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RESEARCH

Evidencing anthropogenic pollution of surface waters in a tropical region: a case study of the Culiacan River basin

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Abstract Nowadays, one of the most critical challenges is reduced access to water. Climate change, industrialization, and population growth have caused many countries to suffer from water crises, especially in arid and semi-arid areas. The Culiacan River basin in Sinaloa is a region of great importance in Mexico due to its intensive agricultural activity. Hence, water quality assessment has become a necessity to ensure sustainable water use. This study describes the spatiotemporal water quality features of the Humaya, Tamazula, and Culiacan Rivers within the Culiacan River basin and their sources of contamination. Twenty-two water quality parameters were analyzed from samples taken every 6 months from 2012 to 2020 at 19 sampling sites in the basin. A multivariate statistical analysis revealed significant correlations ($r > 0.85$) between the water quality parameters. The modified Integrated Water Quality Index (IWQI) identified severe pollution in samples from the urban river section of the basin, while good water quality conditions were found upstream. Severe contamination was observed in 26.32% of the samples, whereas only 13.45% evidenced good water quality. The Water Quality Index (WQI) indicated that 94.74% of the samples presented fair water quality, suggesting that the surface waters of the Culiacan River Basin are suitable for agricultural irrigation. This study provides insights into the current water quality status of the surface waters in the Culiacan River Basin, identifying significant pollution sources and areas of concern. The spatiotemporal dynamics of water quality in the Culiacan River basin revealed the importance of continuous monitoring and effective water management practices to improve water quality and achieve sustainable agricultural practices.

Keywords Water quality assessment · Water contaminants · Water quality index · Culiacan River basin · Intensive agriculture

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Introduction

Water is the most important resource for human beings. In many regions, such as Central America, most freshwater is stored in surface water bodies. However, groundwater is still the primary source of freshwater in several regions worldwide (Bisimwa et al., 2022; Gandhimathi et al., 2024; Kang & Kanniah, 2022; Li et al., 2022a, 2022b). Surface water bodies play an important role in the environment, serving as sources of water for irrigation and other anthropogenic uses (Liu et al., 2024; Ouarda et al., 2022; Pinto-Duarte et al., 2022). However, population growth is driving a decline in water quality, as increased water demand and contamination pose a serious threat to public health and the environment (Guo et al., 2022; Lu et al., 2022; De Anda & Shear, 2021).

The surface water quality is a serious issue since water is often used directly without any prior treatment (Crosato et al., 2022; Paradis et al., 2022). Hence, the monitoring of surface water bodies is required to better comprehend the state of water resources and develop strategies to improve their management, solve conflicts, and enhance the effectiveness of water-related policies (Paudel et al., 2022; Liu et al., 2022; Whelan et al., 2022). In addition, the monitoring of water bodies contributes to maintaining healthy ecosystems, reducing global diseases, guaranteeing the integrity of the environment for future generations, and supporting sustainable development (Quevedo-Castro et al., 2022).

Rivers are essential components of freshwater resources and are highly beneficial for human civilizations, as they contribute to satisfying various needs (Bushero et al., 2022). Water quality evaluation can help to understand the hydrological and anthropogenic impacts that are affecting it (Mnyango et al., 2022; Paradis et al., 2022; Parween et al., 2022). Anthropogenic activities such as land changes, urbanization, industrialization, and agricultural activities cause river stress that results in gradual environmental deterioration (Bushero et al., 2022; Rodriguez-Nuñez et al., 2022). Since the ecological health of rivers is closely related to society, the economy, and the environment, it is necessary to promote their protection and restoration (Ju et al., 2022).

The study of river pollution is gaining more attention. In Mexico, some studies have been carried out on different rivers (Laskar, 2024; Morales-Ruano et al., 2022; Romero-Montoya et al., 2021; De Anda & Shear 2021; Salcedo Sánchez et al., 2022; Sabie et al., 2022; Zepeda et al., 2022; Rodriguez-Nuñez et al., 2022). The evaluation of heavy metals (Vargas-Solano et al., 2022), the determination of antibiotics (Tapia-Arreola et al., 2022), the evaluation of microbiological pollution (González-López et al., 2022), and the study of phytoplankton (Verma et al., 2021) are some recent cases. In Sinaloa, Mexico, a series of factors such as the high rate of urbanization, poor sanitation infrastructure, and agricultural intensification are degrading the quality of river waters. River pollution is progressively increasing because of a variety of natural and anthropogenic processes, such as the input of nutrients and organic matter into the river system from diffuse sources and point sources (Kurwadkar et al., 2022).

Assessing water resources, such as rivers, provides sustainable solutions to water-related problems (Mnyango et al., 2022). Some of the most accurate methods to assess the quality of rivers are the Water Quality Index (WQI) (Bushero et al., 2022; Marselina et al., 2022), the Integrated Water Quality Index (IWQI) (Rajkumar et al., 2022; Ting et al., 2012: Uddin et al., 2022), and multivariate methods (Vehanen et al., 2022; Zhu et al., 2022) as they have proven to be effective to determine the degree of contamination and have been useful tools to identify the causes or sources of pollution (Khouri et al., 2022).

In this study, the impact of natural and anthropogenic processes on the main rivers located in the Culiacan River basin (Humaya, Tamazula, and Culiacan Rivers) was evaluated. A systematic evaluation of the water resources in the Culiacan River basin is presented using the Water Quality Index, the Integrated Water Quality Index, and multivariate statistics. Twenty-two water quality parameters were analyzed from samples taken every 6 months from 2012 to 2020 at 19 sampling sites in the basin. The relationship between hydrological and climatological variables and some anthropogenic activities with the spatial and temporal behavior of water quality parameters is presented to identify the sources of water quality alteration.

