Asian Journal of Environment & Ecology

Volume 23, Issue 6, Page 91-108, 2024; Article no.AJEE.116532
ISSN: 2456-690X

Assessment of Water Quality, Ecological and Health Risks of Inland Water Bodies in Mexico: A Case Study of Lake Chapala

Hermes Ulises Ramírez-Sánchez [a,b*]
and Aida Lucia Fajardo-Montiel [b]

[a] Institute of Astronomy and Meteorology CUCEI, University of Guadalajara, Av. Vallarta 2602. Col. Arcos Vallarta, Guadalajara, Jalisco, México.
[b] University Center of Tonalá, University of Guadalajara, Av. Nuevo Periférico No. 555 Ejido San José Tateposco, C.P. 45425, Tonalá, Jalisco, México.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJEE/2024/v23i6558

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/116532

Original Research Article

Received: 01/03/2024
Accepted: 02/05/2024
Published: 04/05/2024

ABSTRACT

Water security threatens the world's population, so the assessment of the quality of water in reservoirs is one of the priority issues and represents a challenge for the sustainability of ecosystems and the human population. The aim is to evaluate the physicochemical parameters and heavy metals of the water of Lake Chapala to evaluate its water quality, during the period 2010-2023, and to estimate the ecological and health risks. The results will provide valuable information on water quality management and protection of human health. The design is an ecological study, using water quality, pollution risk, ecological and health risk indices. The place and duration of the

**Corresponding author: E-mail: ramirez@astro.iam.udg.mx;*

study is the Lake Chapala during the period 2010-2023. The methodology consisted of obtaining the quality data of the Water Lake Chapala through the State Water Commission, the National Water Commission and studies conducted by the University of Guadalajara. The analyses were conducted on a monthly basis from 2010 to 2023. Subsequently, the CWQI, WQI, NP, HPI, HEI, DC, PERI, HQ, HI, THI, CR and TCR indices were calculated to determine water quality and ecological and health risks. The results showed que the distribution of parameter concentration showed great spatial variation, but not temporal; the TDS, Turbidity, pH, Al, As, Cr, Cu, Mn, Pb and Zn with percentages above the CCME standard, but most of them within the NOM-001-SEMARNAT-2021. The heavy metals Al, As, Cr, Pb and Zn have concentration percentages of more than 100% with respect to the international standard. The remaining 14 parameters are within both national and international standards. Pearson's correlation analysis showed that none of the trace elements have positive correlations with each other. Water quality according to the WQI of 178 was categorized as poor quality, while for the CWQI almost all uses except grazing, water quality is poor (20-35). According to the NP index (3.8 to 670), the concentrations of heavy metals showed high levels of contamination. The HPI index (88.6) showed moderate to high levels of heavy metal contamination. The HEI index showed <10 levels, indicating low contamination. The DC had a value of 0.2-18.2, classified as a high degree of contamination. The PERI index showed that the ecological risk from heavy metals is high. Non-carcinogenic risk indices indicate that lake water is not suitable for drinking, and poses a high health risk via ingestion, while dermal contact does not pose a health risk to residential and recreational recipients. The carcinogenic risk index is negligible to acceptable. The conclusion is according to the water quality, ecological and health risk indices, the water quality of Lake Chapala is poor, with a high degree of contamination and represents ecological and health risks (non-carcinogenic). It is recommended that the use of lake water does not include its ingestion to avoid health problems, and it is important to take measures to sanitize the lake to avoid ecological and health risks.

Keywords: Water quality; ecological risks; health risks; lake Chapala.

1. INTRODUCTION

"Water resources are indispensable for a healthy ecological environment and livelihoods. The quality and availability of water have influenced the development of civilizations and the development of populations" [1-5]. "Water quality is highly sensitive to climate variability, climate change and intense anthropogenic activities, as they have a major impact on ecosystems and human health" [6-8]. "Water security threatens the world's population, so the assessment of the water quality of water bodies is one of the important issues that represent a current challenge to ensure the sustainability of ecosystems and the human population" [9-12].

Physicochemical, microbiological, and trace element parameters of water are the most commonly used indicators to determine the health of water bodies. On the other hand, heavy metals in water bodies are among the most dangerous pollutants due to their persistence, carcinogenicity and environmental toxicity [13-17]. Many regions of the planet face severe water pollution, especially heavy metals [12,18-19]. Heavy metal pollution in freshwater bodies has been a global concern in recent years [16,20-22], so contaminated water can make it unsuitable for a wide range of activities such as human consumption, aquatic life development, recreation, irrigation, livestock, among others. "The accumulation of heavy metals in water can cause adverse health effects on aquatic organisms and human" [11,23]. Multiple investigations have been conducted on water quality, health and ecosystem risk assessment; Identification of sources of heavy metals in well water, rivers, shallow groundwater, lakes, and drinking water. However, human activities have increased in recent years, which is a potential threat to the sustainable development and ecological security of water bodies. Previous studies have described the contamination of Lake Chapala, however, the ecological and health risks of the riparian populations and of the Guadalajara Metropolitan Area (GMA), which is fed almost 60% by water from the lake, have not been reported. For this reason, it is important to study the quality of the water and the presence of heavy metals in Lake Chapala that are related to activities such as water consumption, aquatic life, recreation, irrigation, grazing, among others.

In this study, analyses of the physicochemical parameters and heavy metals of the water of

Lake Chapala were collected and analyzed during the period 2010-2023, to evaluate the water quality and the ecological and human health risks they represent. These results can provide valuable insights into water quality management and the protection of human health.

2. MATERIALS AND METHODS

2.1 Study Area

Lake Chapala is the largest inland body of water in Mexico. It is located in the east of the State of Jalisco and in the northwest of the State of Michoacán, it has a maximum area of 114,659 ha, of which Jalisco occupies 86% and Michoacán 14%. It has a maximum storage capacity, at an altitude of 97.80 (equivalent to 1,423.80 meters above sea level) of 7,897 million cubic meters and dimensions of 79 km long and 28 km wide, and average depth of 4.5 m (Pic 1). The lake provides various uses and is a very important natural resource for the region and in particular for the Guadalajara Metropolitan Area (GMA), as it is its main source of supply (approximately 60%). The lake belongs to the Lerma-Chapala-Pacific hydrological basin; the basin of the Lerma River is its main tributary, and industrial, agricultural and urban activities are developed there, in which water has been a determining factor [24]. However, these activities have deteriorated the quality of the lake's water due to wastewater discharges, decreased river flows and water withdrawals for supply to the GMA (with a population of 5,268,642 inhabitants in 2020, distributed in 10 municipalities Guadalajara, Zapopan, Tlajomulco de Zúñiga, San Pedro Tlaquepaque, Tonalá, El Salto, Juanacatlán, Ixtlahuacán de los Membrillos, Acatlán de Juárez and Zapotlanejo [25], with a total area of 3,567.50 km² and an average density of 1476.84 inhabitants per km² [26].

Lake Chapala is considered a shallow lake and this type of lakes located in tropical and subtropical regions have greater conditions of vulnerability, due to a greater photoperiod and warm temperatures, which favors a greater production of phytoplankton, proliferation of cyanobacteria and macrophytes, altering the water balance, the food chain and putting the ecosystem at risk [27-31].

