studies suggest that the use of wastewater inflow patterns is a cost-effective method to reduce pollution and eutrophication levels within polluted urban lakes (Rosińska et al. 2018; Zhu et al. 2019; Chen and Olden 2017).

The diversity of pollutants, within urban water sources, can significantly vary based on location and pollutant type (Goher et al. 2019), this is especially true for nations with active oil production (see Santana et al. 2014; da Costa Cunha et al. 2019; Okoro et al. 2020; Takshe et al. 2010; Winch and Stepnitz 2011), or countries that have a combination of both location and pollution type (see Fayiga et al. 2018), or even LMICs that have a history of unsuccessful environmental remediation projects aimed at reducing pollution of urban surface water, such as in Azerbaijan (Abbasov et al. 2019; Scandizzo and Abbasov 2021). For example, in Azerbaijan's capital, Baku, located on the Absheron peninsula touching the Caspian Sea, there are high pollution levels due to permanent industrial and municipality wastewater releases during the Soviet industrial expansion (Khalilova and Mammadov 2016).

The impact of these pollutant levels in post-Soviet LMIC, Azerbaijan, has negatively impacted inland surface waters. Specifically, our study site, Khojasan Lake, is one of the most polluted urban lakes in Azerbaijan from previous and current industrial and untreated municipal wastewater discharges (Abbasov 2018; WB 2017). This persistent pollution and mismanagement have turned our study site into an industrial and domestic waste reservoir, which poses a serious public health hazard to nearby residents and ecosystems in Baku (i.e., the recent extinction of several fish species in Khojasan Lake) (Abbasov et al. 2019).

To obtain sustainable use of Khojasan Lake, we developed an integrated lake management (ILM) model (see "Materials and methods"). In our model, we use the natural-treated wastewater inflow into the lake to reduce pollutant levels. The results of our study demonstrate that the treated wastewater entering into Khojasan Lake will consistently replace the polluted water, resulting in a gradual and long-term recovery of the lake. The contribution of our study is to establish an economical model that improves ecosystems" services (i.e., wildlife and recreational purposes) within LMICs, since LMICs are most often challenged by the unattended or mismanagement of urban, surface water pollution programs.

Study area

Azerbaijan is a Eurasian nation located in the Caucasus Mountains that is challenged by the mismanagement of Soviet legacy toxic sites (i.e., polluted surface water, soils and air). Therefore, in our study, we examine Khojasan Lake, which is located in the western part of the capital, Baku. The lake's watershed occupies the syncline and is surrounded by two ridges from the east and west side.

Khojasan's watershed area is 16.9 km^2, surface 1.82 km^2, and maximal length: 3.82 km, maximal width: 662 m and depth: 4.01 m. The climate of the Absheron peninsula, where Khojasan Lake is located, is semi-arid and amount of precipitation is notably lower than potential evapotranspiration. Typically, summers in the area are hot and dry, while winters are cool and humid. Average annual temperature for the last 25 years has been 15.2 °C. Additionally, the average annual precipitation for the last 25 years was 302 mm. Most of the precipitation occurs in October–January. However, none of these months are particularly wet. Moreover, the area is predominately windy and the daily, maximum average wind speed for the last 15 years has been 26.8 m/s. Lastly, the maximum speed of winds during that period reached 42.5 m/s.

Khojasan Lake has multiple natural inflows but only one outflow at the south end (see Fig. 1). The lake's watershed is slopped from the north to the south with the lowest point at the south end. The watershed's area is 5.32 km^2 with most of the urbanized area being occupied by shanty houses and small units of food production. The sewage flowing from all houses and production facilities in the area is mixed with rainwater, in addition to 15 oil wells that directly discharge into Khojasan Lake.

Khojasan Lake is unique with respect to its fauna, ecological, and environmental features. Spring ephemeral plant cover of semi-desert areas occupies the lake surroundings. These types of ephemerals emerge quickly due to rising temperatures in the spring and die back quickly because of long droughts of summer periods. Local tamarisk (Tamaricaceae) plants occupy lower reaches of the temporary watercourses. These watercourses are locally known as Gobu (dry riverbed). There are planted groves in the northeastern and western part of the lake area, which occupy nearly 0.96 km^2 of the watershed region. These groves include tree species, such as local eldar pines (*Pinus Eldarica*) and common reeds (*Phragmites australis*), which are occupying lake coastal areas in most places (see Fig. 1).

Furthermore, Khojasan Lake is a preferred wintering place for some types of valuable duck species (e.g., *Anas platyrhynchos*). Common pochard (*Aythya ferina*), Eurasian coot (*Fulica atra*), pygmy cormorant (*Microcarbo pygmeus*) and many other bird types, that are watched in the area. In addition, to these species' wild semi-desert lake landscape with unique flora and fauna could be a preferred leisure area for Baku residents. Its closeness to the city increases economic and recreational value of the area.

Recently, Khojasan Lake has been identified to be of environmental danger. Untreated municipal and industrial wastewater is released directly into the lake and no part of