Study area

The Culiacán River basin in the state of Sinaloa, Mexico, encompasses 5 municipalities. It is located between the coordinates 25° 8′ 29.67″ and 24° 27′ 52.61″ north latitude and 107° 46′ 1.21″ and 106° 51′ 34.13″ west longitude (Fig. 1). It has an approximate area and perimeter of 2596.82 km^2 and 397.57 km, respectively (INEGI 2019). Its highest elevation is 1144 m above sea level (m.a.s.l.) and the lowest is 0 m.a.s.l. (Fig. 1a). Among the ten soil groups that were identified in the study area, the Vertisols, Phaeozem, and Leptosols are predominant, accounting for more than 80% of the surface (Sanhouse-Garcia et al., 2017). The land cover is grouped into two categories: vegetation and agriculture. The dominant vegetation is the low deciduous forest. Recently, a significant change in the land cover has been observed because of the expansion of agricultural activities in the center of the basin (see Fig. 1b). The three main river courses are present in the Culiacan River basin: (1) the Humaya River which originates from the Adolfo López Mateos (ALM) reservoir outflows; (2) the Tamazula River which originates from the Sanalona reservoir outflows; and (3) the Culiacan River formed by the junction of the Humaya and Tamazula Rivers (Renteria-Guevara et al., 2023).

Figure 2 shows the study area, the location of the surface water bodies, and the location of the sampling points in the Culiacan River basin. Sampling site 1 (SP1) is located downstream of the Sanalona reservoir, SP9 is located downstream of the ALM reservoir, and SP6 is located where the two mainstreams join and form a single stream, the Culiacan River. SP9 is the sampling point with the highest elevation (112 m.a.s.l.), while SP19 is the lowest (0 m.a.s.l.). Figure 3 shows that, in the study area, higher temperatures are observed in summer (June–September) while rainfall occurs from June to November (Loaiza et al., 2021).

Materials and methods

Samples collection and water quality parameters

The water quality data were provided by the National Water Commission (CONAGUA, 2021). Through an accredited laboratory, the National Water Commission carried out the sampling and determination of twenty-two water parameters under Mexican regulations. The assistance of an accredited laboratory ensured that the quality requirements were fulfilled (quality control and quality assurance). Water quality samples were collected every 6 months from 2012 to 2020 at the 19 river sampling sites in the basin. The sampling, conservation, and processing of the samples were carried out by applying standard procedures for water analysis (APHA, 2017).

The water quality parameters analyzed at each sampling point were as follows: fecal coliforms (FC), total coliforms (TCol), *Escherichia coli* (Ecoli), total organic carbon (TOC), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonium (NH_3), nitrites (NO_2), nitrates (NO_3), organic nitrogen (ON), total nitrogen (TN), total phosphorus

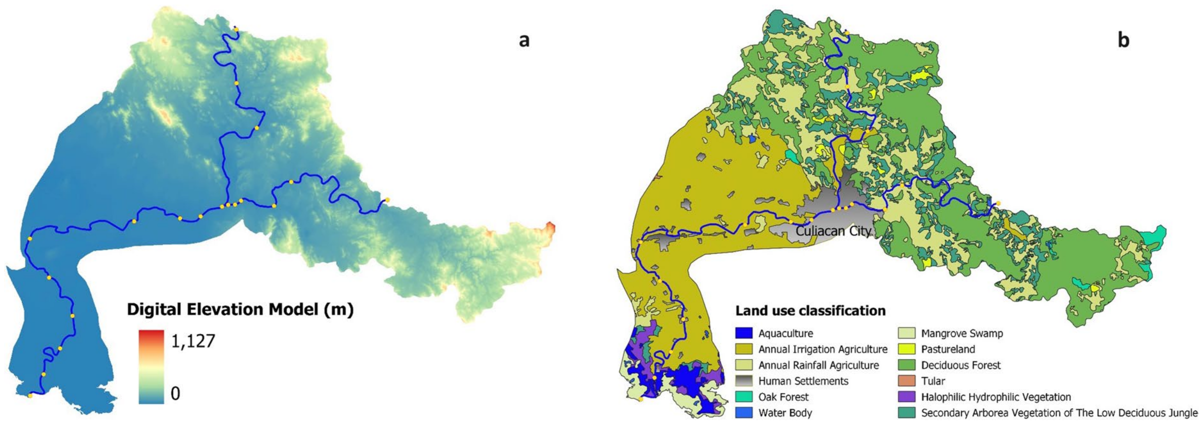


Fig. 1 Digital elevation model of the study area (**a**) and land-use classification of the study area (**b**)