According to de Anda and Maniak [32], Lake Chapala is alkaline, with an average pH of 8.5, a high degree of turbidity, and a minimum transparency of 10 cm in the east and 60 cm in the west. The dissolved O_2 is 6.8-7.0 mg/l with saturation >90%, with no major variations in the water column [33-34]. Organic matter (DBO_5) is 1.4-2.0 mg/l, higher near municipal discharges. The surface temperature is between 17.8 and 23.8°C. The total inorganic P in the area of the mouth of the Lerma River is 0.517 mg/l; and in the rest of the lake 0.6 mg/l and phosphates (PO_4^{-3}) 0.41mg/l [33-34]. Organic N_2 and nitrate decrease in an east-west direction and increase near the Chapala population [35]. Sulfates have concentrations between 47-70 mg/l. Fats and oils between 4.1 and 115.6 mg/l. The total hardness is 100-250 mg/l and the total alkalinity is 196-246 $mgCaCO_3$/l. At the mouth of the Lerma River fecal coliforms are 123-NMP/100ml, and in the rest of the lake 90NMP/100ml [34]. 117 species of algae have been identified and it is estimated that there may be more than 300. The presence of cyanobacteria of the genus Microsystis predominates in autumn and winter, and they are indicative of contamination [36]. These cyanobacteria have an impact on the health of aquatic life and can have consequences on human health by the ingestion of contaminated fish [37].

The main economic activities within the lake basin are tourism, agriculture, fishing and to a lesser extent livestock and handicrafts. Most agricultural land is rainfed, and fertilizers are used only during the rainy season. However, traditional agricultural practices use excessive amounts of fertilizers, which is one of the main sources of nutrient pollution.

The current situation of the lake is very complex, since the extension of the entire basin involves the factors of water exploitation, pollution, silt and climatic effects [25]. In addition, the lake is being lost day by day, as the only thing that saves its water level is the rainy season. Water problems and the fight over water on the Lerma River cause the lake to be lost little by little. Among the main problems are 1) the excessive consumption of water as a result of human activity, 2) high levels of pollution, due to industrial and domestic discharges and proper management of wastewater treatment plants in the lake basin itself, 3) pollution in the entire basin is considered serious due to the water conditions of the Lerma-Santiago basin. The Lerma River crosses the Bajio region, and all kinds of urban and agricultural waste are dumped into it. In addition, the construction of dams on this river worsens the flow of water and waste ends up accumulating. In the River Santiago, the pollution is equally strong, as it receives drainage water from the GMA and nearby towns. All the waste in the rivers comes together, causing the current to be slow and the water to stagnate, further deteriorating the quality of the water, and 4) silting, a product of the degradation of the soils of the basin itself and the dragging of solids by the tributaries that flow into the Lake (Lerma, The Passion and Zula rivers).

The population of the GMA continues to increase and with it the demand for water to meet domestic, commercial, industrial needs, among others. Water quality is a concern in Lake Chapala due to direct discharges of raw and partially treated wastewater from settlements located along its shores and from housing developments located within its watershed. As a result of wastewater pollution, the water has undergone major changes in its chemical, physical and biological characteristics, causing algae blooms, increased water turbidity and various pollutants and, in recent years, the mass die-off of endemic and commercial fish species during the summer.

The lake is of capital importance in the Central-West of Mexico, because it is the largest body of surface water in the country and the one that feeds water to the Guadalajara Metropolitan Area, which is the second largest city in Mexico. An increase in the population of the basin and a rapid process of urbanization of the municipalities are putting at risk the aesthetic, cultural, economic and environmental values of the lake.

In 2018, indigenous communities on the shores of the lake reported health problems, specifically related to outbreaks of kidney disease, brain damage, cancer and malformations that especially affect children and young people in the region. It has been mentioned that these are associated with the direct consumption of water from the lake, from nearby wells, and thermal water that do not receive special treatment. The public health problem is serious, however, there are no official data on the factors that predispose or enhance the development of diseases.

Based on the above, it is of vital importance to evaluate the physicochemical parameters and heavy metals, to determine the quality of the lake's water, the ecological and health risks, to establish whether the quality of the lake's water may be associated with the negative effects on public health of the population that uses its waters as a source of drinking water supply.

Picture 1. Lake chapala basin (Courtesy of Google Earth, 2023)

2.2 Methodology

Water quality data for Lake Chapala were obtained through the State Water Commission (CEA) and the National Water Commission (CNA). The data provided includes monthly monitoring from 2010 to 2023. The data provided includes the following parameters: temperature, TDS, conductivity, oxygen demand, pH, alkalinity, sulfates, chlorides, fluorides, nitrates, Na, P, N, Ba, Fe, Al, Mn, As, Cd, Cr, Cu, Hg, Ni, Pb and Zn. All parameters were compared with the Official-Mexican Standard NOM-001-SEMARNAT-2021, which establishes the maximum permissible limits of pollutants in wastewater discharges into national water bodies [38] and the limits of the Canadian Water Quality Guidelines for the Protection of Aquatic Life Freshwater, Marine [39] and Water Quality Guidelines for the Protection of Agriculture Irrigation, Livestock of the Canadian Environmental Quality Guidelines [40].

“The lake's water samples were taken in accordance with international water sampling standards. The samples were transferred to the laboratories of the State Water Commission and the National Water Commission, which has laboratories accredited to perform water quality analyses in accordance with the regulations approved in Mexico by the National Water Commission itself, which in turn are based on internationally approved protocols” [41-42].

With the results of the parameters analyzed during the period 2010-2023, basic statistical techniques were applied to describe the behavior of the data collected. And the water quality indices CWQI, WQI, NP, HPI, HEI, DC, PERI ecological risk; and HQ, HI, THI, CR and TCR health risks were calculated, according to the following formulas and criteria of affectation:

2.3 Canadian Water Quality Index (CWQI)

“The Canadian Water Quality Index (CWQI) is one of the most widely used indices and was proposed by the Canadian Council of Ministers of the Environment known as CCME-CWQI, it was developed to simplify the reporting of water quality data. It is a tool to generate summaries of quality data useful for both technicians and policymakers, as well as for the general public interested in that knowledge” [36]. “This index is based on the determination of three factors that represent scope, frequency, and amplitude. The scope (F1) defines the percentage of variables that have values outside the range of desirable levels for the use being evaluated with respect to the total number of variables considered. The frequency (F2) is found by the ratio between the number of values outside the desirable levels with respect to the total data of the variables studied. Amplitude (F3) is a measure of the deviation that exists in the data, determined by the magnitude of the excesses of each piece of data out of range when compared to its threshold” [43].

Scope: $F_1 = \frac{\#\ de\ variables\ fuera\ de\ rango}{Total\ de\ variables} * 100$

Frequency: $F_2 = \frac{\#\ de\ datos\ fuera\ de\ rango}{Total\ de\ variables} * 100$

Amplitude:

$$F_3 = \left(\frac{nse}{0.01(nse) + 0.01}\right) * 100 \quad nse = \frac{\sum Excursion}{Total\ de\ datos} \quad Excursion = \left(\frac{Valor\ excedido\ del\ rango}{rango}\right) - 1$$

$$CWQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$$

The CWQI is considered a useful tool for obtaining a comprehensive description of the water quality of a river or lake. The index summarizes the different water quality parameters from a large amount of physicochemical parameter data and element-in-water using a simple number. Five categories of water quality are presented according to the CWQI value between 95-100 Excellent, between 80-94 Good quality, between 65-79 Fair, between 45-64 Marginal and between 0-44 Poor quality [43].

Another water quality index that is considered useful for getting a complete picture of the water quality of rivers or lakes is the WQI. The index summarizes different water quality parameters converted from a large amount of data (physicochemical parameters and trace elements) into a single number. The WQI is calculated as follows:

$$WQI = \sum \left[Wi \times \left(\frac{C_i}{S_i} \right) \right] \times 100$$

where $W_i = \frac{w_i}{\sum w_i}$ which is the relative weight. w_i is the weight of each parameter according to its relative effects on drinking importance and human health. The relative weights of each parameter are: pH=4, TDS=4, Cr=5, Mn=5, Ni=1, Cu=2, Zn=1, As=5, Cd=5, Ba=2 and Pb=5; The other elements have no relative weights. $\sum w_i$ is the sum of which in this case is 39. C_i is the concentration of the element in the water sample, and S_i represents the boundary concentration of the element in the lake water. Five water quality ratings are presented according to the values of the WQI: <50 represents excellent quality, 50-100 represents good quality, 100-200 represents poor quality, 200-300 represents very poor quality, and > 300 indicates that the water is unfit for drinking.