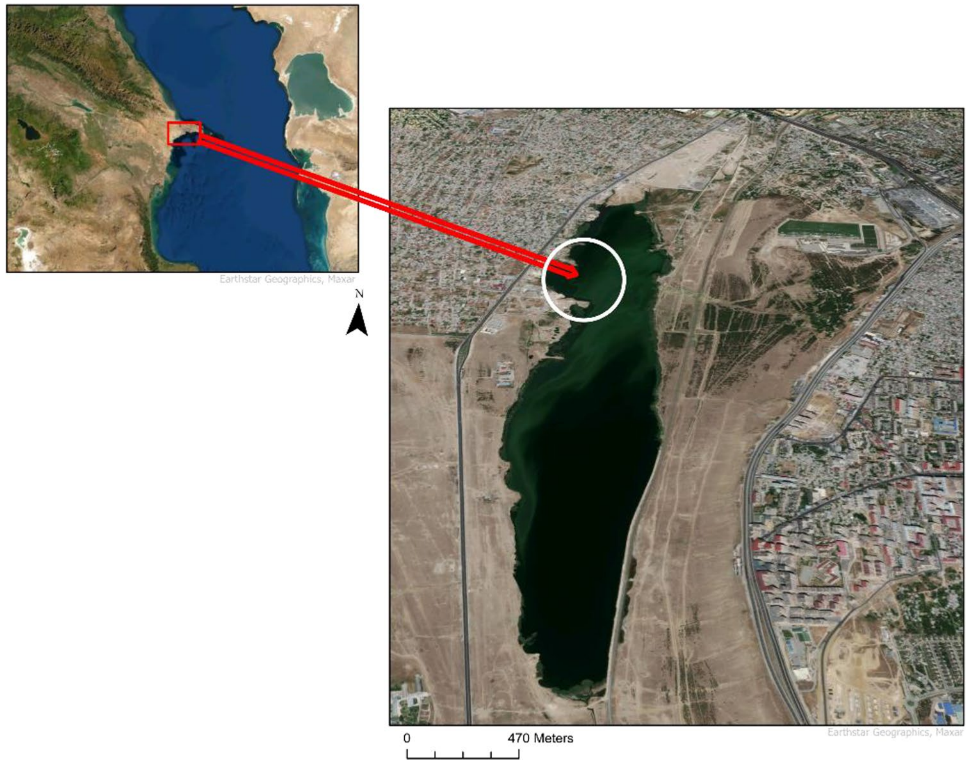

Fig. 1 Khojasan Lake

the wastewater discharged into the lake is treated. On the northern region, located near the Khojasan town, is a coastal area that is heavily developed with numerous unregulated releases of chemical and biological pollutants from nearby factories and other hazardous wastes. All the houses in Khojasan settlement and several industrial units without sewerage systems discharge their wastewater directly into the lake. Also, small oil extraction wells flow directly into Khojasan Lake, while the southern region of the lake remains relatively non-urbanized.

Materials and methods

Estimation of water and pollutant budget

The water budget equation of lakes is based on the law of mass conservation, which shows how much water is stored in the lakes within a given period (Sokolov and Chapman 1974; Swenson and Wahr 2009). The water balance equation is provided in Eq. (1): where, V_{in} and V_{out} is the water volume (m^3 or km^3) that is entering and leaving the lake, respectively, and the value for dV/dt is the rate of volume in change of time.

$$V_{in} - V_{out} = dV/dt. \quad (1)$$

Surface water, that are open and have an outflow pattern is considered to be an open lake, such as Khojasan Lake, which has a water budget (see Eq. (2)). An open lake is when the inflows and outflows exchange processes are very active. The value of P denotes the precipitation on the lake surface, (m^3 or km^3), and V_{sr} denotes surface runoff, whereas E is evaporation from the lake surface (m^3 or km^3), and the value of V_{gr} (m^3 or km^3) is the groundwater. Open lakes, such as Khojasan Lake, have long-term stable water levels because the increase and decrease of the inflow is compensated by the increase and decrease of the outflow patterns

$$P + V_{sr} + V_{in} - E - V_{out} \pm V_{gr} = 0. \quad (2)$$

Therefore, disparity between water input and, as well as evaporation can be considered as groundwater inflow/outflow as displayed in Eq. (3):

$$\pm V_{gr} = V_{in} - V_{out} \pm E. \quad (3)$$

Considering Eqs. (2) and (3), direct natural input is estimated in Eq. (4), where, Vn is natural inflow volume, Vr, is the total runoff volume, Ps, is the direct precipitation on the lake surface.

$$Vn = Ps - Es + Vr. \quad (4)$$

To find the difference between natural input and direct flow, we calculated the wastewater input of the lake.

Knowing the amount of wastewater allows us to calculate both the amount of pollutant discharged into the lake as well as the contribution of treated wastewater in the water balance, in the near future. The input Vww is the amount of wastewater that entered into the surface water. Equation (5) calculates the pollutant budget of the surface water.

$$V_{ww} = V_r - V_n. \quad (5)$$

Total residence time of water in Khojasan Lake is estimated and explained within Eq. (6). The value of V_t is the total water volume in the surface water, whereas Q_{out} is the amount of outflow per second, and T is the total residence time of water in Khojasan Lake, or time for renovation of the surface water.

$$T = V_t/Q_{out}. \quad (6)$$

The average concentration of total pollutants is given in Eq. (7). The day-to-day change in the amount of chemical pollutants in the surface water depends on the differences between the inflow and outflow amounts of pollutants. Our mathematical ILM model suggests that all the inflowing chemical waste is rapidly mixed with the surface water. The value of C_t is the average concentration of total pollutants in Khojasan Lake, whereas W_t is the total weight of pollutants, and V is the water volume.

$$C_t = W_t/V. \quad (7)$$

The pollution budget of the lake can be determined as the difference between pollution inflows and outflows. This process is explained in Eq. (8). It is important to note that within our ILM model if $CV_{in} < CV_{out}$ is true, then, $CV_{out} - CV_{in,}$ will show a reduction of the total amount of pollutants in the lake. The changing difference between CV_{in} and CV_{out} will show changing concentrations of pollutant levels to be the following (see Eq. (8)).

$$CV_{in} - CV_{out} = \pm W_t. \quad (8)$$

If consider Eq. (8) in Eq. (7), then:

$$C_t = W_t + \left(CV_{in} - CV_{out}\right)/V.$$

If $CV_{in} = 0$, then the reduction of the total weight of pollutants is explained in Eq. (9):

$$C_t = W_t - CV_{out}/V. \quad (9)$$

The estimation of residence time for pollutants is necessary to estimate time for surface water cleaning if pollutant inflow will be stopped. The residence time of total pollutants, as shown in Eq. (9), can be expressed as the ratio between the total amount of pollutants and the difference between pollutant inflow and outflow discharges. The pollutant loads of the lake were calculated as a product of volumetric water discharges and concentrations of the pollutants. In case of stopping pollution, the time for total reduction of pollutants can be calculated using Eq. (9). In Eq. (9), we are showing how concentration of the pollutants will be reduced, thus, if the pollutant flows into the surface water it should then be completely stopped. In general, pollutant decay will depend on the differences between inflow and outflow, as well as volume of surface water.

$$T = W_t/CV_{out}. \quad (10)$$

After T days, the concentration of the pollutant in the lake will be the following as explained in Eq. (11):

$$C = W_{in} - TW_{out}/V. \quad (11)$$

Equation (12) defines C_f and C_0 to be the final and initial amounts of pollutant concentrations and, T represents the time for reduction of the pollutants, and b is the reduction factor that proportionally depends closely on resident time of water. In general, reduction of concentrations will have exponential decay and will be reduced gradually.

$$C_f = C_0(1 - b)^T. \quad (12)$$

If we know the current concentration of pollutants and the elements of the water balance, we can calculate the cleaning time in open lakes according to Eqs. (10–12). At the same time, based on the Eqs. (10–12), it is possible to calculate the downward trend of pollutants in the cleaning process.