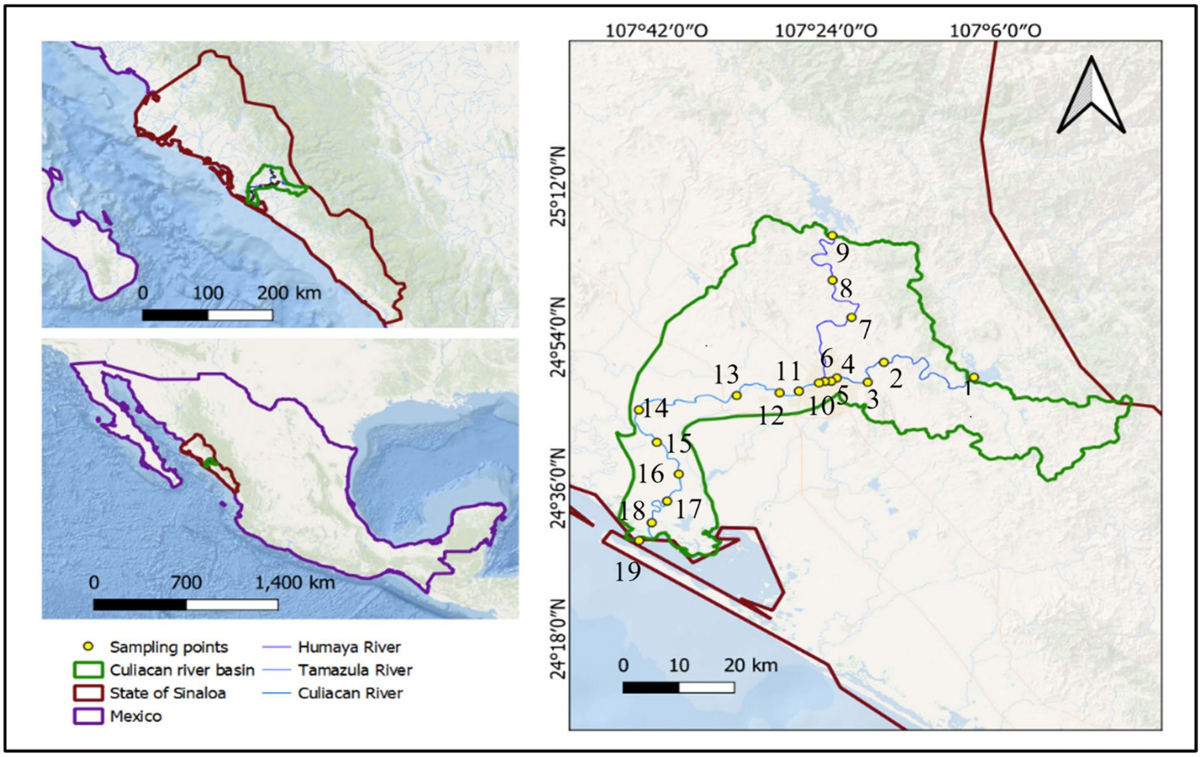
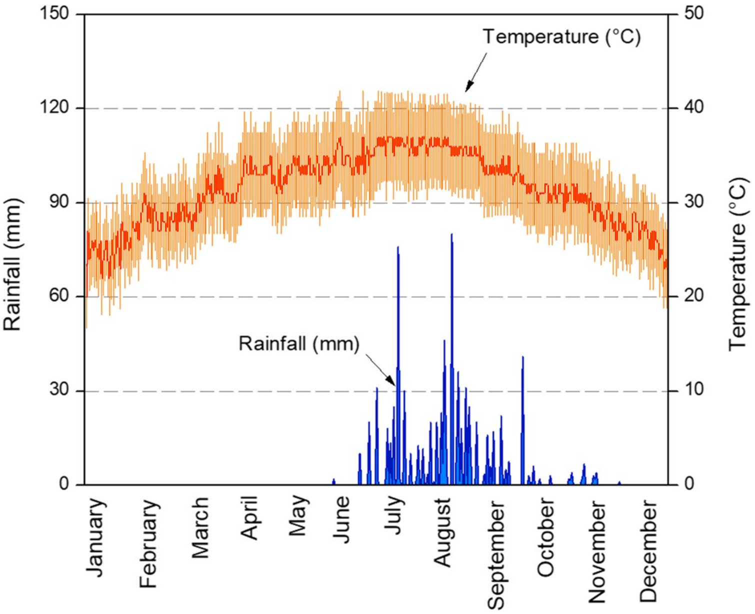


Fig. 2 Study area and geographical locations of the main river courses and the sampling points in the Culiacan River basin

Fig. 3 Temperature and rainfall in the Culiacan River basin



(TP), orthophosphates (O-PO_4), true color (TC), total dissolved solids (TDS), total suspended solids (TSS), electrical conductivity (EC), hydrogen potential (pH), dissolved oxygen (DO), turbidity (TUR), total hardness (TH) and water temperature (WT).

Statistical analysis

The spatial differences for each water quality parameter were analyzed by using Box-and-Whisker plots. Likewise, the seasonal differences were also evaluated for each water quality parameter. Linear correlation matrices were obtained to assess the correlations between the water quality parameters. The Pearson correlation coefficient was used to identify linear correlations between variables (Bushero et al., 2022). Cluster analysis was implemented to group the water quality data according to their similarity. This analysis was performed using the Ward method using the standardized square Euclidean distance. Then, PCA was used to explore relationships among original variables, transforming them into independent principal components (Loaiza et al., 2021). The Pearson correlation matrix and PCA were conducted using Statgraphics software, and a graphical illustration was generated using RStudio.

Integrated water quality index

The modified Integrated Water Quality Index (IWQI) was used to assess surface water quality (Fu et al., 2022; Gautam et al., 2022; Lin et al., 2021; Mukate et al., 2019; Solihu & Bilewu, 2022). This index was determined by Eq. (1).

$$P = \frac{1}{n}\sum_{i=1}^{n}\frac{C_i}{S_i} \tag{1}$$

where P is the Integrated Water Quality Index, C_i is the concentration of each water quality parameter (mg/L), S_i is the recommendation of each parameter (according to Mexican regulations), and n is the number of selected parameters (BOD, COD, FC, TN, TP, and TSS). This method can be used not only to assess the water quality of different sections of the same river but also to compare the water quality of different rivers (Yang et al., 2020).