2.4 Nemerow Pollution Index (NP)

The Nemerow Pollution Index (NP) is applied to comprehensively assess the quality of water, sediment or soil, taking into account the maximum and average values of a simple factor and can highlight the role of heavy pollutants [14,44-45]. The NP is calculated using the equation:

$$NP = \sqrt{\frac{\left(\frac{C_i}{S_i}\right)^2_{mean} + \left(\frac{C_i}{S_i}\right)^2_{max}}{2}}$$

Where:

Ci is the trace element of the water sample,

S_i is represents the permissible limit of drinking water, and $\left(\frac{C_i}{S_i}\right)^2_{mean}$ and $\left(\frac{C_i}{S_i}\right)^2_{max}$ refer to the mean and maximum values of $\left(\frac{C_i}{S_i}\right)^2$ among all trace elements.

NP is divided into five classes: clean (<0.7), still clean (0.7–1.0), low pollution (1.0–2.0), moderate pollution (2.0–3.0), and high pollution (>3.0) [14].

2.5 Heavy Metal Contamination Index (HPI)

The Heavy Metal Pollution Index (HPI) is used to assess the influence of individual heavy metals on overall water quality [39]. The grading system is an arbitrary value between 0 and 1, and the selection depends on the importance of the individual heavy metals [46-47]. The HPI is calculated by:

$$HPI = \frac{\sum_{i=1}^{n}(W_i Q_i)}{\sum_{i=1}^{n} W_i} \text{ and } Q_i = \frac{C_i}{S_i} W_i = \frac{k}{S_i}$$

Where:

n is the number of heavy metal parameters considered;
Wi is the unit weight of the i-th trace element parameter;
Qi is the subscript of the i-th trace element parameter;
Ci is the concentration of the heavy element in the water sample;
S_i represents the permissible limit of drinking water, and
k constant of proportionality. k=1 was selected for the calculation [48].

Calculated HPI values are classified into four levels of heavy element contamination: low (<15), moderate (15-30), moderate to heavy (30-100), and high (HPI>100).

2.6 Heavy Metal Evaluation Index (HEI)

"The Heavy Metal Evaluation Index (HEI) reflects water quality with respect to heavy metal concentrations [49-50]. The HEI is used to rate the combined influence of each parameter on overall water quality and are used to assess the level of pollution caused by heavy metals" [16]. The equation used for the calculation of HEI is [49]:

$$HEI = \sum_{i=1}^{n} \frac{C_i}{MAC_i}$$

Where: C_i are the current concentrations of heavy metals and MAC_i is the maximum permissible concentration of the heavy metal. The classification of surface water quality based on the HEI is low (<10), moderate (10-20), and high pollution (> 20) [51].

2.7 Degree of Contamination (DC)

The Contamination Degree Index (DC) is used to quantify the level of contamination with trace elements. The DC summarizes the combined effects of several elements considered harmful to domestic water [52]. It is determined by the following equation [50,52]:

$$DC = \sum_{i=1}^{n} C_{fi} \qquad y \qquad C_{fi} = \frac{C_i}{MAC_i} - 1$$

Where:

C_{fi} represents the contamination factor,
C_i and MAC_i are the values of the actual concentration and the maximum permissible concentration of the i-th component.

DC values are grouped into three pollution degree categories: low (<1), moderate (1-3), and high (>3) [51].

2.8 Risk Assessment

2.8.1 Ecological risk

The potential impact of trace element contamination on organisms was determined by an ecological risk assessment. The Potential Ecological Risk Index (PERI) is often used in ecological risk assessments of aquatic environments and is calculated as follows [53-54]:

$$PERI = \frac{C_i}{ALC_i}$$

Where:

C_i and ALC_i are the actual values of concentration and aquatic life, respectively. Cui et al. [53] refer to trace element ACL values. Risk levels were classified as no risk (<0.1), low risk (0.1–1), moderate risk (1–10), and high risk (>10) [54].

2.8.2 Health risk

Hazard ratios (HQs) are widely used to assess toxicity caused by trace elements in aquatic ecosystems [21, 55, 56] and the total potential non-carcinogenic risks resulting from different methods are assessed by HI [57]. Carcinogenic risks (CRs) are assessed only for elements that have carcinogenic slope factors (CSFo) [54]. Health risks are calculated separately for residential and recreational recipients (adults and children) with the following equations [57]:

Non-Carcinogenic (HQ) Risks for Residential Receptors:

$$HQ_{injection} = \frac{C_w \times IRW_{res} \times EF_{res} \times ED}{BW \times AT_{res} \times R_f D_o \times 10^3}$$

$$HQ_{dermal} = \frac{C_w \times SA \times K_p \times ET_{res} \times EV \times EF_{res} \times ED}{BW \times AT_{res} \times R_f D_o \times GIABS \times 10^6}$$

Non-Carcinogenic (HQ) Risks to Recreational Receptors:

$$HQ_{injection} = \frac{C_w \times IRW_{rec} \times EF_{rec} \times ED}{BW \times AT_{rec} \times R_f D_o \times 10^3}$$

$$HQ_{dermal} = \frac{C_w \times SA \times K_p \times ET_{rec} \times EV \times EF_{rec} \times ED}{BW \times AT_{rec} \times R_f D_o \times GIABS \times 10^6}$$

The total potential non-carcinogenic risks of all individual trace elements are assessed using the hazard index (HI). The total HI (THI) for different receptors is calculated by summing the IH at each route of exposure.

$$HI = HQ(Al) + HQ(Cr) + \cdots . + HQ(Pb) + HQ(As)$$

$$THI = HI_{injection} + HI_{dermal}$$

If HQ, HI, or THI are > 1, the effects of trace elements on human health should be considered [58].

Carcinogenic (CR) Hazards for Residential Recipients:

$$IFW_{rec} = \frac{EF_{rec} \times ED_a \times IRW_{rec-a}}{BW_a} + \frac{EF_{rec} \times ED_c \times IRW_{rec-c}}{BW_c}$$

$$CR_{injection} = \frac{C_w \times IFW_{rec} \times CSF_o}{AT \times 10^3}$$

$$ET_{event-rec} = \frac{ET_{res-a} \times ED_a + EF_{res-c} \times ED_c}{ED}$$

$$DFW_{res} = \frac{EV_a \times EF_{res} \times ED_a \times SA_a}{BW_a} + \frac{EV_c \times EF_{res} \times ED_c \times SA_c}{BW_c}$$

$$CR_{dermal} = \frac{C_w \times K_p \times 0.001 \times ET_{event-res} \times DFW_{res} \times CSF_o}{AT \times GIABS \times 10^3}$$

Carcinogenic (CR) Hazards to Recreational Recipients:

$$IFW_{res} = \frac{EF_{res} \times ED_a \times IRW_{res-a}}{BW_a} + \frac{EF_{res} \times ED_c \times IRW_{res-c}}{BW_c}$$

$$CR_{injection} = \frac{C_w \times IFW_{res} \times CSF_o}{AT \times 10^3}$$

$$ET_{event-rec} = \frac{EF_{rec-a} \times ED_a + EF_{rec-c} \times ED_c}{ED}$$

$$DFW_{rec} = \frac{EV_a \times EF_{rec} \times ED_a \times SA_a}{BW_a} + \frac{EV_c \times EF_{rec} \times ED_c \times SA_c}{BW_c}$$

$$CR_{dermal} = \frac{C_w \times K_p \times 0.001 \times ET_{event-rec} \times DFW_{rec} \times CSF_o}{AT \times GIABS \times 10^3}$$

Total cancer risk (TCR) is calculated by summing cancer risks (CR).

$$\mathrm{TCR} = CR_{injestion} + CR_{dermal}$$

According to the USEPA [59], cancer risks are classified into three levels based on CR value: negligible (<10^{-6}), acceptable (10^{-6} - 10^{-4}), and high risk (>10^{-4}). International values were used for oral reference dose (RfDo), dermal permeability constant (Kp), oral slope factor (CSFo) and gastrointestinal absorption (GIABS) for each element analyzed.