Water quality analyses

Sampling and physical–chemical, microbiological analysis were determined by standard procedures that assess water quality. The list of the analyzed physical–chemical and biological elements for the lake and sewage water flowing into the lake is given in Table 1. In Table 2, we list the methods used for determining physical–chemical analyses of water. Sampling analyses were carried out within laboratories in Baku.

The total pollutant loads in Khojasan Lake were calculated as a product of volumetric water discharges and concentrations of given pollutants. There are 11 industrial and municipal wastewater flows, 16 lake water samples from 4 points, and 110 water samples (monthly, 10 samples each time) from 11 wastewater discharge places were taken and analyzed. Water and wastewater quality indicators include physiochemical and microbiological parameters and inorganic contaminants.

Table 1 The list of the analyzed physical–chemical and biological elements for the lake and sewage water flowing into the lake

Physicochemical parameters	pH, transparency Secchi (cm), total suspended solids (mg/l), salinity (mg/l), dissolved O_2 (mg O_2/l), Nitric nitrogen (mg NO_3/l), nitrous nitrogen (mg NO_2/l), ammonium nitrogen (mg NH_4/l), total phosphorus (mg P/l), total hydrocarbons (mg/l), total phosphate (mg PO_4^{3-}/l), silicon (mg Si/l), BOD and COD (mg O_2/l)
Eutrophication indicators	Chlorophyll a (mg/l)
Microbiological parameters	Fecal coliforms (No/100 ml), total coliforms (No/100 ml)
Inorganic contaminants	Arsenic (µg As/l), mercury (µg Hg/l), cadmium (µg/Cd/l), copper (µg Cu/l), cobalt (µg Co/l), lead (µg Pb/l), nickel (µg Ni/l), zinc (µg Zn/l)

Table 2 The list of methods used for determining physical–chemical analyses

№	Analyses	Method
1	pH	EPA 150.1 Advanced pH meter 850055
2	Transparency	Secchi disk
3	Total suspended solids	EPA 160.2
4	Salinity	Water quality meter
5	Dissolved oxygen	EPA 410.1
6	Nitrous nitrogen NO_3	GOST 18826-73
7	Nitric nitrogen NO_2	GOST 4192-82
8	Ammonium nitrogen NH_4	GOST 4192-82
9	Total phosphorus P	Atomic absorption spectrophotometer ZEEnit 700P
10	Total hydrocarbons by extraction	EPA 1664a
11	Total phosphate PO_4	EPA 365.2 ГОСТ 1067.1-74
12	Silicon Si	ASTM D5184-12 Atomic absorption spectrophotometer ZEEnit 700P
13	BOD	EPA 405.1
14	COD	EPA 410.1
15	Chlorophyll a	GOST 17.1.4.02.-90
16	Fecal coliforms	MYK4.2.1884-04
17	Total coliforms	MYK4.2.1884-04
18	Arsenic As	ASTM D2972-08 Atomic absorption spectrophotometer ZEEnit 700P
19	Mercury Hg	ASTM D3223-12 Atomic absorption spectrophotometer ZEEnit 700P
20	Cadmium Cd	ASTM D3557-12 Atomic absorption spectrophotometer ZEEnit 700P
21	Copper Cu	ASTM D1688-12 Atomic absorption spectrophotometer ZEEnit 700P
22	Cobalt Co	ASTM D3558-08 Atomic absorption spectrophotometer ZEEnit 700P
23	Lead Pb	ASTM D3559-08 Atomic absorption spectrophotometer ZEEnit 700P
24	Nickel Ni	ASTM D1886-08 Atomic absorption spectrophotometer ZEEnit 700P
25	Zinc Zn	ASTM D1691-12 Atomic absorption spectrophotometer ZEEnit 700P
26	PAH	EPA 8270D
27	TPH	İSO 9377-2
28	BTEX	İSO 11423-2

Results

Lake water budget

The total monthly natural water input is given in Fig. 2. According to our calculations, in January of 2018 0.14 m^3/s of water out of 0.41 m^3/s were natural runoffs, while 0.27 m^3/s or 68% was wastewater that flowed from residential areas. In February, March, and June, the portion of wastewater in total, was the input of 58, 61% and 91%, respectively. During the dry summer months, wastewater generally comprises nearly of all the water input (Figure 3).

Monthly multi-year evaporation values from the lake surface change from 30 mm in January to 320 mm in August. Figure 4 shows monthly evaporation values for