Water quality index

The WQI can be used to assess the status and trends in the environment's ability to support human and ecological health. In this study, the National Sanitation Foundation (NSF)–Brown Water Quality Index (NSF–BROWN) was used. The WQINSF–BROWN showed the water quality status using nine water quality parameters (FC, BOD, NO_3, O-PO_4, PH, DO, TDS, WT, and TUR) from 2012 to 2020. The WQI was calculated by using Eq. (2).

$$WQI = \sum_{i=1}^{9}(Sub_i w_i) \tag{2}$$

where w_i is the relative weight assigned to each parameter weighted between 0 and 1 (the sum of the 9 weights must be equal to 1). The weight values used were FC (0.15), BOD (0.1), NO_3 (0.1), O-PO_4 (0.1), PH (0.12), OD (0.17), TDS (0.08), WT (0.1), and TUR (0.08). The Sub_i value represents the score obtained as a function of the water quality parameter (Quevedo-Castro et al., 2018).

Results and discussion

Descriptive analysis of water quality parameters

Table 1 presents the descriptive statistics of the water quality parameters of the Humaya, Tamazula, and Culiacan Rivers during the rainy and dry seasons. A high standard deviation can be observed for the microbiological parameters since a high spatial variation was observed at the different sampling points. A higher concentration of fecal coliforms, total coliforms, and *E. coli* was observed in the sampling sites located in the urban zone. The total dissolved solids and the electrical conductivity presented a high coefficient of variation because the sampling points located near the coastal zone showed values almost 1000 times greater than the ones observed in the river.

Due to the low rainfall in the area, significant differences were identified in the concentrations during the rainy and dry seasons. In the rainy season, the values of the water quality parameters increased except for dissolved oxygen and total hardness. This situation demonstrated that the hydrological regime

Table 1 Descriptive statistical analysis of the surface water quality data of the Culiacan River basin in the rainy and dry seasons

Parameter	Units	Mean	Min	Max	Range	Standard deviation	Coefficient of variation	Mexican standard
Rainy season								
Fecal coliforms	MPN/100 mL	17717	1	241960	241959	36641	2.07	1000 *
Total coliforms	MPN/100 mL	32113	72	241960	241888	51051	1.59	1 **
E.coli	MPN/100 mL	9021	1	241960	241959	30264	3.35	0 **
Total organic carbon	mg/L	4.41	0.09	22.23	22.14	2.71	0.61	NE
Biochemical oxygen demand	mg/L	4.84	2.00	45.48	43.48	5.62	1.16	30 *
Chemical oxygen demand	mg/L	31.08	10.00	250.80	240.80	30.04	0.97	150 *
Ammonium	mg/L	0.40	0.00	11.80	11.80	1.20	2.99	NE
Nitrites	mg/L	0.03	0.00	0.40	0.39	0.04	1.38	1.0 **
Nitrates	mg/L	0.40	0.00	3.15	3.15	0.48	1.19	10 **
Organic nitrogen	mg/L	1.01	0.00	10.03	10.03	0.86	0.85	40 *
Total nitrogen	mg/L	1.84	0.09	21.51	21.42	1.84	1.00	40 *
Total phosphorus	mg/L	0.29	0.01	3.47	3.45	0.32	1.10	5 *
Orthophosphates	mg/L	0.13	0.00	2.45	2.45	0.20	1.63	NE
True color	mg/L	78.06	3.00	1000	997	126	1.62	20 **
Total suspended solids	mg/L	97.97	5.00	1220	1215	145	1.49	30 *
Total dissolved solids	mg/L	6353	98	71,200	71,102	16,249	2.56	1000 **
Electric conductivity	µS/cm	8020	153	89,000	88,847	20,282	2.53	1500 **
pH	pH	8.09	6.80	9.70	2.90	0.43	0.05	6.5–8.5 **
Dissolved oxygen	mg/L	6.90	1.00	13.86	12.86	1.86	0.27	2 *
Turbidity	PtCo scale	64.17	0.45	850.00	849.55	104.69	1.63	5 **
Total hardness	mg/L	142.32	40.28	407.62	367.34	59.69	0.42	500 **
Water temperature	°C	31.46	25.50	36.70	11.20	1.95	0.06	3 °C+
Dry season								
Fecal coliforms	MPN/100 mL	4635	10	61310	61300	6937	1.50	1000 *
Total coliforms	MPN/100 mL	11980	12	155310	155298	11522	0.96	1 **
E. coli	MPN/100 mL	1613	1	54750	54749	5377	3.33	0 **
Total organic carbon	mg/L	4.01	0.09	21.71	21.62	2.47	0.62	NE
Biochemical oxygen demand	mg/L	4.61	2.00	57.85	55.85	5.79	1.26	30 *
Chemical oxygen demand	mg/L	29.01	10.00	363.60	353.60	36.88	1.27	150 *
Ammonium	mg/L	0.25	0.00	17.70	17.70	1.15	4.66	NE
Nitrites	mg/L	0.02	0.00	0.25	0.25	0.03	1.70	1.0 **
Nitrates	mg/L	0.26	0.00	2.14	2.14	0.33	1.25	10 **
Organic nitrogen	mg/L	0.70	0.00	6.71	6.71	0.65	0.93	40 *
Total nitrogen	mg/L	1.22	0.05	20.75	20.70	1.51	1.23	40 *
Total phosphorus	mg/L	0.18	0.03	3.06	3.03	0.25	1.40	5 *
Orthophosphates	mg/L	0.09	0.00	2.80	2.80	0.17	1.95	NE
True color	mg/L	41.63	2.50	1250	1247	124.29	2.99	20 **
Total suspended solids	mg/L	31.47	5.00	350	345	42.67	1.36	30 *
Total dissolved solids	mg/L	5049.92	70.40	52640	52570	12665	2.51	1000 **