2.9 Statistical Analysis

Descriptive statistics, Pearson correlation matrix of heavy metals, and all indices were calculated using Excel 2017.

3. RESULTS AND DISCUSSION

Descriptive statistics of the physicochemical and heavy metal parameters of the water of the Lake Chapala are presented in Table 1. The temperature ranges from 17.8 to 33.0°C with an average of 23.6°C. Conductivity ranged from 576 to 1842 μS/cm and average of 950 μS/cm. Dissolved Total Solids (TDS) ranged from 286 to 1101 mg/l with an average of 645 mg/l. Turbidity ranged from 26 to 125 NTU and average 67.6 NTU. Dissolved oxygen DO range from 1.1 to 20.1 mg/l with an average of 8.99 mg/l. The water showed pH between 7.4 and 9.7 and an average alkaline of 9.1. Total alkalinity ranged from 258 to 561 mg/l with an average of 388 mg/l. Na ranged from 0 to 254 mg/l and average 123 mg/l. Sulfates ranged from 20 to 68 mg/l with an average of 51 mg/l. Chlorides ranged from 35 to 157 mg/l and average 76 mg/l. Fluorides ranged from 0.5 to 5.9 mg/L, with an average of 1.05 mg/L. Phosphorus (P) ranged from 0.21 to 1.75 mg/l and average 1.10 mg/l. Nitrate ranged from 0.1 to 1.3 mg/l with an average of 0.14 mg/l. N ranged from 0.5 to 19.8 mg/l and mean 9.20 mg/l. Al ranged from 0.01 to 4.7 mg/l with an average of 0.3 mg/l. Trace elements (including heavy metals) showed the following concentrations: As ranged from 0.0025 to 0.1080 mg/l with an average of 0.0213 mg/l, Ba ranged from 0.0026 to 0.2530 mg/l and average of 0.0848 mg/l, Cd presented values of 0.0191 mg/l, Cr presented values between 0.0670 to 0.0950 mg/l and average of 0.0810 mg/l, Fe ranged from 0.0360 to 2.7260 mg/l and average of 0.1444 mg/l, Hg ranged from 0.0011 to 0.0674 mg/l and average of 0.0035 mg/l, Mn ranged from 0.044 to 0.2740 mg/l with an average of 0.0623 mg/l, Ni ranged from 0.0023 to 0.0514 mg/l and value of 0.0163 mg/l, Pb ranged from 0.0025 to 0.10 mg/l with an average of 0.0054 mg/l, Zn ranged from 0.02 to 3.002 mg/l and average 0.0786 mg/l. The physicochemical and heavy metal parameters have increased as a function of time, since the values reported here are higher than those of De Anda and Maniak [32], Sanchez et al. [60] and CNA [61].

The distribution of concentrations showed significant spatial variation. The parameters with percentages above the CCME standard are: TDS (3111895%), Turbidity (6657%), pH (7%), F (5%), Al (5956%), As (326%), Cr (8000%), Cu (2425%), Mn (25%), Pb (438%) and Zn (162%), however, most are within NOM-001. The heavy metals Al, Cr, Pb, Zn and As are those with concentrations of more than 100% with respect to the international standard. The remaining 14 parameters are within national and international standards. Pearson's correlation analysis showed that no trace elements have positive correlations with each other. (Table 2). Variations in some heavy metals were significant, including As, Cd, Hg. Pb and Zn with larger standard deviations than the other trace elements. The results indicated the geological-chemical-physical properties of the lake and its reservoir. According to average values, heavy metals can be divided into two categories: moderately abundant elements such as Ba, Cd, and Hg; and high-abundance elements such as Al, Cr, Ni, Pb, Zn, and As. The heavy metals reported in this study are higher than those reported by De Anda and Maniak [32], Sanchez et al. [60] and CNA [61].

For De Anda and Maniak [32], Sanchez et al. [60] and CNA [61] heavy metals do not pose a risk. In the present assessment, practically all heavy metals represent a risk and are most likely the result of metal deposition processes.

The WQI and CWQI indices are assessment tools to represent the combined effects of various water quality parameters and measure the suitability of water for consumption in different activities. The WQI and CWQI values for Lake

Chapala are shown in Table 3 and Figs. 1-3. The indices were very similar in the period analyzed.

The WQI is a useful tool for managing and monitoring surface water resources, summarizing different water quality parameters converted from a large amount of data into a single number [62]. Lake Chapala WQI values ranged from 111 to 269, with an average of 178 (Table 3 and Fig. 3). The quality of the water according to the WQI was categorized as poor quality, unlike what was reported by CNA [61].

The Canadian Water Quality Index (CWQI) is the most widely used index globally as it allows water quality to be analyzed in a general way and for each specific water use. Overall CWQI values ranged from 28 to 36 in the water samples, with an average of 30 classifying it as poor-quality water. For the use of drinking water, the CQWI value presented an average of 38 with a category of poor quality. For aquatic life, the average CQWI value was 18 with poor quality category. For recreational uses, the average CQWI value was 29 with low quality category.

Table 1. Descriptive statistics of water quality parameters analyzed in Lake Chapala during the period 2010-2023

	Mean	SD	CV	Maximum	Minimum	NOM-001	CCME
Temp	23.6190	2.3242	0.098	33.0000	17.8000	35.0000	
Condl	950.1884	210.5534	0.222	1842.0000	576.0000		
TDS	644.8750	125.4245	0.194	1101.2000	286.0000	20.0000	
Turb	67.5714	22.3545	0.331	125.0000	26.0000		1
DO	8.9860	3.7915	0.422	20.1000	1.1400	100.0000	9.5
pH	9.1039	0.3366	0.037	9.7000	7.3700	45175	8.5
Alk	387.6229	63.9232	0.165	561.2800	258.0000		
Na	123.0373	31.1620	0.253	254.1000	0.0025		200
Sulphate	50.9315	10.2143	0.201	68.3929	20.0000		500
Chloride	76.2586	20.4326	0.268	157.2900	35.0000		110
Fluoride	1.0516	0.7123	0.677	5.8700	0.4900		1
P	1.1042	0.3437	0.311	1.7500	0.2110	5.0000	
Nitrate	0.1422	0.1388	0.976	1.3300	0.1000		100
N	9.1759	2.6716	0.291	19.8000	0.5000	15.0000	
Al	0.3028	0.5255	1.736	4.7300	0.0100		0.005
As	0.0213	0.0146	0.685	0.1080	0.0025	0.1000	0.005
Ba	0.0848	0.0757	0.893	0.2530	0.0026		1
Cd	0.0191	0.0000	3E-15	0.0191	0.0191	0.1000	0.005
Cr	0.0810	0.0141	0.174	0.0950	0.0670	0.5000	0.001
Cu	0.0505	0.0031	0.061	0.0740	0.0500	4.0000	0.002
Fe	0.1444	0.2555	1.77	2.7260	0.0360		0.3
Hg	0.0035	0.0107	3.043	0.0674	0.0011	0.005	0.003
Mn	0.0623	0.0262	0.421	0.2740	0.0435		0.05
Ni	0.0163	0.0092	0.564	0.0514	0.0023	2.0000	0.025
Pb	0.0054	0.0102	1.9	0.1000	0.0025	0.2000	0.001
Zn	0.0786	0.2955	3.759	3.0020	0.0200	10.0000	0.03

