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Evaluation of Water Quality and the Potential Ecological and Health Risk in the Cajititlán Lagoon

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Water security threatens the world's population, so the evaluation of the water quality of water bodies is one of the critical issues and is a current challenge to ensure the sustainability of ecosystems and human population.

Objective: The aim is to estimate the physicochemical parameters and heavy metals of the water of the Cajititlán Lagoon during the period 2009-2023, to evaluate its water quality, ecological and health risks. The results will supply valuable information on water quality management and human health protection.

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Study Design: Ecological study, using water quality, pollution, ecological and health risk indices.
Place and Duration of the Study: Cajititlán Lagoon during the period 2009-2023.
Methodology: The water quality data of Lagoon Cajititlán were obtained through the State Water Commission of the government of the State of Jalisco. The analyses were performed monthly from 2009 to 2023. CWQI, WQI, NP, HPI, HEI, DC, PERI, HQ, HI, THI, CR and TCR indices were then calculated to find water quality and ecological and health risks.
Results: The distribution of parameter concentration showed a drastic spatial variation, but not temporal. The TDS, Turbidity, pH, F, Al, As, Cr, Cu, Mn, Ni, Pb and Zn showed percentages above the CCME regulations, however most are within the NOM-001-SEMARNAT-2021. The heavy metals Al, Cr, Ni, Pb, Zn and As are those that present the % concentration 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 most heavy metals have positive correlations with each other, except for Cr, Pb and Cu. Water quality according to WQI of 112 was categorized as poor-quality, while for CWQI all uses except livestock, water quality is poor (20-35). According to the NP index (0.19 to 670), heavy metal concentrations showed high contamination levels. The HPI index (89) showed moderate to elevated levels of heavy metal contamination. The HEI index showed levels <10, showing low pollution. The DC presented a value of 4, classified as a high degree of contamination. The PERI index showed that the ecological risk from heavy metals is high. Non-carcinogenic risk indices show that lagoon water is not suitable for drinking, and poses a high health risk via ingestion, while dermal contact poses no health risk to residential and recreational recipients. The results say that As would not pose a carcinogenic risk to residents and recreational receptors in different surface waters, while Cr may pose a slight carcinogenic risk to recreational receptors.
Conclusions: According to the indices of water quality, ecological risk and health, the water quality of the Cajititlán Lagoon is poor, with a high degree of contamination and stands for ecological and health risks (non-carcinogenic).

Keywords: Water quality; ecological risks; health risks; Cajititlán Lagoon.

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 extremely 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 evaluation of the water quality of water bodies is one of the critical issues and that represent a current challenge, to ensure the sustainability of ecosystems and the human population [9-12].

The physicochemical, microbiological and trace element parameters of water are the most used indicators to find 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 metal contamination [12,18-19]. Heavy metal contamination in freshwater bodies has been a global concern in recent years [16,20-22], so contaminated water can make it unsuitable for a wide variety of activities such as human consumption, development of aquatic life, recreation, irrigation, livestock, among others. The accumulation of heavy metals in water can cause adverse health effects on aquatic organisms and humans [11,23-24]. Multiple investigations have been conducted on water quality, health and ecosystem risk assessment; The identification of sources of heavy metals in well water, rivers, shallow groundwater, lakes and drinking water in the world. However, human activities have increased in recent years, which has caused a potential threat to the sustainable development and ecological security of water bodies. Most previous studies have focused on large rivers and lakes; however, few studies have focused on small shallow lakes, therefore, it is important to study water quality and the presence of heavy metals in lakes that are related to activities such as consumption, aquatic life, recreation, irrigation, livestock, among others, regardless of its dimensions [24].

In this study, the analyses of the physicochemical parameters and heavy metals of the water of the Cajititlán Lagoon were collected and analyzed during the period 2009-2023, to evaluate the quality of water and the ecological and human health risks they represent. These results can supply valuable insights into water quality management and human health protection.

1.1 Background

Lagoon Cajititlán is classified as an endorheic lagoon of small dimensions, with a largest axial length of 10.4 km and a maximum width of 3.2 km, with an average surface area of 17.44 km^2, maximum depth of 3.87 m and an average storage volume of 70.89 Hm^3. It is located in the municipality of Tlajomulco de Zúñiga in the state of Jalisco, Mexico at 1551 m.a.s.l. between coordinates 20° 26′ 13" and 20° 24′ 08" north latitude and 103° 22′ 31" and 103°17′00" west longitude (Fig. 1). Rainwater, intermittent and perennial streams, and sewage discharges are the main water inputs to the lagoon. The main water outlets of the lagoon are evaporation and extractions to supply water for irrigation [25-27]. It is considered a subtropical lagoon, located in a closed basin surrounded by small hills with an extension of approximately 201.8 km^2. Because it has shallow characteristics and in a closed basin with rapid population growth, the lagoon's water has suffered severe anthropogenic pollution causing damage to its intrinsic aesthetic, social, environmental, and economic values [25,28].

The main economic activities within the lagoon basin are agriculture and fishery. The agricultural land is rainfed, and fertilizers are used in the field only during the rainy season. However, traditional agricultural practices use excessive amounts of fertilizer, which is one of the main diffuse sources of nutrient pollution [28-29]. The lagoon is an important body of water for nesting local and migratory waterfowl, and a large belt of wetlands has been created that grows along the shore of the lagoon, and constitutes an important nesting habitat for several species of waterfowl, but also functions as a natural barrier that intercepts excess nutrients and other agricultural pollutants in runoff to the lagoon during the storm.