Table 1 (continued)

Parameter	Units	Mean	Min	Max	Range	Standard deviation	Coefficient of variation	Mexican standard
Electric conductivity	µS/cm	6385.51	110.00	65800	65690	15805	2.48	1500 **
pH	pH	8.18	6.30	9.54	3.24	0.40	0.05	6.5–8.5 **
Dissolved oxygen	mg/L	8.07	1.00	16.96	15.96	1.83	0.23	2 *
Turbidity	Pt-Co scale	21.67	0.49	465.00	464.51	55.51	2.56	5 **
Total hardness	mg/L	163.07	29.00	2761.21	2732.21	168.97	1.04	500 **
Water temperature	°C	26.16	18.20	35.20	17.00	3.12	0.12	3 °C+

*NOM-001-SEMARNAT-2021, ** NOM-127-SSA1-1994

$^{+}$above the room temperature

NE Not specified

altered the water quality of surface water bodies in the Culiacan River basin. The entry of pollutants such as nitrogen, phosphorous, and organic matter by runoff was evidenced during the rainy season and promoted a decrease in dissolved oxygen.

Evidencing anthropogenic pollution

Some of the water quality parameters, such as turbidity, ammonium ions, and microbiological indicators, exceeded the limits established in Mexican regulations for waterbodies. In the rainy season, some samples showed high concentrations of fecal coliforms that reached 241,960 MPN/100 mL, while the mean value was 17,717 MPN/100 mL. These values exceed the permissible limit of the Mexican regulation of 1000 MPN/100 mL. The presence of fecal coliforms indicates that a source of pollution, such as a septic system or animal waste, could be present in the surroundings of the river (Hampel et al., 2023) suggest that livestock operations and faulty septic systems are the two main sources of fecal coliforms in surface waters. According to these results, the water quality of the river is not suitable for some uses. Microbiological pollution in water bodies is identified through indicator organisms such as total coliform (TCol), fecal coliform (FC), and *E. coli* (Studer et al., 2017). The lack of sanitation systems in most settlements contributes to the release of a high number of diverse contaminants, such as fecal coliforms (Hampel et al., 2023). Therefore, TCol, FC, and *E. coli* parameters are very important indicators in water bodies because they provide information about anthropogenic sources of pollution.

COD concentrations up to 250.8 mg/L and 363.6 mg/L were found during rainy and dry seasons, respectively, exceeding the maximum permissible level of 150 mg/L. These high COD concentrations were found close to Culiacan City but a mean COD concentration of 30.06 mg/L was observed for the rest of the sampling sites. This organic matter content affects the color, taste, and odor of the water, and reduces the dissolved oxygen of the water (Gudiño-Sosa et al., 2023; Quevedo-Castro et al., 2022). Total suspended solids reached a concentration of 1220 mg/L, which was above the maximum permissible level of 60 mg/L. This high solid content affects turbidity and also decreases dissolved oxygen levels (Nasrabadi et al., 2016). Another important factor is the pH which reached a value of 9.7 in some samples, while the regulations recommend a range of 6–8. The alkaline conditions suggest eutrophication in the Culiacán River basin and lead to toxic conditions for aquatic organisms (Quevedo-Castro et al., 2018).

Because of runoff, the highest concentration of organic matter in the surface water bodies of the Culiacan River basin was registered in the rainy season. The mean TOC, BOD, and COD concentrations were 4.41, 4.84, and 31.08 mg/L, respectively. According to Zeng et al. (2023), these parameters are highly related to organic matter transportation to lotic ecosystems via stormwater runoff, mainly in zones that have been altered by land-use changes associated with urbanization. Organic matter pollution was found low in comparison with other studies and met Mexican regulations.

Regarding nutrients in the water (ammonia, nitrites, nitrates, organic nitrogen, total nitrogen, total phosphorus, orthophosphates), the results show that these parameters increased their concentration in the rainy season with mean values of 0.40, 0.03, 0.40, 1.01, 1.84, 0.29, and 0.13 mg/L, respectively. These values meet with the Mexican water quality regulations (Table 1). The maximum concentration of these nutrients was observed at sampling point 12. These nutrients can be found in the surface waters due to nutrient leaching, soil erosion, and the presence of detergents in wastewater discharges (Rao et al., 2022).

DO is essential in water to maintain the balance of aquatic ecosystems (Zeng et al., 2021). In the Culiacan River basin, most of the sampling sites were found to be saturated with dissolved oxygen, but some samples showed low DO concentrations (below 1 mg/L), such as the one observed at sampling site 12. The concentration of DO showed a high spatial variation from the upstream to the coastal zone. The mean concentration was 6.89 mg/L in the rainy season and 8.07 mg/L in the dry season. The DO values varied because industrial and domestic wastewater is discharged directly into rivers without adequate treatment.