Table 2. Multiple correlation of heavy metals analyzed in Lake Chapala water during the period 2010-2023

	Al	*As*	*Cd*	*Cr*	*Cu*	*Hg*	*Ni*	*Pb*	*Zn*
Al the	1								
As	0.1730	1							
Cd	0.0000	7.5E-17	1						
Cr	0.0292	7.2E-02	-5.0E-15	1					
Cu	-0.0427	-3.0E-02	3.6E-14	-0.0810	1				
Hg	-0.0445	-9.4E-03	3.6E-17	-0.1641	-0.0245	1			
Ni	-0.0389	-5.4E-02	6.6E-16	-0.0419	-0.0673	0.0201	1		
Pb	-0.0310	-5.8E-02	9.8E-16	0.1733	0.0370	-0.0382	-0.0256	1	
Zn	-0.0474	2.7E-02	3.7E-16	-0.0554	0.1126	-0.0169	-0.0860	-0.0198	1

For irrigation, the average CQWI value was 50 with a marginal quality. For livestock, the average CQWI value was 77 with the fair quality. In summary, for all uses except livestock, the water quality of Lake Chapala is poor according to CWQI (Table 3 and Figs. 1 and 2).

Nemerov Contamination Indices (NP), Heavy Metal Contamination (HPI), Heavy Metal Evaluation (HEI) and Contamination Degree indices (DC) were evaluated for the following elements As, Cd, Cr, Ni, Pb, Al, Cu, Hg, Mn, Ba and Zn. The values of NP, HPI, HEI and DC of the water of the lake Chapala are shown in tables 4 and 5. The values were temporally similar throughout the period 2010-2023. However, the values indicated that the risk of heavy metals in most water samples was at a high level.

NP values take into account the maximum and average values of individual trace elements and can highlight the role of heavy contaminants [14,45]. The NP values of heavy metals were high, ranging from 3.80 to 670, depending on the NP classification criterion [14], the NP indices showed high levels of contamination. The NP values from highest to lowest were as follows: Al > Cr > Pb > Zn > Hg > As > Cd > Ni (Table 4).

The HPI index has been used to assess total trace element contamination in water samples in many studies [63-65]. The selection of HPI depends on the importance of individual heavy metals [46]. According to the HPI classification criteria [63], the HPI values for heavy metals ranged from moderate to high, with an average value of 89. The HEI and DC indices are calculated based on the integration of the maximum and maximum permissible concentrations of the element [49,52]. HEI values ranged from 9.2 to 9.3. The HEI index shows levels below the limit of 10, which indicates a low contamination status. DC values ranged from 4 to 18 with an average value of 11, described as a high degree of contamination (Table 5).

3.1 Ecological Risks

Ecological risks were assessed using the values of the PERI index of trace elements in surface waters; they are calculated by dividing the concentration of each element in the water by the ALC value. The ALC values of the trace elements analyzed are As=4.66, Cd=0.43, Cr=7.06, Ni=4.46, Pb=5.65, Hg=0.3 and Zn=25.64. The PERIs of the elements in the surface water samples from Lake Chapala are shown in Table 6. The results show that all PERI values >1, indicating a high risk for the organisms in the lake. PERI's indicate higher risk in the following order of heavy metals: Hg > Zn, > Cd, > As, > Pb > Cr > Ni; for the Al, Cu do not apply. The results show that the ecological risk posed by heavy metals in Lake Chapala is high in most water samples. More attention should be paid to all heavy metals with regard to ecological risks.

3.2 Health Risks

3.2.1 Non-carcinogenic risks

The hazard quotient method is used in health risk assessment and was developed by USEPA [58]. The total hazard quotient values for Lake Chapala are shown in Table 7. The total hazard ratios of trace water elements for residential adults and children averaged 4.00 and 5.7, respectively (Table 7). Risk ratios for adults and children were above the threshold of 1.0, suggesting that non-carcinogenic risks for adults and children are high. The total hazard ratios of trace water elements for adults and children for recreational use had average values of 0.68 and 1.01, respectively, which does not represent a risk (Table 7). Non-carcinogenic risks for adults and residential children were 3.58 and 5.21 by ingestion of water and 0.43 and 0.49 for dermal contact, while the non-carcinogenic risks for recreational adults and children were 0.0790 and 0.3092 for water ingestion; and 0.6032 and 0.7013 for dermal contact (Table 7).

These results revealed that recreational receptors via water ingestion were less sensitive than residential receptors. In addition, the adverse effect via water ingestion on residents' health was greater than that of the dermal contact route. Notably, the non-carcinogenic risks to ingestion and dermal contact routes for residential and recreational adults were lower than for residential and recreational children, indicating that children were more sensitive than adults when exposed to trace elements in surface water, which is consistent with the results of other studies [11,66]. In terms of the route of exposure to water ingestion, Cr was the element with the highest risk ratios for residential and recreational receptors. The highest order of exposure by the route of ingestion is as follows: Cr > Pb > Zn > Hg > As > Cd > Ni > Cu > Al. Thus, the water of Lake Chapala is not suitable for drinking, so it represents a high health risk via ingestion. In terms of dermal exposure pathway, Cr was also the element with the highest hazard ratios for residential and recreational receptors. The highest order of dermal exposure is as follows: Cr > As > Ni > Cu > Pb > Al > Zn. Thus, the lake water is suitable for dermal contact for both residential and recreational use in both adults and children, so they do not pose a health risk by contact.

In both children and adults, the heavy metals with the highest hazard ratios for residential and recreational receptors are Cr, As, Ni, and Cu, while Pb, Al, and Zn contributed the least to hazard ratios for both ingestion and contact.

3.3 Carcinogenic Risks

The carcinogenic risk (CR) values are shown in Table 8. As and Cr, which have carcinogenic slope factor, are the two elements that were used to evaluate CR and CRT. The total CRT of As and Cr for residential receptors presented values of 5.53×10^{-8} and 2.10×10^{-7} respectively, while for recreational receptors it presented values of 2.22×10^{-6} for As and 8.45×10^{-6} for Cr. Consequently, according to the indicators, these do not represent high risks for residential and recreational receptors.

Analyzing the CR values of Cr by routes of ingestion and dermal contact for residential and recreational receptors, these were lower than the target risk of 1×10^{-4} (Table 8); likewise, the values of As via ingestion and dermal contact for residents were lower than the target risk (Table 8). CR by ingestion was the predominant contributor to total CRT and the dermal route was the least contributor to total CRT. The results indicate that As would not pose a carcinogenic risk to residents and recreators in different surface waters, while Cr may pose a slight carcinogenic risk to recreational receptors.

Perhaps one of the consequences of the increase in poor water quality and ecological and human health risks is due to the change in land use that the Lake Chapala basin has experienced in recent decades. Due to the increased demand for water due to the growth of the GMA in the present century and anthropogenic pollution; Heavy metals are a concern because along with the average pH > 9; It puts agricultural production at risk and enables the transfer of heavy metals via food.