The population of the municipality of Tlajomulco de Zúñiga has increased more than fifteen times during the period from 1970 to 2015 and almost doubled between 2000 and 2010 in the Cajititlán basin. This exorbitant growth also increased the demand for local resources, including water, for both local and external users. The main source of water supply in the municipality of Tlajomulco de Zúñiga is groundwater. In the municipality there are 140 water wells with an annual extraction of 101.47 Mm^3 which is 99.44% of the total water used. The main uses of water are agriculture (47.28%), municipal services (27.60%), urban public supply (18.79%), industry (4.79%) and domestic use (1.03%). Livestock activities consume only 0.51% of the total. The use of surface water provided by Cajititlán Lagoon is mainly for agricultural purposes and has minimal impact compared to the volume of groundwater used in the municipality [30].

Water quality is a concern in Lagoon Cajititlán due to direct discharges of raw and partially treated wastewater from settlements located along its banks and from housing developments located within its basin. As a result of wastewater pollution, the water has undergone major changes in its chemical, physical and biological characteristics, causing algal blooms, increased water turbidity and various pollutants and in recent years, the massive death of endemic and commercial fish species during the summer [31].

The lagoon is important because it is the largest body of surface water located within the Guadalajara Metropolitan Area, which is the second largest city in Mexico. An increase in the population of the lagoon basin and a rapid urbanization process of the municipality are putting at risk the aesthetic, cultural, economic and environmental values of the lagoon [28].

Around the lagoon three wastewater treatment plants (WWTP) were built that discharge their treated water into it. The WWTP with the highest capacity is San Miguel Cuyutlán, with a treatment capacity of 60 l/s, followed by Cajititlán, with a treatment capacity of 12 l/s, and finally, San Juan Evangelista, with a treatment capacity of 4 l/s. Unfortunately, WWTPs have problems; Discharge water often does not meet national standards required by federal regulations. As a result, the lagoon has experienced elevated levels of eutrophication. In all three cases, the treated wastewater is discharged into the lagoon. The sewer systems of the communities around the lagoon and outside the basin do not have separation of sewage and rainwater. During the rainy season, WWTPs receive a significant excess of water with respect to their installed ability and decrease their operational efficiency. Excess sewage mixed with rainwater during the storm is discharged directly into the lagoon. In addition, the communities settled on the banks, discharge their wastewater directly without any treatment, hence the importance of evaluating the physicochemical and heavy metals, to find the quality of the lagoon water, the ecological and health risks when its waters are used.

2. MATERIALS AND METHODS

The water quality data of Lagoon Cajititlán were obtained through the State Water Commission (CEA) of the government of the State of Jalisco. The data supplied includes monthly monitoring from 2009 to 2023. The data supplied includes the following parameters: temperature, 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 in national water bodies [32] and the limits of the Canadian water quality guidelines: Water Quality Guidelines for the Protection of Aquatic Life Freshwater, Marine [33] and Water Quality Guidelines for the Protection of Agriculture Irrigation, Livestock of the Canadian Environmental Quality Guidelines [34].

The lagoon water samples were made according to international water sampling standards. The samples were transferred to the laboratory of the CEA of the state of Jalisco which has an accredited laboratory to perform water quality analysis following the regulations approved in Mexico by the National Water Commission, which in turn are based on internationally approved protocols [35-36].

With the results of the parameters analyzed during the period 2009-2023, basic statistical techniques were applied to describe the behavior of the data collected. And the water quality indices CWQI, WQI, NP, HPI, HEI, DC, ecological risk PERI, and health risks HQ, HI, THI, CR and TCR were calculated, according to the following formulas and criteria of affectation:

2.1 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

Fig. 1. Lagoon Cajititlán Basin (Courtesy of Google Earth, 2023)

quality data. It is a tool for generating summaries of quality data useful for both technicians and policymakers, as well as for the public interested in that knowledge [37]. This index is based on the determination of three factors being 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 variables considered. The frequency (F2) is found by the relationship between the number of values outside the desirable levels with respect to the total data of the variables studied. While amplitude is a measure of the deviation that exists in the data, found by the size of the excesses of each data out of range when compared with its threshold [37].

Scope: $F_1 = \frac{\#\, de\ variables\ fuera\ de\ rango}{Total\ de\ variables} * 100$ (1)

Frequency: $F_2 = \frac{\#\, de\ datos\ fuera\ de\ rango}{Total\ de\ variables} * 100$ (2)

Amplitud: $F_3 = \left(\frac{nse}{0.01(nse)+0.01}\right) * 100 \quad nse = \frac{\sum Excursion}{Total\ de\ datos} \quad Excursion = \left(\frac{Valor\ excedido\ del\ rango}{rango}\right) - 1$ (3)

And

$$CWQI = 100 - \frac{\sqrt{F_1^2+F_2^2+F_3^2}}{1.732} \quad (4)$$

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 of a large amount of physicochemical parameter data and elements in water using a simple number. Five categories of water quality are presented according to 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 [37].

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 [24]:

$$WQI = \sum \left[Wi \times \left(\frac{C_i}{S_i}\right)\right] \times 100 \quad (5)$$

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 the importance of drinking 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 w_i which for this case is 39. C_i is the concentration of the element in the water sample, and S_i is the boundary concentration of the element in the lake water [24]. Five water quality ratings are presented according to the values of WQI: <50 is 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 unsuitable for drinking [24].

2.2 Nemerow Pollution Index (NP)

The Nemerow Pollution Index (NP) is applied to comprehensively assess water, sediment, or soil quality, considering maximum and average values of a simple factor and can highlight the role of heavy pollutants [14,38-39]. The NP is calculated using the equation:

$$NP = \sqrt{\frac{\left(\frac{C_i}{S_i}\right)^2_{mean} + \left(\frac{C_i}{S_i}\right)^2_{max}}{2}} \quad (6)$$

Where:

C_i is the trace element of the water sample,
S_i is 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) [24].