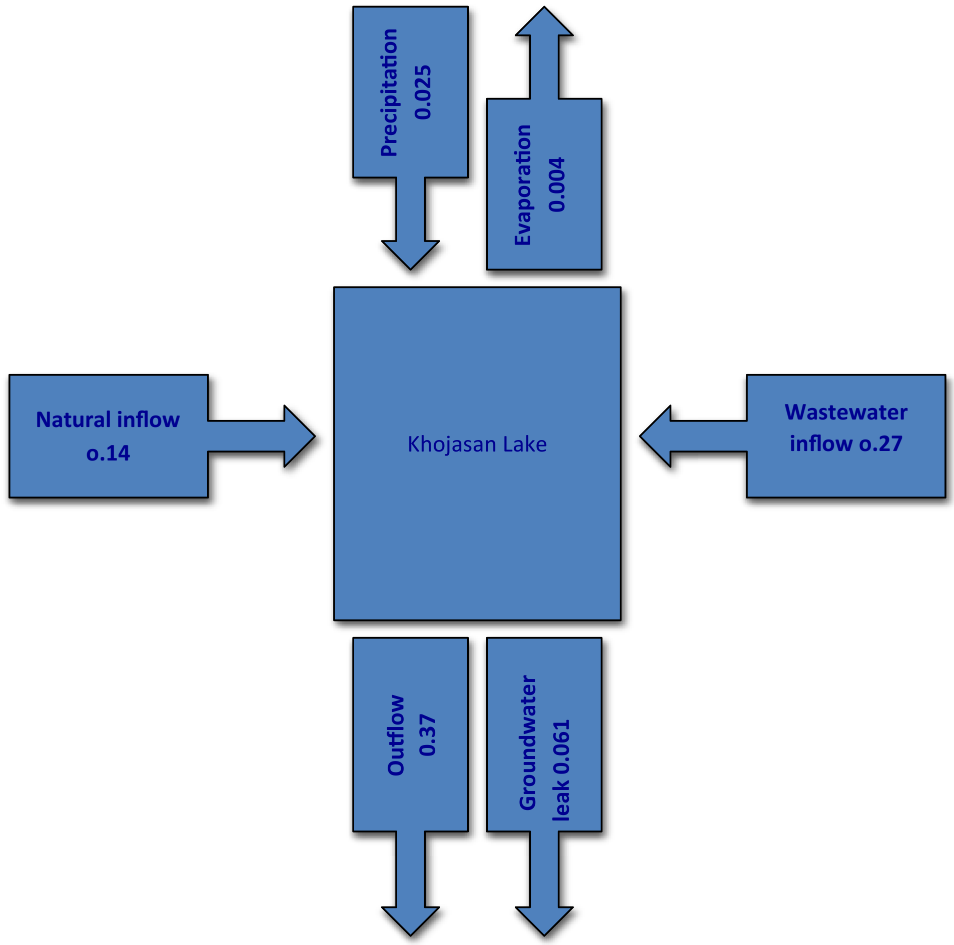

Fig. 2 Water balance diagram of the Lake Khojasan for January, 2017 that shows inputs and outputs in m^3/s

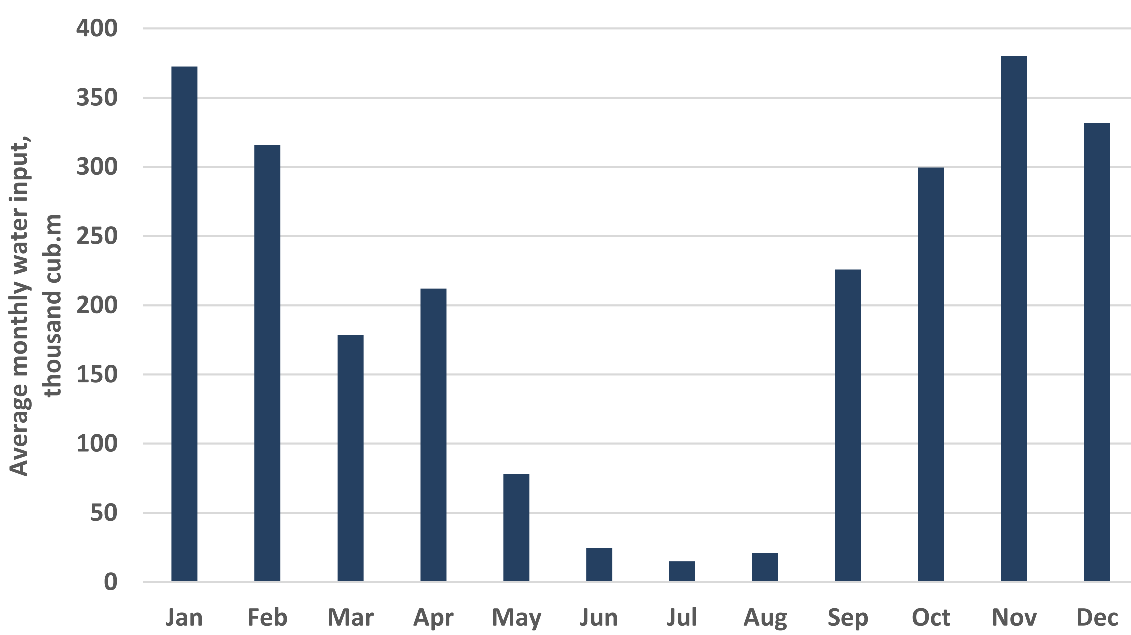

Fig. 3 Average monthly water input to the lake (1990–2018)

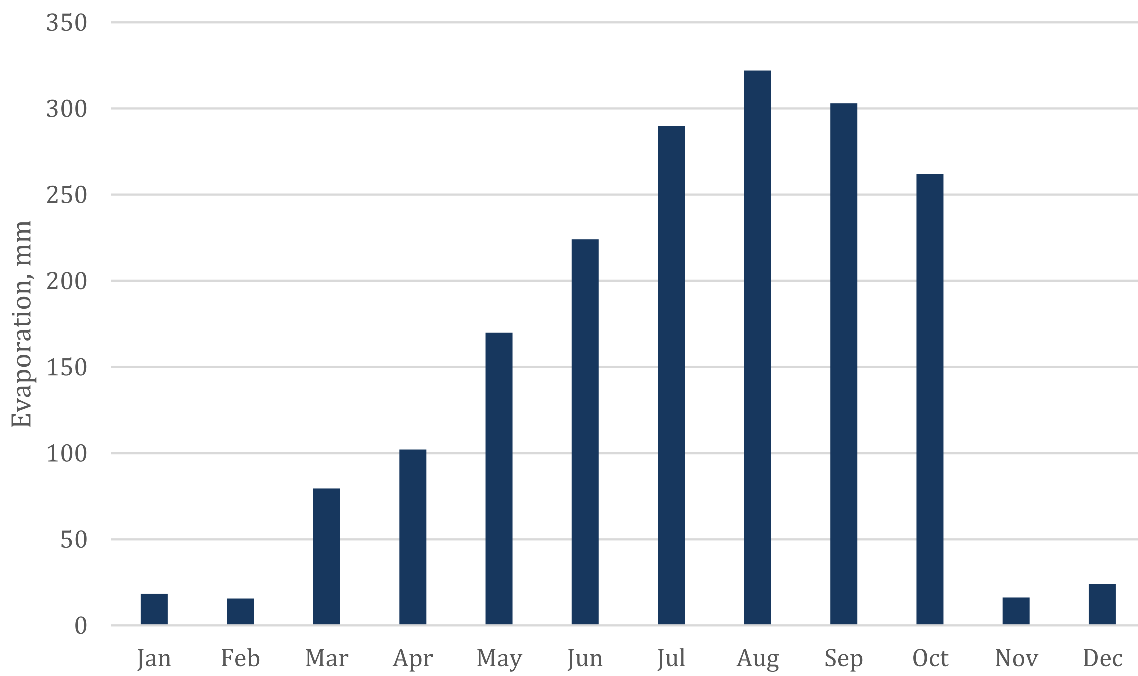

Fig. 4 Monthly average multiyear evaporation from the Khojasan lake surface (1990–2018)