Table 3. Canadian Water Quality Index (CWQI) for Lake Chapala by year and over the entire period 2010-2023

Year	CWQI	Category	WQI	Category
2010	29	Poor	136	Poor Quality
2011	30	Poor	197	Poor Quality
2012	28	Poor	185	Poor Quality
2013	32	Poor	142	Poor Quality
2014	30	Poor	118	Poor Quality
2015	31	Poor	116	Poor Quality
2016	31	Poor	143	Poor Quality
2017	28	Poor	219	Very Bad Quality
2018	29	Poor	227	Very Bad Quality
2019	28	Poor	209	Very Bad Quality
2020	32	Poor	269	Very Bad Quality
2021	24	Poor	213	Very Bad Quality
2022	31	Poor	195	Poor Quality
2023	36	Poor	186	Poor Quality
2010-2023	29.9285714	Poor	182	Poor Quality
Mean	29.9285714	Poor	182.38384	Poor Quality
SD	2.63124864		43.7563495	
Max	36		268.78374	
Min	24		115.671537	

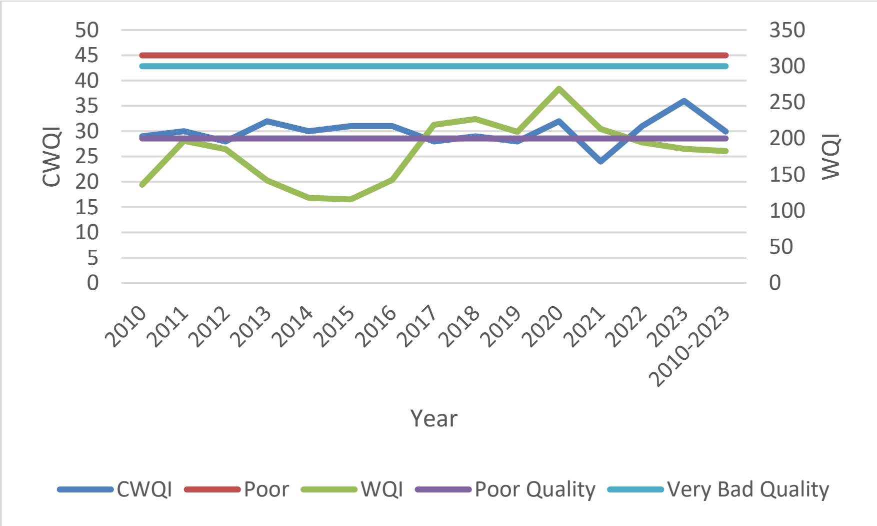

Fig. 1. Canadian Water Quality Index (CWQI) and Lake Chapala WQI Index by year and over the entire period 2010-2023

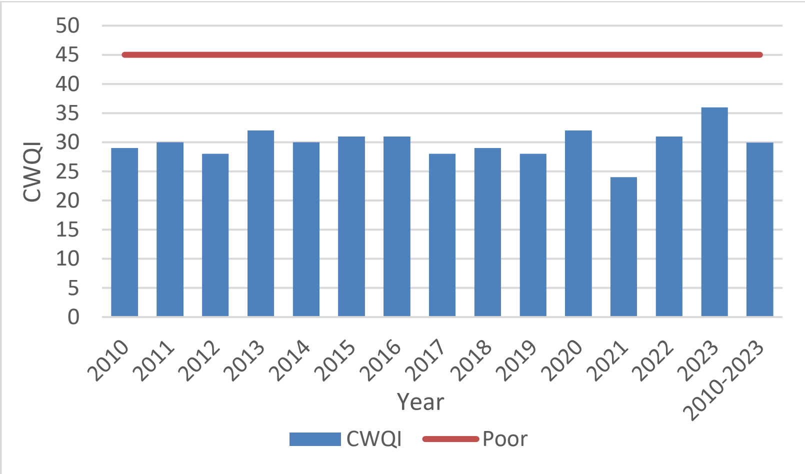

Fig. 2. Canadian Overall Water Quality Index (CWQI) for Lake Chapala by year and over the entire period 2010-2023

Fig. 3. Water Quality Index (WQI) of Lake Chapala by year and over the entire period 2010-2023

Table 4. Nemerow pollution index (NP) of Lake Chapala during the period 2010-2023

	Turb	PH	Na	SO_4^{2-}	Cl^-	F^-	NO_3^-	Al	As	Ba	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	TDS
NP	100.5	1.1	1.0	0.12	1.1	4.2	0.01	670	16	0.19	3.8	88.3	31.7	6.4	15.9	4.0	1.5	70.8	70.8	0.9

Table 5. HPI, HEI and DC pollution indices of Lake Chapala during the period 2010-2023

	Mean	Max
HPI	89	88
HEI	9	9
DC	4	18

Table 6. Ecological risk index of Lake Chapala by year during the period 2019-2023

	As	Cd	Cr	Ni	Pb	Al	Cu	Hg	Zn
PERI	23.18	44.42	13.46	11.52	17.70	NA	NA	333.33	117.08

Table 7. Non-carcinogenic risk index for residential and recreational residents (adults and children) of Lake Chapala water during the period 2010-2023

Non-Carcinogenic Risks	HI Ingestion		HI Dermal		THI	
	Adults	Children's	Adults	Children's	Adults	Children's
Residential	3.5786	5.2104	0.4276	0.4919	4.0062	5.7023
Recreational	0.0790	0.3092	0.6032	0.7013	0.6822	1.0105

Table 8. Carcinogenic risk index in residential and recreational residents of Lake Chapala water during the period 2010-2023

Carcinogenic Risks	As			Cr		
	CRIngestion	CRDermal	TCR	CRIngestion	CRDermal	TCR
Residential	$4.69x10^{-8}$	$8.39x10^{-9}$	$5.53x10^{-8}$	$1.78 x10^{-7}$	$3.19 x10^{-8}$	$2.10 x10^{-7}$
Recreational	$1.57x10^{-6}$	$6.51x10^{-7}$	$2.22X10^{-6}$	$5.98 x10^{-6}$	$2.48 x10^{-6}$	$8.45 x10^{-6}$

Discharges of poorly treated wastewater and the lack of measures to control runoff from agricultural areas result in a visible and consequential detriment of the physicochemical characteristics and increase in heavy metal pollution of the water and the loss of several of its potential uses as a reserve area for aquatic and terrestrial species. It also puts agriculture and human health at risk due to ingestion and dermal contact with the waters of Lake Chapala. Likewise, the health problems (kidney diseases, brain damage, cancer and malformations) that affect children and young people from the indigenous communities of the lakeshore could be the result of high levels of pollution, mainly by heavy metals, however, epidemiological studies are needed to be able to affirm that the diseases are associated with the direct consumption of water from the lake, nearby wells, and polluted hot springs.

4. CONCLUSION

The main conclusions are:

- ✓ The distribution of concentrations showed significant spatial variation. The parameters with percentages above the CCME standard are: TDS (3111895%), Turbidity (6657%), pH (7%), F (5%), Al (5956%), As (326%), Cr (8000%), Cu (2425%), Mn (25%), Pb (438%) and Zn (162%), however, most are within NOM-001.
- ✓ Pearson's correlation analysis showed that no trace elements have positive correlations with each other.
- ✓ Water quality according to the WQI of 178 was categorized as poor quality, while for the CWQI for all uses except livestock it was categorized as poor (20-35).
- ✓ According to the NP index (3.80 to 670), the concentrations of heavy metals showed high levels of contamination. The HPI index (89) showed moderate to high levels of heavy metal contamination. The HEI index (9) with levels < 10 indicates a low pollution status. The DC value was 4 to 9, classified as a high degree of contamination.
- ✓ The PERI index showed that the ecological risk from heavy metals is high.
- ✓ Non-carcinogenic risk indices indicate that Lake Chapala water is not suitable for drinking, and poses a high health risk, while dermal contact does not pose a health risk to residential and recreational recipients.
- ✓ According to the water quality, ecological risk and health indices, the water quality of Lake Chapala is poor, with a high degree of contamination and represents ecological and health risks (non-carcinogenic).
- ✓ The health problems (kidney diseases, brain damage, cancer and malformations) that affect the indigenous communities of the lakeshore could be the result of high levels of pollution, mainly by heavy metals, however, epidemiological studies are needed to be able to affirm that the diseases are associated with the direct consumption of water from the lake and nearby wells.