In the aquatic environment, the pH concentration often increases due to the activity of photosynthetic algae that consume carbon dioxide (Wu et al., 2022). In the study area, the pH was alkaline and showed a value close to 8. The water samples at all the sampling points presented a very similar pH value. This situation means that the buffer capacity of the rivers is high. EC varied significantly between 110 and 89,000 µS/cm at all sampling sites. This is an indirect measure of the salt concentration in water and a good indicator of saline intrusion in water resources (Angello et al., 2021). This situation coincided with the one observed in the Culiacan River since the maximum concentration occurred where the river meets the coastal waters, where saline intrusion takes place. On the other hand, the mean TDS concentration was 103.4 mg/L, while a maximum concentration of 71,200 mg/L was observed close to the coastal zone (samples from sites 17–19). Samples from sites 1 to 16 had TDS concentrations below the maximum values established by the WHO for drinking water (500 mg/L). In this study, the high TDS values reflected that the water is highly mineralized (WHO, 2011).

Spatio-temporal variation of water quality parameters

Figure 4 presents Box-and-Whisker plots of water quality parameters. This figure shows that the concentration of pollutants showed high spatial variation. The greatest variability was observed at sampling site 12, where TP, TN, BOD, and COD parameters showed high changes. This situation could be related to the influence of land-use changes since this zone is characterized by grasslands and agricultural areas, which are highly susceptible to erosion. Figure 5 presents the water quality behavior during the rainy and dry seasons. According to this figure, a high water quality variation (increase) was noticed in the rainy season suggesting that runoff plays a crucial role in the water quality of the Humaya, Tamazula, and Culiacan Rivers. The results showed that some parameters, such as COD and TDS concentrations, decreased over time. However, most of the water quality parameters showed a seasonal behavior. Figure 6 presents the spatial behavior of water quality parameters in the Humaya, Tamazula, and Culiacan Rivers. The highest concentrations of COD, TOC, BOD, TH, TP, and TN were observed at the confluence of the Humaya and Tamazula Rivers (sampling site 12). The most highly populated area is located precisely at this point. The lowest concentrations were found downstream of the ALM and Sanalona dams. The spatial distribution of organic matter and nutrients suggests a strong influence from nearby urban areas. This situation is evidenced at sampling site 12 since elevated levels of organic matter and nutrients were found pointing to potential pollution from untreated urban wastewater discharges.

The spatial analysis also revealed a significant increase in TDS values along the river course, with the highest concentrations observed at site 19, close to the river's discharge into the sea. This progressive TDS increase from upstream to downstream is evidence of the influence of seawater as suggested by Uddin et al. (2024). TSS registered the highest concentrations at sites 2–7, 10, and 11, possibly due to soil erosion in these areas. Turbidity also exhibited a significant and progressive increase along the river course, from sampling points 11 to 19, likely due to the river's shallow depth. FC were absent in the waters downstream of the ALM and Sanalona reservoir but increased within the urban area (sites 4 to 10), exceeding the limits established by Mexican