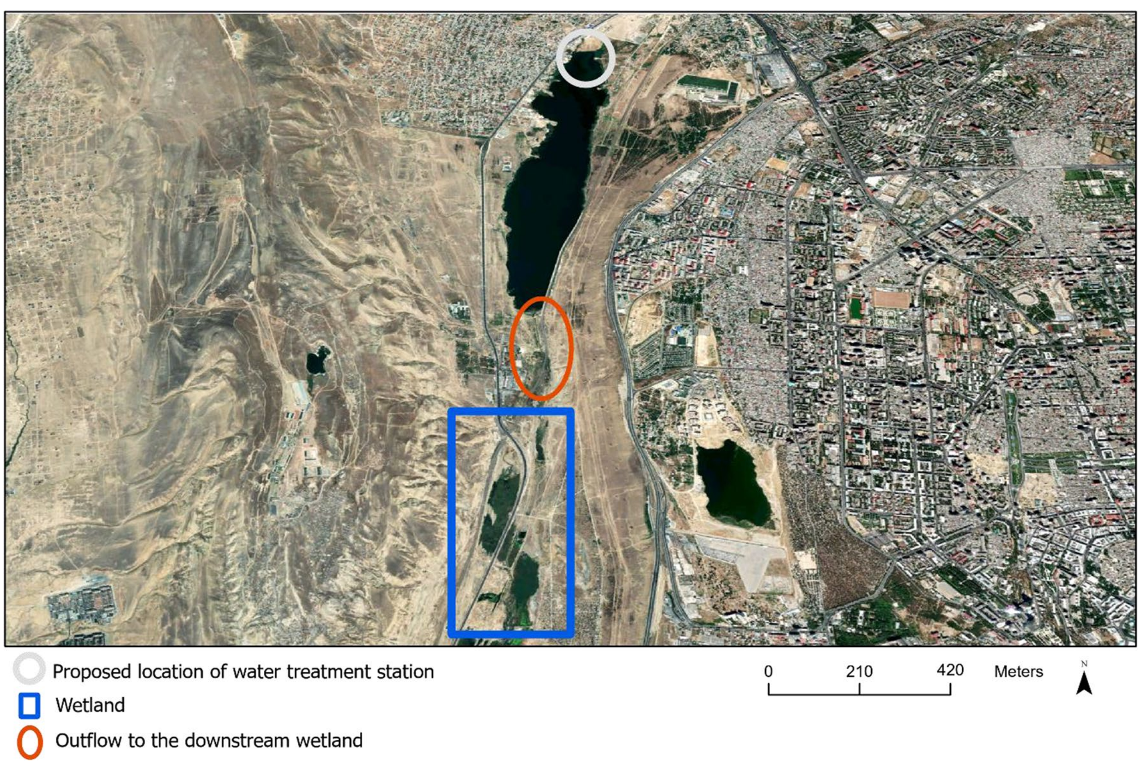

Fig. 5 Lake-wetland system

Table 3 Water budget of the Lake Khojasan for selected months

Water balance component	Water budget for selected months			
	January, 2019	February, 2019	July, 2019	November, 2019
Direct natural inflow, m^3/s	0.14	0.12	0.02	0.16
Wastewater inflow, m^3/s	0.27	0.26	0.23	0.29
Precipitation to lake surface, m^3/s	0.025	0.023	0.001	0.031
Groundwater leak, m^3/s	0.053	0.042	0.047	0.032
Evaporation from the lake surface, mm (m^3/s)	0.012	0.011	0.038	0.014
Outflow, m^3/s	0.37	0.35	0.28	0.49

the period of 1990–2018. According to recorded observations, the multiyear (1990–2018) evaporation rate from the water surface in the area reached approximately 1827 mm. Additionally, Figure 5 identifies the outflow from Khojasan Lake into the downstream wetland.

The information about the outflow discharges measured is included in Table 3. Lastly, the assessment of the water balance model confirms that the average residence time in Khojasan Lake is nearly 120 days.

Water quality

The final results showed that pH levels tend to be alkaline in the range of 7.7–8.0. Khojasan Lake's salinity changes from 1647 to 1977 mg/l. In the northern region, salinity is slightly lower and consists of 1647 mg/l, while in the southern area, salinity is equal to 1920 mg/l.

Around 80% of the wastewater discharged into Khojasan Lake, is household and industrial wastewater discharge. The total amount of coliform in wastewater is somewhere in the range of 680–2240. Fecal coliform changes are within the 160–1000 range. Moreover, the transparency of the southern part of the lake changes from 16.6 to 21.6 cm.

The total yearly nutrient loads flowing into Khojasan Lake are 942 kg of Phosphorus (P) and 12,345 kg of Nitrogen (N). The main sources of Phosphorus and Nitrogen in the wastewater enter into the lake flows through 11 inflows.

The concentration of nitrites in the lake changes from 0.05 to 0.11 mg/l. This is because surface water flowing into the lake is of household origin (80%). Coliform total amount in the lake's surface water changes in the range of 72–142 mg/l, and the fecal coliform changes in the range of 21–24 mg/l. Lastly, the amount of petroleum products in sediments range from 960 to 3100 mg/kg (0.09–0.3%) originated from small-size oil wells located in the lake watershed. Furthermore, water which contains petroleum products, originated from the oil wells, is mixed with wastewater and flows into Khojasan Lake.

Concentrations of heavy metals in the surface waters are shown in Table 4. Arsenic and cadmium concentration levels

Table 4 Concentrations of heavy metals in a lake water

	Targeted concentration, mg/l	Accepted standard (Azerbaijan maximum allowable concentration), mg/l
Arsenic	0.79	0.010
Barium	6.9	2
Cadmium	0.31	0.005
Chromium (total)	3.1	0.1
Copper	0.005	0.01
Iron	0.25	0.3
Lead	0.51	0.015
Mercury	0.021	0.002
Nickel	0.01	0.01
Zinc	0.01	0.01

in the samples ranged between 0.029 and 0.032 mg/l, and lead concentrations changes between 0.034 and 0.045 mg/l. National threshold value for both arsenic and lead is 0.01 mg/l. Iron concentrations were 1.1 mg/l, while the national threshold value for this metal is 0.05 mg/l. Concentrations of other heavy metals were lower than threshold values.