ACKNOWLEDGEMENTS

We thank the State Water Commission of the Government of the State of Jalisco and the National Water Commission for their support of the databases of the physicochemical and heavy metal analyses of Lake Chapala.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Nichols SJ, Dyer FJ. Contribution of national bioassessment approaches for assessing ecological water security: An AUSRIVAS case study. Front. Environ. Sci. Eng. 2013;7:669–687.
2. Ahmed SS, Bali R, Khan, Hasim, Mohamed HI, Sharma SK. Improved water resource management framework for water sustainability and security. Environ. Res. 2021;201:111527.
3. Lu J, Lin Y, Wu J, Zhang C. Continental-scale spatial distribution, sources, and health risks of heavy metals in seafood: Challenge for the water-food-energy nexus sustainability in coastal regions. Environ. Sci. Pollut. Res. 2021;28:63815–63828.
4. Lu J, Wu J, Wang J. Metagenomic analysis on resistance genes in water and microplastics from a mariculture system. Front. Environ. Sci. Eng. 2022a;16(1):4.
5. Lu J, Zhang Y, Wu J, Wang J. Intervention of antimicrobial peptide usage on antimicrobial resistance in aquaculture. J. Hazard. Mater. 2022b;427:128154.

6. Singh VB, Ramanathan A, Pottakkal JG, Kumar M. Seasonal variation of the solute and suspended sediment load in Gangotri glacier meltwater, central Himalayas, India. J. Asian Earth Sci. 2014;79:224–234.
7. Aalirezaei A, Khan MSA, Kabir G, Ali SM. Prediction of water security level for achieving sustainable development objectives in Saskatchewan, Canada: Implications for resource conservation in developed economies. J. Clean. Prod. 2021;311:127521.
8. Badola N, Bahuguna A, Sasson Y, Chauhan JS. Microplastics removal strategies: A step toward finding the solution. Front. Environ. Sci. Eng. 2022;16: 7.
Available:https://doi.org/10.1007/s11783-021-1441-3.
9. He J, Charlet L. A review of arsenic presence in China drinking water. J. Hydrol. 2013;492:79–88.
10. Chowdhury S, Jafar Mazumder MA, Al-Attas O, Husain T. Heavy metals in drinking water: Occurrences, implications, and future needs in developing countries. Sci. Total Environ. 2016;569–570:476–488.
11. Xiao J, Wang L, Deng L, Jin Z. Characteristics, sources, water quality and health risk assessment of trace elements in river water and well water in the Chinese Loess Plateau. Sci. Total Environ. 2019; 650(2):2004–2012.
12. Islam ARMT, Islam HMT, Mia MU, Khan R, Habib MA, Bodrud-Doza M, Siddique MAB, Chu R. Co-distribution, possible origins, status and potential health risk of trace elements in surface water sources from six major river basins, Bangladesh. Chemosphere. 2020;249:126180.
13. Milicevic T, Relic D, Skrivanj S, Tesic Z, Popovic A. Assessment of major and trace element bioavailability in vineyard soil applying different single extraction procedures and pseudo-total digestion. Chemosphere. 2017;171:284–293.
14. Li L, Wu J, Lu J, Min X, Xu J, Yang L. Distribution, pollution, bioaccumulation, and ecological risks of trace elements in soils of the North eastern Qinghai-Tibet Plateau. Ecotoxicol. Environ. Saf. 2018; 166:345–353.
15. Li L, Wu J, Lu J, Xu J. Trace elements in Gobi soils of the northeastern Qinghai-Tibet Plateau. Chem. Ecol. 2020a;36(10): 967–981.
16. Saleem M, Iqbal J, Shah MH. Seasonal variations, risk assessment and multivariate analysis of trace metals in the freshwater reservoirs of Pakistan. Chemosphere. 2019;216:715–724.
17. Mokarram M, Pourghasemi HR, Zhang H. Predicting non-carcinogenic hazard quotients of heavy metals in pepper (*Capsicum annum L*.) utilizing electromagnetic waves. Front. Environ. Sci. Eng. 2020;14:114.
18. Carafa R, Faggiano L, Real M, Munn'e A, Ginebreda A, Guasch H, Flo M, Tirapu L, Carsten von der Ohe P. Water toxicity assessment and spatial pollution patterns identification in a Mediterranean River Basin District. Tools for water management and risk analysis. Sci. Total Environ. 2011;409:4269–4279.
19. Chanpiwat P, Sthiannopkao S. Status of metal levels and their potential sources of contamination in Southeast Asian rivers. Environ. Sci. Pollut. Res. 2014;21:220–233.
20. Canpolat O, Varol M, Okan OO, Eris KK, Ça˘glar M. A comparison of trace element concentrations in surface and deep water of the Keban Dam Lake (Turkey) and associated health risk assessment. Environ. Res. 2020;190:110012.
21. Githaiga KB, Njuguna SM, Gituru RW, Yan X. Water quality assessment, multivariate analysis and human health risks of heavy metals in eight major lakes in Kenya. J. Environ. Manag. 2021;297:113410.
22. Li D, Yu R, Chen J, Leng X, Zhao D, Jia H, An S. Ecological risk of heavy metals in lake sediments of China: A national-scale integrated analysis. J. Clean. Prod. 2022; 334:130206.
23. Ustaoglu F, Tepe Y, Tas B. Assessment of stream quality and health risk in a subtropical Turkey river system: A combined approach using statistical analysis and water quality index. Ecol. Indic. 2020;113:105815.
24. Cotler H, Mazari-Hiriart M, De Anda-Sánchez J. Atlas of the Lerma-Chapala Basin: Building a Joint Vision. National Institute of Ecology/UNAM. Mexico. 2006;210.
25. Delimitación De Las Zonas Metropolitanas De México (PDF). Instituto Nacional De Estadística Y Geografía. Consultado el 8 de agosto De 2008. 2005;182.
26. Área Metropolitana De Guadalajara (PDF). Delimitación De Las Zonas Metropolitanas