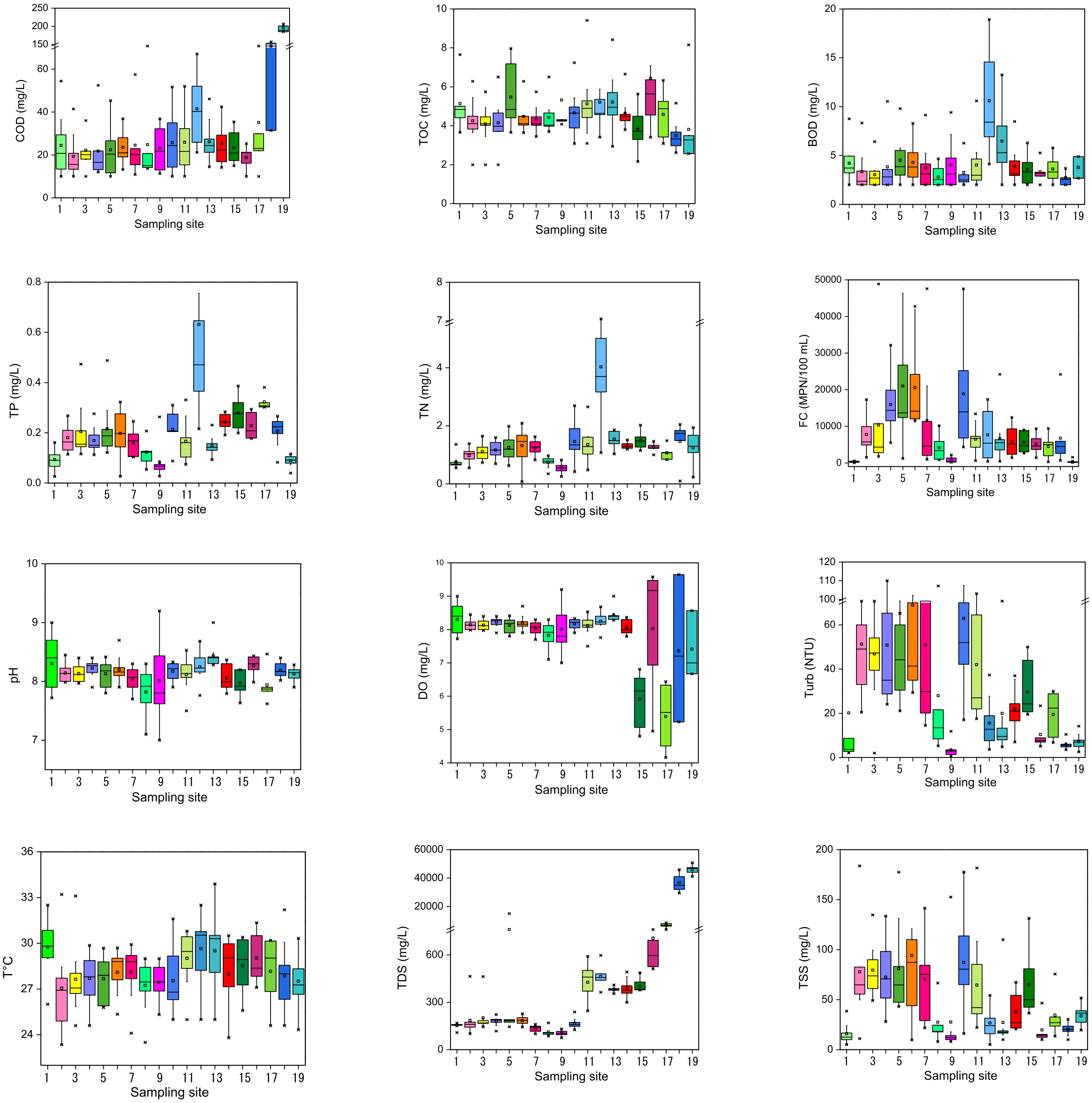


Fig. 4 Box and whisker plots of water quality parameters

regulations. This rise in FC levels poses a significant public health risk due to inadequate wastewater treatment.

During the rainy season, water quality parameters such as TDS, TSS, turbidity, fecal, and total coliforms, and *E. coli* showed significantly higher concentrations. This seasonal pattern is linked to increased surface runoff, which transports pollutants from agricultural areas, urban settlements, and industrial sites of the Culiacan River basin into the rivers. According to these results, stricter environmental regulations for industries, agriculture, and urban

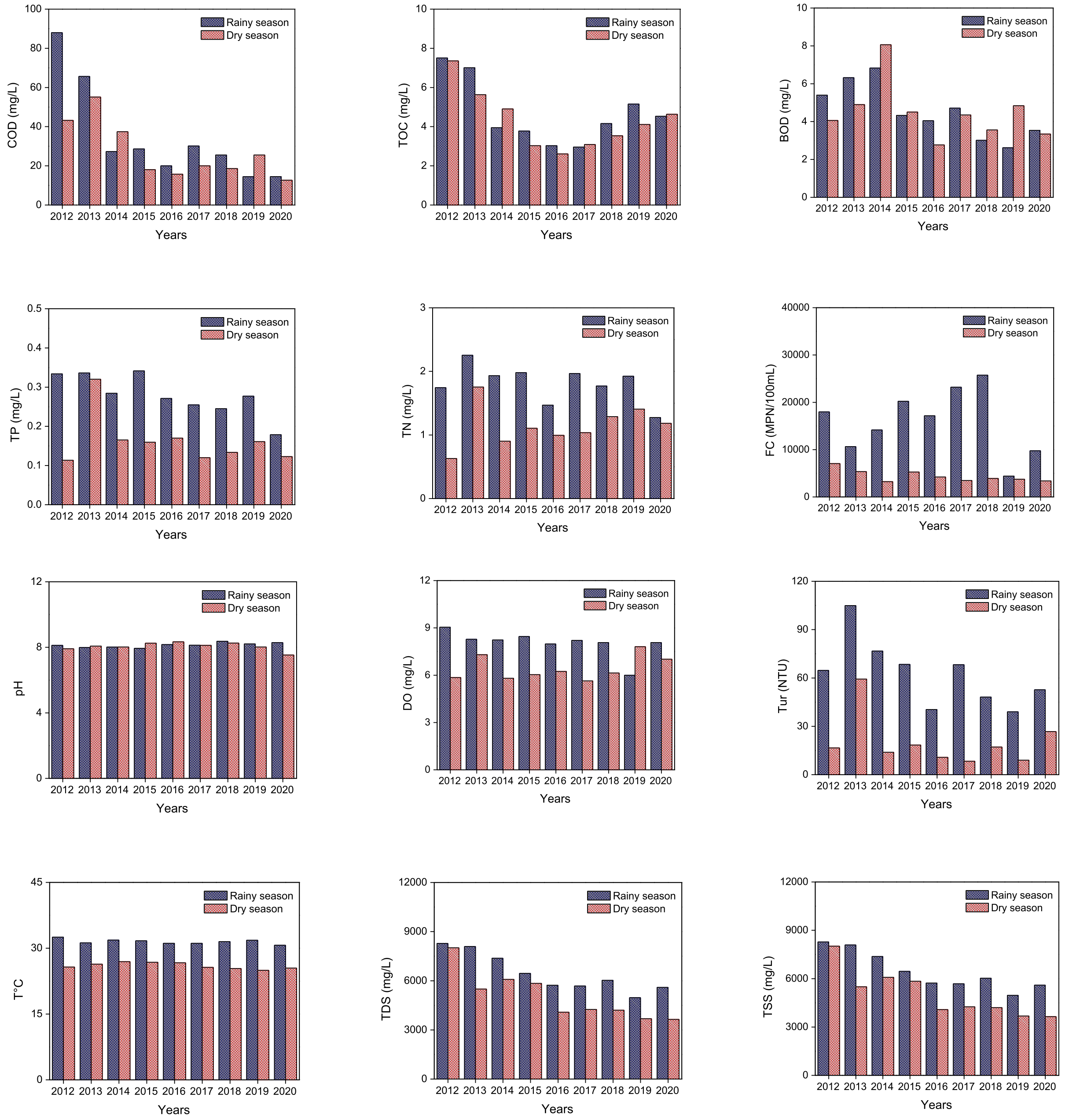


Fig. 5 Water quality in the rainy and dry seasons

development are mandatory to regulate surface water pollution in the Culiacan River basin. In addition, promoting sustainable agriculture practices and limiting development in sensitive areas prone to runoff could reduce erosion and nutrient runoff (Cai et al., 2024).