2.3 Heavy Metal Contamination Index (HPI)

The Heavy Metal Contamination Index (HPI) is used to assess the influence of individual heavy metals on overall water quality [40]. The rating system is an arbitrary value between 0 and 1, and choice depends on the importance of individual heavy metals [39-41]. HPI is calculated by [24]:

$$HPI = \frac{\sum_{i=1}^{n}(W_i Q_i)}{\sum_{i=1}^{n} W_i} \quad (7)$$

$$Q_i = \frac{C_i}{S_i} \times 100 \quad \text{and} \quad W_i = \frac{k}{S_i} \quad (8)$$

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 of the water sample;
Si is the permissible limit of drinking water and
k constant of proportionality. k=1 was selected for the calculation [42].

The calculated HPI values are classified into three levels of heavy element contamination: low (<15), moderate (15-30), moderate to heavy (30-100), and high (I>100) [24].

2.4 Heavy Metals Evaluation Index (HEI)

The Heavy Metal Evaluation Index (HEI) reflects water quality with respect to heavy metal concentrations [24,43-44]. The HEI is used to rate the combined influence of each parameter on overall water quality and are used to assess the level of contamination caused by heavy metals [16]. The equation used for the calculation of HEI is [24,43]:

$$HEI = \sum_{i=1}^{n} \frac{C_i}{MAC_i} \quad (9)$$

where C_i are the current concentrations of heavy metals and MAC_i is the maximum permissible concentration of the heavy metal. The HEI-based surface water quality rating is low (<10), moderate (10-20), and high contamination (> 20) [24,45].

2.5 Degree of Contamination (DC)

The degree of contamination (DC) index is used to quantify the pollution level with trace elements. The DC summarizes the combined effects of several elements considered harmful to domestic water. It is found by the following equation [24,44,46]:

$$DC = \sum_{i=1}^{n} C_{fi} \quad (10)$$

$$C_{fi} = \frac{C_i}{MAC_i} - 1 \quad (11)$$

Where:

C_{fi} is the pollution factor,
C_i and MAC_i are the values of the actual concentration and the maximum permissible concentration of the ith component.
DC values are grouped into three categories of degree of contamination: low (<1), moderate (1-3) and high (>3) [24,45].

2.6 Risk Assessment

2.6.1 Ecological risk

The potential impact of trace element contamination on organisms was found 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 [47-48]:

$$PERI = \frac{C_i}{ALC_i} \quad (12)$$

Where:

C_i and ALC_i are the actual values of concentration and aquatic life criterion, respectively. Cui et al. [47] refer to ALC values of trace elements. Risk levels were classified as: no risk (<0.1), low risk (0.1–1), moderate risk (1–10), and high risk (>10) [24,48].

2.6.2 Health risk

Hazard quotients (HQs) are widely used to assess the toxicity caused by trace elements in aquatic ecosystems [21,49-50] and the total potential non-carcinogenic risks resulting from different methods are assessed by HI [51]. The Carcinogenic risks (CRs) are assessed only for trace elements having carcinogenic slope factors (CSFo) [48]. Health risks are separately calculated for residential and recreational receptors (adults and children) using the following equations [24,51]:

Non-carcinogenic risks (HQ) for residential receptors:

$$HQ_{injection} = \frac{C_w \times IRW_{res} \times EF_{res} \times ED}{BW \times AT_{res} \times R_f D_o \times 10^3} \quad (13)$$

$$HQ_{dermal} = \frac{C_w \times SA \times K_p \times ET_{res} \times EV \times EF_{res} \times ED}{BW \times AT_{res} \times R_f D_o \times GIABS \times 10^6} \quad (14)$$

Non-carcinogenic risks (HQ) for recreational receptors:

$$HQ_{injection} = \frac{C_w \times IRW_{rec} \times EF_{rec} \times ED}{BW \times AT_{rec} \times R_f D_o \times 10^3} \quad (15)$$

$$HQ_{dermal} = \frac{C_w \times SA \times K_p \times ET_{rec} \times EV \times EF_{rec} \times ED}{BW \times AT_{rec} \times R_f D_o \times GIABS \times 10^6} \quad (16)$$

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 adding the HI in each route of exposure.

$$HI = HQ(Al) + HQ(Cr) + \cdots . + HQ(Pb) + HQ(As) \quad (17)$$

$$THI = HI_{injection} + HI_{dermal} \quad (18)$$

If the HQ, HI or THI are > 1, the effects of the trace elements on human health should be considered [24,52].

Carcinogenic risks (CR) for residential receptors:

$$IFW_{rec} = \frac{EF_{rec} \times ED_a \times IRW_{rec-a}}{BW_a} + \frac{EF_{rec} \times ED_c \times IRW_{rec-c}}{BW_c} \quad (19)$$

$$CR_{injection} = \frac{C_w \times IFW_{rec} \times CSF_o}{AT \times 10^3} \quad (20)$$

$$ET_{event-rec} = \frac{ET_{res-a} \times ED_a + EF_{res-c} \times ED_c}{ED} \quad (21)$$

$$DFW_{res} = \frac{EV_a \times EF_{res} \times ED_a \times SA_a}{BW_a} + \frac{EV_c \times EF_{res} \times ED_c \times SA_c}{BW_c} \quad (22)$$

$$CR_{dermal} = \frac{C_w \times K_p \times 0.001 \times ET_{event-res} \times DFW_{res} \times CSF_o}{AT \times GIABS \times 10^3} \quad (23)$$