De México. Instituto Nacional De Estadística Y Geografía. P. 2. Consultado el 18 de agosto De; 2008.
27. Lewis WM. Basis for the protection and management of tropical lakes. Lake's reserve. Res. Manag. 2000;5:35–48.
28. Arfi R, Bouvy M, Cecchi P, Pagnao M, Thomas S. Factors limiting phytoplankton productivity in 49 shallow reservoirs of north Côte D'Ivoire (West Africa). Aquat. Ecosyst. Health Manag. 2001;4:123-138.
29. Settacharnwit S, Buckney RT, Lim RP. The nutrient status of nongang, a shallow tropical lake in North-Eastern Thailand: Spatial and temporal variations. Lake's reserve. Res. Manag. 2003;8:189–200.
30. Romo S, Miracle MR, Villena MJ, Rueda J, Ferriol C, Vicente E. Mesocosm experiments on nutrient and fish effects on shallow lake food webs in a Mediterranean climate. Freshwater biol. 2004;49:1593–1607.
31. Wu SK, Xie P, Liang GD, Wang SB, Liang XM. Relationships between microcystins and environmental parameters in 30 subtropical shallow lakes along the Yangtze River, China. Freshwater Biol. 2006;51:2309-2319.
32. De Anda, José, Maniak, Ulrich. Modificaciones En El Régimen Hidrológico Y Sus Efectos En La Acumulación De Fósforo Y Fosfatos En El Lago De Chapala, México. Interciencia. 2007;32(2): 100-107. Recuperado En 12 de abril De 2024, De
Available:http://Ve.Scielo.Org/Scielo.Php?Script =Sci_ Arttext&Pid=S037818442007000200007& Lng=Es&Tlng=Es
33. Shear H, De Anda J. Phosphorus and eutrophication in a Sub-Tropical Basin: Lake Chapala-Mexico. In Reddy Mv (Ed.) Restoration and Management of tropical eutrophic lakes. Science Publishers. USA. Pp. 2005;77-95.
34. Limón JG, Lind OT, Vodopich DS, Doyle R, Trotter BG. Long- and short-term variation in the physical and chemical limnology of a large, shallow, turbid tropical lake (Lake Chapala, Mexico). Arch. Hydrobiol. 1989;83:57-81.
35. De Anda J, Shear H, Maniak U, Riedel G. Phosphates in Lake Chapala, Mexico. Lakes Reserve. Res. Manag. 2001;6:313-321.
36. Mora-Navarro MR. Fitoplancton Del Lago De Chapala, Jalisco, México. Tesis. Universidad De Guadalajara. México. 2001;87.
37. Chorus I (Ed.) Cyanotoxins - Occurrence, Causes, Consequences, Springer. New York, USA. 2001;357.
38. DOF NOM-001-SEMARNAT-2021 Norma Oficial Mexicana NOM-001-SEMARNAT-2021, que establece los límites permisibles de contaminantes en las descargas de aguas residuales en cuerpos receptores propiedad de la nación. Declaratoria de vigencia publicada en el Diario Oficial de la Federación el 11 de marzo de; 2022
39. CCME. Water Quality Guidelines for the Protection of Aquatic Life Freshwater, Marine. Canadian Environmental Quality Guidelines. Canadian Council of Ministers of the Environment; 2003.
Available:https://ccme.ca/en/resources/water-aquatic-life
40. CCME. Water Quality Guidelines for the Protection of Agriculture Irrigation, Livestock of the Canadian Environmental Quality Guidelines. Canadian Environmental Quality Guidelines. Canadian Council of Ministers of the Environment; 2003.
Available:https://ccme.ca/en/resources/water-aquatic-life
41. CNA Normas Mexicanas Vigentes del Sector Hídrico. Comisión Nacional del Agua. V
Available:https://www.gob.mx/conagua/acciones-y-programas/normas-mexicanas-83266. 2016.Consultado 20 sept 2023
42. AWWA. Standard methods for the examination of water and wastewater (23rd ed.). In Rice EW, Baird RB, Eaton AD. (Eds.), American Public Health Association, American Water Works Association, Water Environment Federation; 2017.
ISBN: 9780875532875
43. Canada, Department of Environment and Conservation, Government of Newfoundland and Labrador: Site Specific Water Quality Index 1.0 calculator [WQI(SS) 1.0], Canada; 2005.
Available:http://www.env.gov.nl.ca/env/waterres/quality/background/wqi(ss).xls
[Accessed: 25 July 2023]
44. Karunanidhi D, Aravinthasamy P, Subramani T, Chandrajith R, Janardhana Raju N, Antunes, IMHR. Provincial and seasonal influences on heavy metals in the Noyyal River of South India and their

human health hazards. Environ. Res. 2022;204:111998.
45. Mahmudul H, Mahfujur R, Alif A, Md Atikul I, Mahfuzur R. Heavy metal pollution and ecological risk assessment in the surface water from a marine protected area, Swatch of No Ground, North-Western part of the Bay of Bengal. Reg. Stud. Sea. Sci. 2022;52:102278.
46. Mohan SV, Nithila P, Reddy SJ. Estimation of heavy metal in drinking water and development of heavy metal pollution index. J. Environ. Sci. Health Part A Environ. Sci. Eng. 1996;31(2):283–289.
47. Reddy SJ. Encyclopedia of environmental pollution and control. Environ. Media, Karela, India. 1995;1:342.
48. Wanda EMM, Gulula LC, Phiri G. Determination of characteristics and drinking water quality index in Mzuzu City, Northern Malawi. Phys. Chem. Earth. 2012;50–52:92–97.
49. Edet AE, Offiong OE. Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo-Odukpani area, Lower Cross River Basin (southeastern Nigeria). Geo Journal. 2002;57:295–304.
50. Prabakaran K, Eswaramoorthi S, Nagarajan R, Anandkumar A, Franco MF. Geochemical behavior and risk assessment of trace elements in a tropical river, Northwest Borneo. Chemosphere. 2020;252:126430.
51. Prasanna MV, Praveena SM, Chidambaram S, Nagarajan R, Elayaraja A. Evaluation of water quality pollution indices for heavy metal contamination monitoring: A case study from Curtin Lake, Miri City, East Malaysia. Environ. Earth. Sci. 2012;67:1987–2001.
52. Backman B, Bodis D, Lahermo P, Rapant S, Tarvainen T. Application of a groundwater contamination index in Finland and Slovakia. Environ. Geol. 1997; 36:55–64.
53. Cui L, Wang X, Li J, Gao X, Zhang J, Liu Z. Ecological and health risk assessments and water quality criteria of heavy metals in the Haihe River. Environ. Pollut. 2021;290:117971.
54. Gao XY, Wang XN, Li J, Ai SH, Fu XL, Fan B, Li WW, Liu ZT. Aquatic life criteria derivation and ecological risk assessment of DEET in China. Ecotoxicol. Environ. Saf. 2020;188:109881.
55. Carvalho VSD0, Santos IFD, Almeida LC, Souza CTD, Júnior JBDS, Souza LA, Santos LOD, Ferreira SLC. Spatio-temporal assessment, sources and health risks of water pollutants at trace levels in public supply river using multivariate statistical techniques. Chemosphere. 2021; 282:130942.
56. Ozgür C, Memet V, Özlem ÖO, Kürsad KE, Metin Ç. A comparison of trace element concentrations in surface and deep water of the Keban Dam Lake (Turkey) and associated health risk assessment. Environ. Res. 2020;190: 110012.
57. USEPA. Regional Screening Level (RSL) Summary Table (TR=1E-06 THQ=1.0); 2018b. Available:https://semspub.epa.gov/work/HQ/197414.pdf. (Accessed 20 September 2023).
58. USEPA. Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment) Final; 2004. OSWER 9285.7-02EP, July 2004
59. USEPA. Human health evaluation manual, supplemental guidance: Standard default exposure factors; 1991.OSWER Directive 9285.6-03.
60. Sánchez-Torres JD, Nuño-Sánchez SA, Martínez-Alvarado JCY, Ruiz-Cruz R. Reporte de análisis de datos de calidad del agua del Lago de Chapala. Departamento de Matemáticas y Física. Tlaquepaque, Jalisco: ITESO; 2018. Available:http://hdl.handle.net/11117/5614. Accessed 17 Apr 2024
61. CNA. Diagnóstico De Calidad Del Agua Superficial Y Subterránea En El Lago De Chapala, Jalisco Subdirección General Técnica Gerencia De Calidad Del Agua. Available:https://Files.Conagua.Gob.Mx/Conagua/Generico/Calidad_Del_Agua/Diagnostico_Lago_Chapala_2012-2018.Pdf. Accessed 17 Apr 2024
62. Tiwari TN, Mishra M. A preliminary assignment of water quality index of major Indian rivers. Indian J. Environ. Prot. 1985;5(4):276–279.
63. Qiao J, Zhu Y, Jia X, Shao M, Niu X, Liu J. Distributions of arsenic and other heavy metals, and health risk assessments for groundwater in the Guanzhong Plain region of China. Environ. Res. 2020;181: 108957.

64. Rajkumar H, Naik PK, Rishi MS. A new indexing approach for evaluating heavy metal contamination in groundwater. Chemosphere. 2020;245:125598.
65. Siegel FR. Environmental Geochemistry of Potentially Toxic Metals; 2002.
66. Li Y, Chen H, Teng Y. Source apportionment and source-oriented risk assessment of heavy metals in the sediments of an urban river-lake system. Sci. Total Environ. 2020b;737: 140310.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/116532