Lastly, chlorophyll level in the northern region of the lake is very high, ranging from 45.3 to 69.9 µg/l. In the southern region, the chlorophyll levels reduce in range between 17.2 and 34.5 µg/l. The same pattern is observed for total phosphorus levels, which vary between 5.51–5.56 mg/l and 1.11–2.54 mg/l, respectively. According to Secchi disk measurements, transparency in the lake water is very low. The transparency in Khojasan Lake in the southern region, varies from 16.6 to 21.6 cm, while in the northern region, the transparency values range from 12.1 to 17.3 cm. The physical–chemical properties of wastewater are shown in Table 5.

Table 5 Physical–chemical properties of wastewater

	Unit	Sample 1	Sample 2	Sample 3	Sample 4
Physicochemical parameters					
pH	–	7.2	6.05	6.51	7.15
Total suspended solids	mg/l	479	274	1548	435
Salinity	mg/l	1560	927	825	721
Dissolved O_2	mg/l	4.0	0.7	0.6	1.4
Nitric nitrogen (NO_3)	mg/l	0.38	0.22	0.05	4.04
Nitrous nitrogen (NO_2)	mg/l	0.08	0.14	0.02	0.97
Ammonium nitrogen (NH_4)	mg/l	4.938	1.98	0.98	1.86
Total phosphate (PO_4^{3-})	mg/l	0.07	0.04	0.01	0.53
BOD	mg/l	76	48	27	19
COD	mg/l	68	79	46	36
Inorganic contaminants					
Total phosphorus (P)	μg/l	12.32	11.52	18.65	11.24
Silicon (Si)	μg/l	0.15	0.18	0.11	0.17
Arsenic (As)	μg/l	2.63	3.35	2.14	1.36
Mercury (Hg)	μg/l	7.72	4.65	2.69	1.59
Cadmium (Cd)	μg/l	8.09	8.74	9.05	7.94
Copper (Cu)	μg/l	3.48	3.79	2.00	3.08
Cobalt (Co)	μg/l	0.78	0.48	0.65	0.78
Lead (Pb)	μg/l	3.64	3.11	5.05	4.62
Nickel (Ni)	μg/l	0.55	0.87	0.59	0.97
Zinc (Zn)	μg/l	0.64	3.89	7.61	5.67

Table 6 Decay of pollutant concentrations of the lake, after cessation of pollution

Pollutant	Concentration, mg/l	Total, kg	Daily reduction of pollutants, kg	After 30 days cut of pollution		After 1 year cut of pollution		After 526 days cut of pollution	
				Concentration, mg/l	Total, kg	Concentration, mg/l	Total, kg	Concentration, mg/l	Total, kg
Arsenic	0.79	2458	4.7	0.65	2317	0.27	1705	0.00	1.48
Barium	6.9	21,466	40.8	5.1	20,242	2.3	14,887	0.00	12.9
Cadmium	0.31	9645	18.3	0.27	9095	0.11	6689	0.00	5.8
Chromium	3.1	16	0.03	3.0	15.9	1.7	11.1	0.00	0.01
Copper	0.005	778	1.5	0.004	733	0.002	539.5	0.00	0.47
Iron	0.25	1587	3.0	0.21	1496	0.12	1100	0.00	0
Lead	0.51	65	0.12	0.49	61	0.28	45.08	0.00	0.95
Mercury	0.021	31	0.06	0.012	29	0.06	21.5	0.00	0.04
Nickel	0.01	31	0.06	0.01	29	0.01	21.5	0.00	0.02
Zinc	0.01	31	0.06	0.01	29	0.01	21.5	0.00	0.02

Discussion

According to our proposed integrated lake management (ILM) model, wastewater will be treated and discharged into Khojasan Lake. The wastewater will then be discharged into the wetland below the lake to establish long-term rehabilitation of the surface water and downstream wetland. The assessment of the water balance confirms that average residence time in Khojasan Lake is 120 days. This means that replacing wastewater with treated water can help clean and fully rehabilitate the lake in a short period of time. According to Eqs. (11) and (12), rapid reduction of pollution levels and full restoration of the lake will occur in 526 days (see Table 6).

This period of restoration time may be notably prolonged by mixing the bottom sediments with lake water. However, it is believed that the constant supply of clean water to the lake will eventually lead to the gradual cleaning of the bottom sediments of Khojasan Lake. Additionally, our ILM model does not provide the direct removal and treatment of bottom sediments. Removal of the bottom sediments may cause the surface water to become very polluted in a short period of time and degrade the already vulnerable ecosystem.

In 2019, the Azerbaijani water company, Azersu, began to build a new wastewater system in attempt to eliminate the polluted wastewater from Khojasan Lake's watershed. At first glance, cutting all of the wastewater input was considered the best solution to reduce pollution levels in the surface water. However, in our ILM model, the water balance calculations confirm that a total wastewater inflow comprises 60–90% of the total water input into the surface water. This is an issue because it will reduce inflows to the lake and will continue evaporation from the surface, driving the mineralization (e.g., salinity) of the surface water to gradually increase. This would raise the biological oxygen demand (BOD) level and intensify eutrophication of the lake making Khojasan Lake a lifeless body of water. The results of this, allude to the fact that any inaccurate management may lead to unexpected consequences, which are explained in Table 7.

According to scenario 1, cutting off all wastewater inflows and redirecting them into the centralized sewage system of the capital, Baku, will result in fatal consequences for Khojasan Lake's hydrology and ecology. Restriction of all inflows will cut the lake outflow as well, making Khojasan Lake a closed system. This will result in a reduced ecosystem and recreational importance. Reducing the inflows may have some negative consequences in the downstream wetland as well, which may fully dry up as a result of inflow cuts. According to scenario 2, construction of a new water treatment plant is suggested. After the proper treatment, all wastewater and rainwater can be directed into Khojasan Lake. This approach is intended to improve the hydrological regime of the surface water, while simultaneously improving the ecosystem and environmental values of the lake.

Our proposed equations suggest that the process of cleaning the surface water can be accelerated. The polluted water will be replaced by the inflow of the treated water flowing into the lake. Looking toward the near future, Azerbaijan's urban expansion will continue, which will directly affect the increase of water inflow of the treated wastewater in Khojasan Lake, and in turn, will accelerate its recovery pollutant build-up.