Carcinogenic (CR) risks for recreational receptors:

$$IFW_{res} = \frac{EF_{res} \times ED_a \times IRW_{res-a}}{BW_a} + \frac{EF_{res} \times ED_c \times IRW_{res-c}}{BW_c} \quad (24)$$

$$CR_{injection} = \frac{C_w \times IFW_{res} \times CSF_o}{AT \times 10^3} \quad (25)$$

$$ET_{event-rec} = \frac{EF_{rec-a} \times ED_a + EF_{rec-c} \times ED_c}{ED} \quad (26)$$

$$DFW_{rec} = \frac{EV_a \times EF_{rec} \times ED_a \times SA_a}{BW_a} + \frac{EV_c \times EF_{rec} \times ED_c \times SA_c}{BW_c} \quad (27)$$

$$CR_{dermal} = \frac{C_w \times K_p \times 0.001 \times ET_{event-rec} \times DFW_{rec} \times CSF_o}{AT \times GIABS \times 10^3} \quad (28)$$

Total cancer risk (TCR) is calculated by adding up cancer risks (CRs).

$$\text{TCR} = CR_{ingestion} + CR_{dermal} \quad (29)$$

According to USEPA [53], 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) values for each element analyzed.

2.7 Statistical Analysis

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

3. RESULTS AND DISCUSSION

The descriptive statistics of the physicochemical and heavy metal parameters of the water of the Cajititlán Lagoon are presented in Table 1. The temperature ranges between 15.06 and 33.00°C with an average value of 23.10°C. Conductivity ranged from 576 to 1852 µS/cm and average value of 941 µS/cm. Dissolved Total Solids (TDS) ranged from 286 to 1300 mg/L with an average value of 644 mg/L. Turbidity ranged from 20.80 to 123.47 NTU and average value of 66.99 NTU. Dissolved Oxygen did vary from 1.14 to 20.10 mg/L with an average value of 8.79 mg/L. The water showed pH between 7.37 and 9.70 and average value of 9.10. Total Alkalinity ranged from 258 to 561 mg/L with and average value of 388 mg/L. Na ranged from 0 to 254 mg/L and average value of 125 mg/L. Sulfates ranged from 2.95 to 44.59 mg/L with an average value of 10.43 mg/L. Chlorides ranged from 34.84 to 157.29 mg/L and average value of 75.46 mg/L. Fluorides ranged from 0.49 to 5.87 mg/L, with an average value of 1.05 mg/L. The P ranged from 0.21 to 1.96 mg/L and average value of 1.23 mg/L. Nitrate ranged from 0.10 to 1.33 mg/L and average value of 0.14 mg/L. The N ranged from 0.50 to 19.80 mg/L and average value of 9.20 mg/L. Al ranged from 0.01 to 4.73 mg/L and average value of 0.31 mg/L. Trace elements (including heavy metals) showed the following concentrations: The As ranged from 0.0000 to 0.2860 mg/L and average value of 0.00690 mg/L, the Ba ranged from 0.0026 to 0.2530mg/L and average value of 0.0848 mg/L, the Cd ranged from 0.0005 to 0.0183 mg/L and average value of 0.0008 mg/L, the Cr only presented values of 0.0500 mg/L, the Fe ranged between 0.0360 and 2.7260 mg/L and average value of 0.1444 mg/L, the Hg ranged between 0.0003 and 0.0500 mg/L and average value of 0.0010 mg/L, the Mn ranged between 0.0500 and 0.2740 mg/L and average value of 0.0621 mg/L, Ni ranged between 0.0005 and 0.1000 mg/L and average value of 0.0991 mg/L, Pb ranged between 0.0025 and 0.1000 mg/L with average value of 0.0054 mg/L, Zn ranged between 0.0200 and 3.0020 mg/L and average value of 0.0786 mg/L.

The concentration distribution of parameters showed drastic spatial variation. The following parameters showed percentages above the CCME regulations, however most are within NOM-001: TDS (312000%), Turbidity (6600%), pH (7.10%), OD (7.5%), F (5.2%), Al (6013%), As (37%), Cr (4900%), Cu (24%), Mn (24%), Ni (2965%), Pb (438%) and Zn (162%). The high levels of TDS, Turbidity and pH were probably associated with discharges from treatment plants that do not operate properly, runoff from the lagoon's own basin that provides a large amount of sediment, and discharges from populations established on the shore that do not have methods of treating their domestic water, and industrial processes near the lagoon. The heavy metals Al, Cr, Ni, Pb, Zn and As are those that present the % concentration 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 most heavy metals have positive correlations with each other, except for Cr, Pb, and Cu (Table 2). The results of heavy metals Al, Cr, Ni, Pb and Zn could come from industrial metal deposition processes.

Variations in some heavy metals were significant, including As, Cd, Hg and Pb which had larger standard deviation values than the other trace elements. According to the average values, heavy metals can be divided into two categories: moderately abundant such as Ba, Cd, and Hg; and of high abundance such as Al, Cr, Ni, Pb, Zn and As.

The sediment-water analysis concentrations in the Cajititlán Lagoon for the physicochemical parameters and heavy metals reported by de Anda [28] are like those reported here. However, he reports lesser amounts of dissolved Al, Fe and Mn. It also reports for Hg, Cd, As, Cu, Pb, Cr and Zn, degree of contamination and ecological risk without potential risk to aquatic biota; with water unfit for local human consumption due to bacterial and nutrient contamination factors [54-59]. The results of the present study differ since here the concentrations of heavy metals are potential risk both ecological and for human health. The differences lie in the permissible limits used for the evaluation, while de Anda [59] takes the NOM-001, here it was analyzed with the Canadian standard CMME [36].

For de Anda [28] heavy metals do not pose a risk except for Al, whose average concentration is high and proposes that dissolved Al is associated with anthropogenic pollution, since it is often found in wastewater discharges treated with Al based coagulants to reduce phosphate loads. In the present evaluation, all heavy metals are a risk and are most likely the result of metal deposition processes.

The WQI and CWQI indices are assessment tools to stand for the combined effects of various water quality parameters and measure the suitability of water for consumption in different activities. WQI and CWQI values are shown in Table 3 and Figs. 1-3. The WQI and CWQI indices were similar throughout the period analyzed.

The WQI is a useful tool for managing and monitoring surface water resources. It summarizes different water quality parameters converted from a large amount of data into a single number [54]. WQI values in the study area ranged from 56 to 190 in the water samples, with an average of 112 (Table 3 and Fig. 3). Water quality according to the WQI was categorized as poor-quality.

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 20 to 35 in water samples, with an average of 26.8 classifying it as poor-quality water. For the use of drinking water, CQWI values ranged from 38 to 62 and an average of 49.8 with poor-quality category. For the use of aquatic life, CQWI values ranged from 14 to 34 and an average of 20.1 with poor-quality category. For recreational uses, CQWI values ranged from 18 to 100 and an average of 37.3 with low quality category. For irrigation uses, CQWI values ranged from 48 to 74 and an average of 68.5 with a regular quality category. For livestock uses, CQWI values ranged from 70 to 100 and an average of 92 with good quality category. In summary, for all uses except livestock, the water quality of the Cajititlán Lagoon is poor according to this index (Table 3 and Figs. 1 and 2).

Table 1. Descriptive statistics of water quality parameters analyzed in the Cajititlán Lagoon during the period 2009-2023

	Mean	SD	CV	Maximum	Minimum	NOM-001	CCME
Temp	23.1008	2.8083	12	33.0000	15.0600	35.0000	
Condl	941.0402	217.2071	23	1842.0000	576.0000		
TDS	643.7899	121.9626	19	1030.0000	286.0000	20.0000	
Turb	66.9872	23.1338	35	123.4700	20.8000		1
DO	8.7972	3.8075	43	20.1000	1.1400	100.0000	9.5
PH	9.1039	0.3366	4	9.7000	7.3700	6-9	8.5
Alk	387.6229	63.9232	16	561.2800	258.0000		
Na	125.2329	31.2817	25	254.1000	0.0025		200
Sulphate	10.4327	3.8318	37	44.5900	2.9500		500
Chloride	75.4592	21.0334	28	157.2900	34.8400		110
Fluoride	1.0516	0.7123	68	5.8700	0.4900		1
P	1.2305	0.4028	33	1.9600	0.2110	5.0000	
Nitrate	0.1422	0.1388	98	1.3300	0.1000		100
N	9.2031	2.6867	29	19.8000	0.5000	15.0000	
Al	0.3057	0.5253	171	4.7300	0.0100		0.005
As	0.0069	0.0285	414	0.2860	0.0000	0.1000	0.005
Ba	0.0848	0.0757	89	0.2530	0.0026		1
Cd	0.0008	0.0017	211	0.0183	0.0005	0.1000	0.005
Cr	0.0500	0.0000	0	0.0500	0.0500	0.5000	0.001
Cu	0.0501	0.0057	11	0.0740	0.0005	4.0000	0.002
Fe	0.1444	0.2555	177	2.7260	0.0360		0.3
Hg	0.0010	0.0047	449	0.0500	0.0003	0.005	0.003
Mn	0.0621	0.0266	43	0.2740	0.0500		0.05
Ni	0.0991	0.0094	9	0.1000	0.0005	2.0000	0.025
Pb	0.0054	0.0102	190	0.1000	0.0025	0.2000	0.001
Zn	0.0786	0.2955	376	3.0020	0.0200	10.0000	0.03

Table 2. Pearson correlation matrix of heavy metals analyzed in the water of the Cajititlán Lagoon during the period 2009-2023 (significance level of 0.05)

	As	Cd	Cr	Ni	Pb	Al	Cu	Hg	Zn
As	1								
Cd	0.9291	1							
Cr	0.0000	-1.8E-16	1						
Ni	-0.9343	-0.9713	2.2E-14	1					
Pb	-0.0394	-0.0452	1.0E-15	0.0269	1				
Al	0.9336	0.9706	1.1E-16	-0.9989	-0.0294	1			
Cu	-0.0193	-0.0222	-5.2E-16	0.0140	0.0703	-0.0106	1		
Hg	0.9275	0.9691	3.0E-17	-0.9939	-0.0279	0.9926	-0.0160	1	
Zn	0.9339	0.9726	1.5E-16	-0.9996	-0.0274	0.9985	-0.0140	0.9938	1

The Nemerow Contamination (NP), Heavy Metal Contamination (HPI), Heavy Metal Evaluation (HEI) and Contamination Grade (DC) indices 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 Cajititlán Lagoon are shown in tables 4 and 5. The values were temporally similar throughout the period 2009-2023. NP values consider the maximum and average values of individual trace elements and can highlight the role of heavy contaminants [14,39]. The NP values of heavy metals were high, ranging from 0.19 to 670 considered as high contamination. According to the NP classification criterion [14], heavy metal indices showed high contamination levels. The NP values from highest to lowest were as follows: Al > Pb > Zn > Cr > As > Cu > Hg > Ni > Mn > Cd > Ba (Table 4).