According to scenario 2, it is also possible to separate stormwater from wastewater. The stormwater system separates the rain and sewage water flows, which enables rainwater release directly to Khojasan Lake. Scenario 3, as a basic business-as-usual scenario, suggests that the current situation around the lake will remain. Taking into account our integrated lake management (ILM) model, the local

Table 7 Possible scenarios of lake water inflow management

#	Actions	Consequences	Projected value
Scenario 1	Cutting of all inflows and re-direction them into the centralized sewage system of Baku	Reduced lake level, volume and area makes Khojasan Lake a closed lake with no outflow. Increase of salinity and mineralization. Reduced level and volume of downstream lakes. Frequent level fluctuations. Changes in hydrological regime. Changes in ecosystems	Reduced ecosystem services. Reduced recreational importance. Reduced values. Reduced property prices around the lake. Full drying of downstream Gu lake
Scenario 2 (integrated lake-wetland model)	Constructions of new water treatment station around the lake. Treatment of wastewaters and direction to the lake	More water input to the lake and more outflow. Stable lake level. Reduced eutrophication. Improved hydrological regime and ecological regime	Increased ecosystem services. Increased recreational importance. Increased values. Increased property prices around the lake
Scenario 3 (business as usual)	Current situation remains. No interventions are made	Stable lake level, increased pollution, increased eutrophication, worsened ecological regime, worsened environmental situation	Reduced ecosystem services. Reduced recreational importance. Reduced values. Reduced land prices around the lake. Increased health risks

company, Azersu Water, agreed to apply our model by building a water treatment plant at the location we identified.

Table 7 shows that future water budget will be strongly affected by management decisions and good governance regarding recreational use, fishing, and tourism. Respectively, a functioning institutional setup will most likely play a key role in sustainable management of Khojasan Lake.

Our model supports the practice of implementing a wastewater management approach as demonstrated within scenario 2. According to scenario 2, treated wastewater and stormwater input into the lake will be increased, resulting in an accelerated cleanup. Also, we observed in our tested scenarios excess water can be redirected into the wetland located downstream.

To keep water levels in Khojasan Lake stable, it is essential to implement correct regulation of the outflow through gateway. This gateway includes a meter that will monitor the water level regularly. Additionally, activities involving deep drilling or digging around the south areas of the lake will increase groundwater outflow as well.

Conclusion

In this study, we proposed an integrated lake management (ILM) model to restore Khojasan Lake located in Azerbaijan's capital, Baku. The results of our model showed that we can successfully eliminate pollutant levels through the treatment of treated wastewater flowing into the upper section of Khojasan Lake.

In this study, we explored the possibility of rehabilitating lakes in urban areas without direct intervention, because remediation programs are generally costly and challenging to successfully conduct in LMICs. For this purpose, we consider Khojasan Lake, located in Azerbaijan's capital, Baku, because of the long-term influx of domestic and industrial pollutants impacting the quality of its surface water and previous implemented projects failing to remedy the pollutant levels.

Our results confirmed that active intervention measures are not required for rehabilitation in open lakes of an urban areas because our developed model demonstrates that stopping the flow of pollutants into the lake will lead to the gradual recovery of the lake from wastewater. Additionally, our results suggest that if wastewater is treated and transported into Khojasan Lake, increased urbanization may accelerate the process of cleaning the surface water. Thus, the treated water entering Khojasan Lake will gradually remove the pollutants while flowing downstream.

Our ILM model does not provide treatment of the contaminated bottom sediments, because when the bottom sediments are cleaned, the water quality of Khojasan Lake becomes extremely polluted, which has a negative impact on the existing ecosystem. Lastly, our ILM model demonstrates that the areas surrounding the surface water become more urbanized, since the amount of treated water entering Khojasan Lake will increase because the treated water will gradually remove pollutants that will transfer into the wetland flowing southward. To expand among our ILM model, we suggest future studies to consider the impact of treated urban water systems, specifically on the eutrophication process in urban lakes.

Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of interest Rovshan Abbasov and Chelsea L. Cervantes de Blois declare that they have no conflict of interest. Both authors contributed equally to this article and are therefore considered the first authors.

References

Abbasov RK (2018) Assessment of the fresh water ecosystem services of Reservoirs/ HPP Dams in the Kura-Aras river basin. 17th World Lake Conference, Lake Kasumigaura, Ibaraki, Japan. https://www.ilec.or.jp/wp-content/uploads/e_WLC17programabstract_full.pdf

Abbasov R, Smakhtin V (2012) Indexing the environmental vulnerability of mountain streams in Azerbaijan. Mt Res Dev 32(1):73–82. https://doi.org/10.1659/MRD-JOURNAL-D-11-00012.1

Abbasov R, Cervantes de Blois CL, Sharov P, Temnikova A, Karimov R, Karimova G (2019) Toxic site identification program in Azerbaijan. Environ Manag. https://doi.org/10.1007/s00267-019-01215-1

Carpenter SR, Lathrop RC (1999) Lake restoration: capabilities and needs. Hydrobiologia 395:19–28. https://doi.org/10.1023/A:1017046729924

Chen W, Olden JD (2017) Designing flows to resolve human and environmental water needs in a dam-regulated river. Nat Commun 8(1):2158. https://doi.org/10.1038/s41467-017-02226-4

da Costa Cunha G, Pinho NC, Alves Silva IA, Santos Silva L, Santana Costa JA, da Silva CMP, Romão LPC (2019) Removal of heavy crude oil from water surfaces using a magnetic inorganic-organic hybrid powder and membrane system. J Environ Manag 247:9–18. https://doi.org/10.1016/j.jenvman.2019.06.050

Effler SW, Hennigan RD (1996) Onondaga Lake, New York: legacy of pollution. Lake Reserv Manag 12(1):1–12. https://doi.org/10.1080/07438149609353992

Fayiga AO, Ipinmoroti MO, Chirenje T (2018) Environmental pollution in Africa. Environ Dev Sustain 20(1):41–73. https://doi.org/10.1007/s10668-016-9894-4

Goher ME, Mahdy E-SM, Abdo MH, El Dars FM, Korium MA, Elsherif AAS (2019) Water quality status and pollution indices of Wadi El-Rayan lakes, El-Fayoum, Egypt. Sustain Water Resour Manag 5(2):387–400. https://doi.org/10.1007/s40899-017-0162-z