The HPI index has been used to assess total trace element contamination in water samples in many studies [55-57]. The choice of HPI depends on the importance of individual heavy metals [40]. According to the HPI classification criterion [54], heavy metal HPI values were 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 [43,46]. HEI values ranged from 5 to 9 and mean 5. The HEI index shows levels below the limit of 10, which indicates a state of low contamination. DC values ranged from 4 to 18 with an average value of 4, described as a high degree of contamination (Table 5).

3.1 Ecological Risks

Ecological risks were assessed using PERI index values for 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 the Cajititlán lagoon are shown in Table 6. The results show that all PERI values >1, showing a high risk for lagoon organisms. The PERI's show increased risk in the following order of heavy metals Hg > Zn > As > Cd > Ni > Pb > Cr. The results show that the ecological risk posed by heavy metals in Cajititlán Lagoon is high in water. More attention should be paid to all heavy metals about ecological risks. De Anda [59] reported in the Cajititlán lagoon very high primary productivity and low ecological risks, which differs from what is reported here where ecological risks are high.

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 [52]. The total values of the hazard quotients for Cajititlán Lagoon are shown in Table 7. The total hazard ratios of trace elements for residential adults and children had mean values of 1.9838 and 2.8078, 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 0.4066 and 0.5772 respectively, which does not stand for a risk (Table 7). The non-carcinogenic risks for residential adults and children were 1.7194 and 2.5035 for water ingestion and 0.2644 and 0.3043 for dermal contact, while the non-carcinogenic risks for recreational adults and children were 0.0379 and 0.1486 for water intake; and 0.3686 and 0.4286 for dermal contact (Table 7).

These results revealed that recreational water intake receivers were less sensitive than residential receivers. In addition, the adverse effect via water ingestion on the health of residents was greater than that of the dermal contact route. Notably, non-carcinogenic risks for ingestion and dermal contact pathways for residential and recreational adults were lower than for residential and recreational children, showing that children were more sensitive than adults when exposed to trace elements in surface water, consistent with the results of other studies [11,58]. Regarding the route of exposure to water ingestion, Cr was the element with the highest risk ratios for residential and recreational recipients. The highest order of exposure by the route of ingestion is the following Cr > As > Ni > Pb > Cu > Al > Zn. Thus, the water of the Cajititlán Lagoon is not suitable for drinking, so it is a high risk to health via ingestion.

Regarding the dermal exposure route, Cr was also the element with the highest risk ratios for residential and recreational recipients. The highest order of exposure by dermal route is the following Cr > As > Ni > Cu > Pb > Al > Zn. Thus, the lagoon water is suitable for dermal contact for both residential and recreational use in both adults and children, so they do not stand for a health risk by contact. In both children and adults, heavy metals with the highest hazard ratios for residential and recreational receptors are Cr, As, Ni, and Cu, while Pb, Al, and Zn contributed less to hazard ratios by both ingestion and contact.

3.3 Carcinogenic Risks

Carcinogenic risk (CR) values are shown in Table 8. The As and Cr that 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 receivers presented values of 1.7908E-08 and 7.1968E-07 respectively, while for recreational present values of 1.2985E-07 for As and 5.2185E-06 for Cr. Consequently, according to the indicators, these do not represent high risks for residential and recreational recipients.

Analyzing the CR values of Cr by ingestion and dermal contact routes for residential and recreational recipients, these were lower than the objective risk of $1{\times}10^{-4}$ (Table 8); likewise, the values of As via ingestion and dermal contact for residents were lower than the objective risk (Table 8). CR by ingestion was the predominant contributor to total CRT and the dermal pathway contributed the least to total CRT. The results show 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.

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 Cajititlán Lagoon basin has experienced in recent decades. In 1970, the total population of the municipality of Tlajomulco de Zúñiga was 35,145, and in 50 years, the population increased 21-fold to 727,750 in 2020 [60-61]. The average annual population growth in this municipality has not significantly affected the land use of the Lagoon Cajititlán basin.

Table 3. Canadian Water Quality Index (CWQI) of the Cajititlán Lagoon by year during the period 2009-2023

Year	WQI	CWQI	Drinking	Aquatic	Recreation	Irrigation	Livestock	Category
2009	56	35	62	34	100	73	100	Poor
2010	62	24	49	18	39	73	95	Poor
2011	119	29	52	24	39	74	100	Poor
2012	108	25	51	19	18	72	94	Poor
2013	70	29	49	23	25	64	87	Poor
2014	73	28	52	23	22	72	95	Poor
2015	68	26	51	20	25	70	90	Poor
2016	117	25	44	18	22	52	70	Poor
2017	147	27	51	17	25	72	95	Poor
2018	149	26	49	17	29	72	95	Poor
2019	144	25	49	15	25	65	88	Poor
2020	190	28	47	20	100	70	92	Poor
2021	140	23	46	17	39	72	100	Poor
2022	117	28	53	20	25	74	100	Poor
2023	116	31	54	23	35	73	100	Poor
2009-2023	113	20	38	14	29	48	71	Poor
Mean	56	26.8	49.8	20.1	37.3	68.5	92	Poor
Max	190	20	38	14	18	48	70	Poor
Min	112	35	62	34	100	74	100	Poor

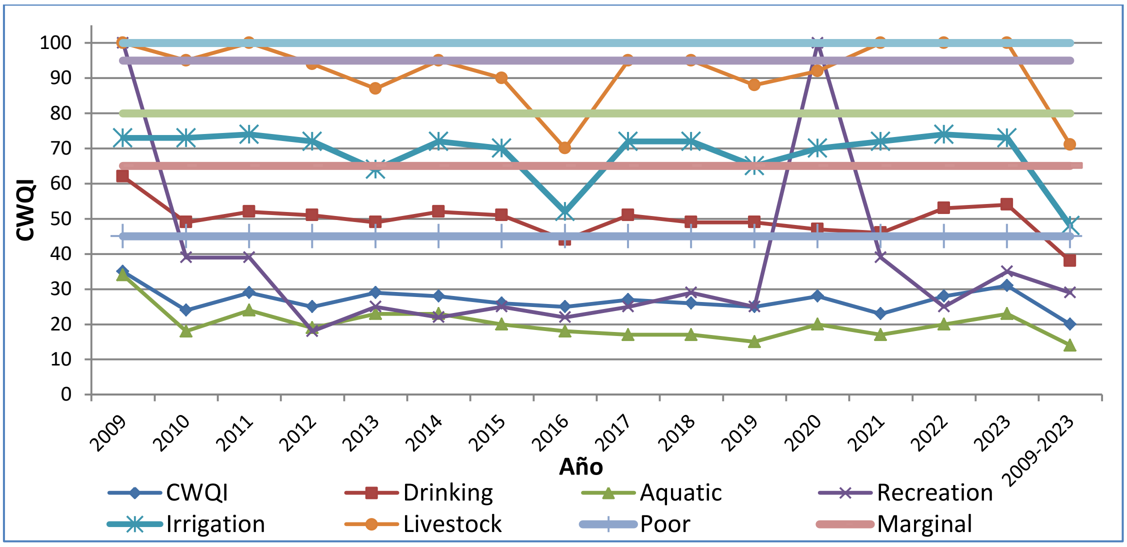

Fig. 1. Canadian Water Quality Index (CWQI) of the Cajititlán lagoon according to the different uses, by year during the period 2009-2023

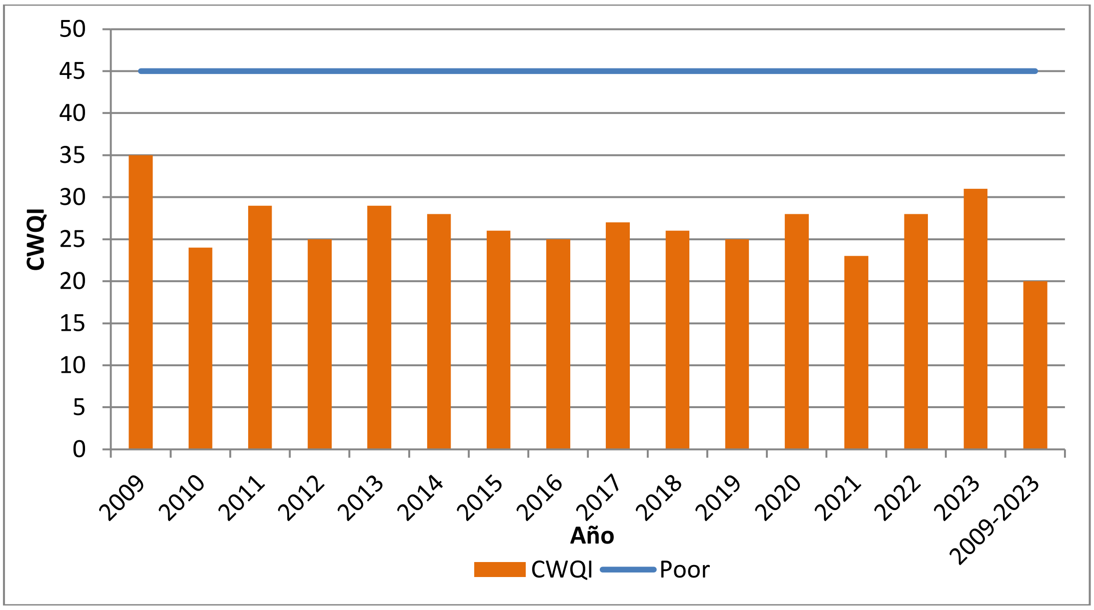

Fig. 2. Canadian General Water Quality Index (CWQI) of the Cajititlán lagoon by year during the period 2009-2023