Jirka GH, Weitbrecht V (2005) Mixing models for water quality management in rivers: continuous and instantaneous pollutant releases. In: Czernuszenko W, Rowiński PM (eds) Water quality hazards and dispersion of pollutants. Springer, New York, pp 1–34. https://doi.org/10.1007/0-387-23322-9_1

Kagalou I, Papastergiadou E, Leonardos I (2008) Long term changes in the eutrophication process in a shallow Mediterranean lake ecosystem of W. Greece: Response after the reduction of external load. J Environ Manag 87(3):497–506. https://doi.org/10.1016/j.jenvman.2007.01.039

Kayani GM, Ashfaq S, Siddique A (2020) Assessment of financial development on environmental effect: implications for sustainable development. J Clean Prod 261:120984. https://doi.org/10.1016/j.jclepro.2020.120984

Kertész A, Loránd A, Nagy BBalázs (2019) Effect of land use change on ecosystem services in Lake Balaton Catchment. Land Use Policy 80430–438. https://doi.org/10.1016/j.landusepol.2018.04.005

Khalilova H, Mammadov V (2016) Assessing the anthropogenic impact on heavy metal pollution of soils and sediments in urban areas of Azerbaijan's oil industrial region. Pol J Environ Stud 25(1):159–166. https://doi.org/10.15244/pjoes/60723

Khan MYA, Gani KM, Chakrapani GJ (2017) Spatial and temporal variations of physicochemical and heavy metal pollution in Ramganga River—a tributary of River Ganges, India. Environ Earth Sci 76(5):231. https://doi.org/10.1007/s12665-017-6547-3

Khan MYA, Hu H, Tian F, Wen J (2020) Monitoring the spatio-temporal impact of small tributaries on the hydrochemical characteristics of Ramganga River, Ganges Basin, India. Int J River Basin Manag 18(2):231–241. https://doi.org/10.1080/15715124.2019.1675677

Le C, Zha Y, Li Y, Sun D, Lu H, Yin B (2010) Eutrophication of lake waters in China: cost, causes, and control. Environ Manag 45(4):662–668. https://doi.org/10.1007/s00267-010-9440-3

Liu et al (2008) Fraction distribution and risk assessment of heavy metals in sediments of Moshui Lake. J Environ Sci 20(4):390–397. https://doi.org/10.1016/S1001-0742(08)62069-0

Mrdjen I, Fennessy S, Schaal A, Dennis R, Slonczewski J, Lee S, Lee J (2018) Tile drainage and anthropogenic land use contribute to harmful algal blooms and microbiota shifts in inland water bodies. Environ Sci Technol. https://doi.org/10.1021/acs.est.8b03269

Okoro EE, Okolie AG, Sanni SE, Joel ES, Agboola O, Omeje M (2020) Assessment of naturally occurring radiation in lithofacies of oil field in Niger Delta region and its possible health implications. J Environ Manag 264:110498. https://doi.org/10.1016/j.jenvman.2020.110498

Rahman IU, Ijaz F, Afzal A, Iqbal Z (2017) Effect of foliar application of plant mineral nutrients on the growth and yield attributes of chickpea (*Cicer arietinum* L.) under nutrient deficient soil conditions. Bangladesh J Bot 46:111–118

Reynaud A, Lanzanova D (2017) A Global meta-analysis of the value of ecosystem services provided by lakes. Ecol Econ 137184–194. https://doi.org/10.1016/j.ecolecon.2017.03.001

Rosińska J, Kozak A, Dondajewska R, Kowalczewska-Madura K, Gołdyn R (2018) Water quality response to sustainable restoration measures – case study of urban Swarzędzkie Lake. Ecol Indic 84:437–449. https://doi.org/10.1016/j.ecolind.2017.09.009

Salonen V-P, Alhonen P, Itkonen A, Olander H (1993) The trophic history of Enäjärvi, SW Finland, with special reference to its restoration problems. Hydrobiologia 268(3):147–162. https://doi.org/10.1007/BF00014050

Santana et al (2014) Influence of water quality on the embodied energy of drinking water treatment. Environ Sci Technol. https://doi.org/10.1021/es404300y (**retrieved 17 Oct 2020**)

Scandizzo P, Abbasov R (2021) Do people appreciate economic value of water in Baku city of Azerbaijan? In: Dhyani S., Basu M., Santhanam H., Dasgupta R (eds) Blue-Green Infrastructure across Asian Countries - Improving Urban Resilience and Sustainability. Springer, Singapore. (In Press)

Sokolov AA, Chapman TG (1974) Methods for water balance computations. An International Guide for Research and Practice. Studies and Reports in Hydrology 17. Paris: UNESCO

Søndergaard M, Jeppesen E, Torben L, Lauridsen, Skov C, Van Nes HE, Roijackers R, Lammens E, Rob Portielje R (2007) Lake restoration: successes failures and long-term effects. J Appl Ecol 44(6):1095–1105. https://doi.org/10.1111/j.1365-2664.2007.01363.x

Swenson S, Wahr J (2009) Monitoring the water balance of Lake Victoria East Africa from space. J Hydrol 370(1–4):163–176. https://doi.org/10.1016/j.jhydrol.2009.03.008

Takshe AA, Huby M, Frantzi S, Lovett JC (2010) Dealing with pollution from conflict: analysis of discourses around the 2006 Lebanon oil spill. J Environ Manag 91(4):887–896. https://doi.org/10.1016/j.jenvman.2009.11.005

WB (Worldbank) (2017) Combined project information documents/integrated safeguards data sheet (pid/isds). Concept stage. https://documents1.worldbank.org/curated/en/931611468005092100/pdf/Concept-Project-Information-Document-Integrated-Safeguards-Document-Absheron-Lakes-Cleanup-and-Rehabilitation-P157091.pdf. Acsessed 5 Oct 2021

Winch P, Stepnitz R (2011) Peak oil and health in low- and middle-income countries: impacts and potential responses. Am J Public Health 101(9):1607–1614. https://doi.org/10.2105/AJPH.2011.300231

Zhu D, Ryan MC, Gao H (2019) The role of water and mass balances in treatment assessment of a flooded natural wetland receiving wastewater effluent (Frank Lake, Alberta, Canada). Ecol Eng 137:34–45. https://doi.org/10.1016/j.ecoleng.2019.01.010

Zurbrügg C (2002) Urban solid waste management in low-income countries of Asia how to cope with the garbage crisis. In: South Africa, p 13

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.