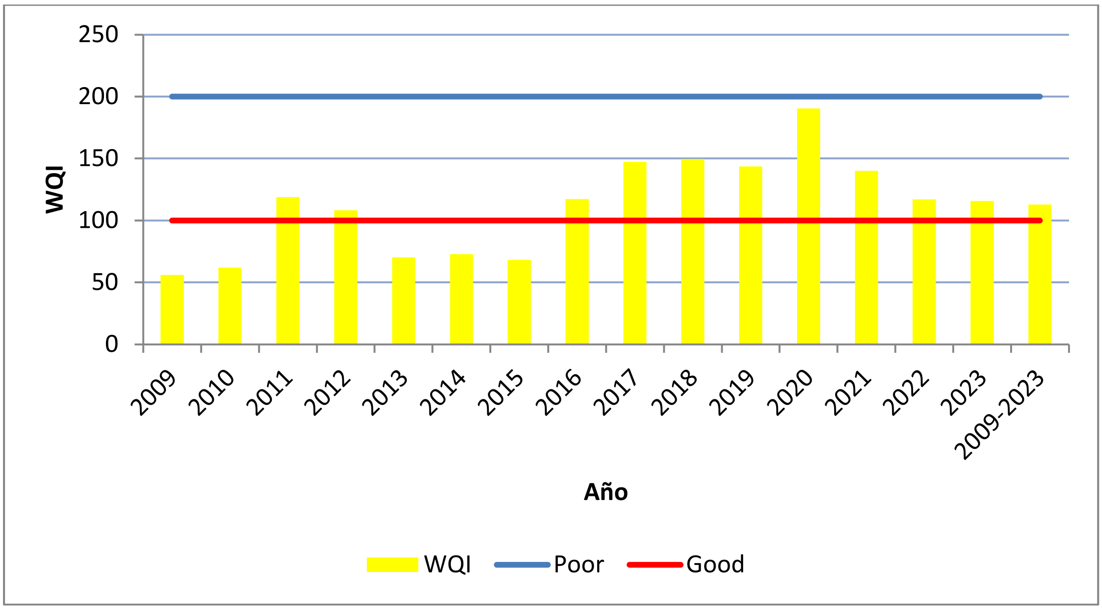

Fig. 3. Water Quality Index (WQI) of the Cajititlán lagoon during the period 2009-2023

However, the increase in job opportunities in the Metropolitan Area of Guadalajara is the reason for the accelerated increase in the population in this municipality. Forest and shrub vegetation represent the most affected areas with a loss of 3.1 and 3.5% of the surface of the basin. The forest was disturbed by deforestation and its vegetation density decreased alternating with shrubby vegetation, while grazing areas used in the past for livestock were transformed into agriculture and shrub vegetation. Agriculture is the most important activity with an increase of 4.8% of the total area of the basin in the same period. The waters of Lagoon Cajititlán are alkaline with a high content of dissolved salts. The parameters associated with anthropogenic pollution are also clear. Heavy metals are a concern, the average pH value for Lagoon Cajititlán is > 9, which puts agricultural production at risk and enables the transfer of heavy metals via food.

Table 4. Nemerow Pollution Index (NP) of the Cajititlán Lagoon by year during the period 2009-2023

	Turb	PH	Na	SO_4^{2}-	Cl^-	F^-	NO_3^-	Al	As	Ba	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
NP	99.33	1.11	1.00	0.06	1.12	4.22	0.01	670	40.46	0.19	2.59	50.00	31.59	6.43	11.79	3.97	3.98	70.81	70.78

Table 5. HPI, HEI and DC pollution indices of the Cajititlán Lagoon during the period 2009-2023

Index	Mean	Max
HPI	89	88
HEI	5	9
DC	4	18

Table 6. Index of ecological risks of the Cajititlán Lagoon by year during the period 2009-2023

	As	Cd	Cr	Ni	Pb	Al	Cu	Hg	Zn
PERI	61.37	42.56	7.08	22.42	17.70	NA	NA	166.67	117.08

Table 7. Risk index non-carcinogenic in residential and recreational residents (adults and children) of the water of the Cajititlán Lagoon during the period 2009-2023

Non-Carcinogenic Risks	HIIngestion		HIDermal		THI	
	Adults	Childrens	Adults	Childrens	Adults	Childrens
Residential	1.7194	2.5035	0.2644	0.3043	1.9838	2.8078
Recreational	0.0379	0.1486	0.3686	0.4286	0.4066	0.5772

Table 8. Index of carcinogenic risks in residential and recreational residents of the water of the Cajititlán Lagoon during the period 2009-2023

Carcinogenic Risks	Ace			Cr		
	CRIngestion	CRDermal	TCR	CRIngestion	CRDermal	TCR
Residential	1.52E-08	2.71E-09	1.79E-08	5.09E-07	2.11E-07	7.20E-07
Recreational	1.10E-07	1.97E-08	1.30E-07	3.69E-06	1.53E-06	5.22E-06

Discharges of poorly treated wastewater and the lack of measures to control run-off from agricultural areas lead to a visible and consequential detriment to physico-chemical characteristics and increased heavy metal pollution of water and the loss of several of its potential uses as a reserve area for aquatic and terrestrial species, the nesting of migratory species. It also puts agriculture and human health at risk by ingestion and dermal contact with the waters of the lagoon.

4. CONCLUSION

The main findings are:

- ✓ The distribution of concentration of parameters showed a drastic spatial variation, but not temporal. The TDS (312000%), Turbidity (6600%), pH (7.10%), OD (7.5%), F (5.2%), Al (6013%), As (37%), Cr (4900%), Cu (24%), Mn (24%), Ni (2965%), Pb (438%) and Zn (162%) showed percentages outside the CCME regulations, however most are within the NOM-001-SEMARNAT-2021.
- ✓ Pearson's correlation analysis showed that most heavy metals have positive correlations with each other, except for Cr, Pb, and Cu.
- ✓ Water quality according to WQI of 112 was categorized as poor-quality, while for CWQI for all uses except livestock it was classified as poor (20-35).
- ✓ According to the NP index (0.19 to 670), heavy metal concentrations showed high contamination levels. The HPI index (89) showed moderate to elevated levels of heavy metal contamination. The HEI index with levels < 10, shows a state of low contamination. The DC value presented a value of 4, classified as a high degree of contamination.
- ✓ The PERI index showed that the ecological risk from heavy metals is high.
- ✓ Non-carcinogenic risk indices show that Lagoon water is not suitable for drinking, and poses a high health risk if ingested, while dermal contact poses no health risk to residential and recreational recipients.
- ✓ According to the indices of water quality, ecological risk and health, the water quality of the Cajititlán Lagoon is poor, with a high degree of contamination and is ecological and health risks (non-carcinogenic).
- ✓ The results show 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.
- ✓ The findings of this research will allow us to prove guidelines for future research, arguments for the development of public policies, and a point of comparison for future evaluations of the same parameters.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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