Correlation of water quality parameters

The correlation between water quality parameters is shown in Fig. 7. Significant correlations were observed between most of the water quality parameters, including positive and negative correlations.

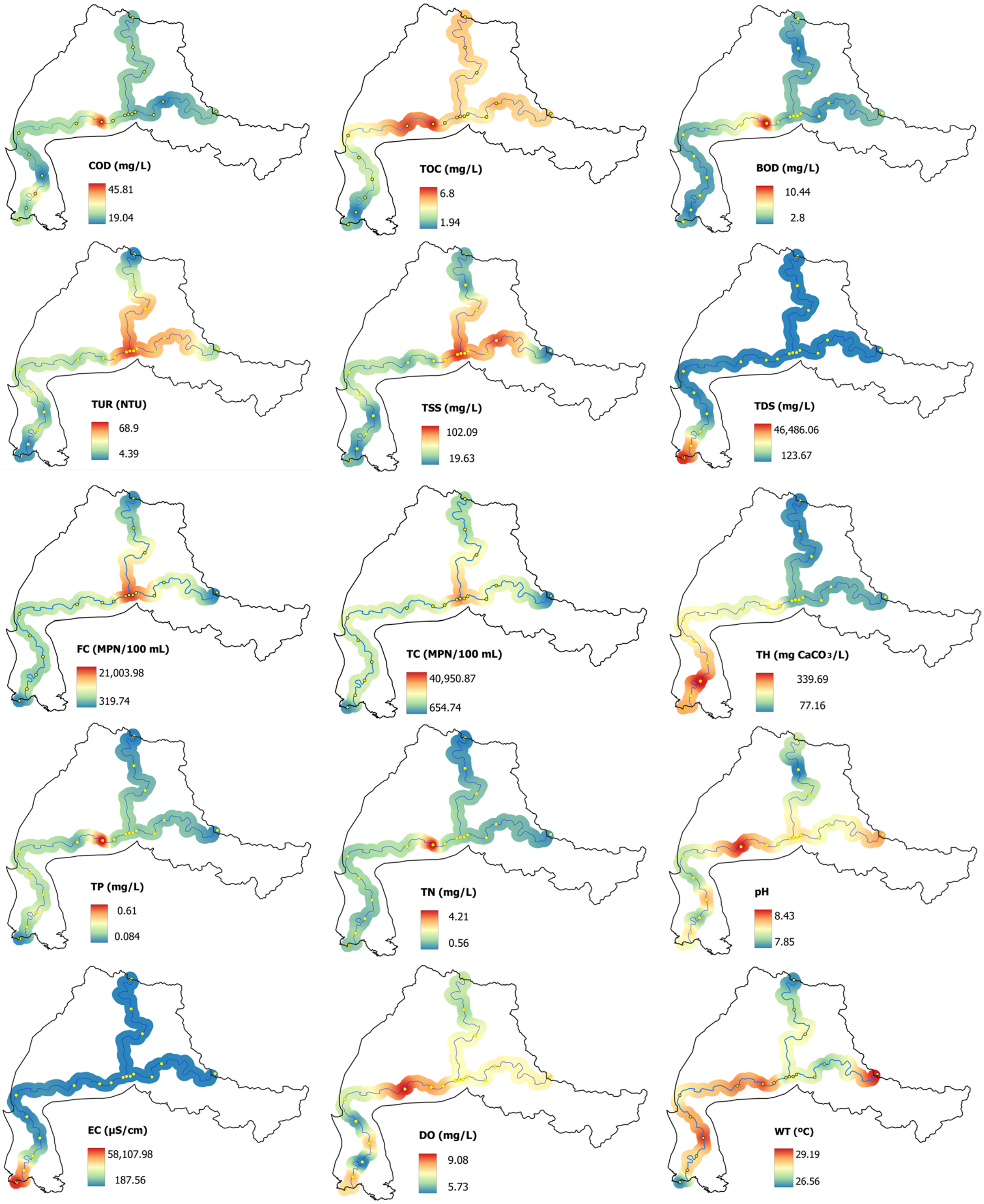


Fig. 6 Spatial distribution of water quality parameters in the rivers of the Culiacan River basin

These correlations represent the strength of the linear relationship between the parameters (Bushero et al., 2022; Ghale et al., 2024; Kothari et al., 2021; Zhou et al., 2023). Most of the parameters presented a positive correlation; FC showed a linear correlation with total coliforms (0.9201), *E. coli* (0.9048), Turb (0.8440), TSS (0.8168), and TC (0.7621). Organic matter was related to a few parameters. Total organic carbon showed a significant correlation with EC (−0.7035) and TDS (−0.7022). Chemical oxygen demand is related to the EC (0.9429), while biochemical oxygen demand is related to nutrients such as NH_3 (0.9111), NO_2 (0.8513), ON (0.7227), TN (0.8863), and TP (0.7532). Hampel et al. (2023) reported that the presence of fecal coliforms increases BOD, which explains the relationship between both parameters. On the other hand, the relationship of biochemical oxygen demand with nitrogenous compounds is possibly related to the denitrification process, where high oxygen is needed because of the oxidation of reduced forms of nitrogen such as ammonia and organic nitrogen, mediated by microorganisms. The high level of organic matter in the river points to a significant depletion of DO, as suggested by Mercado et al. (2024). This organic matter, originating from various sources like farms and residential areas, poses a serious threat to aquatic life.

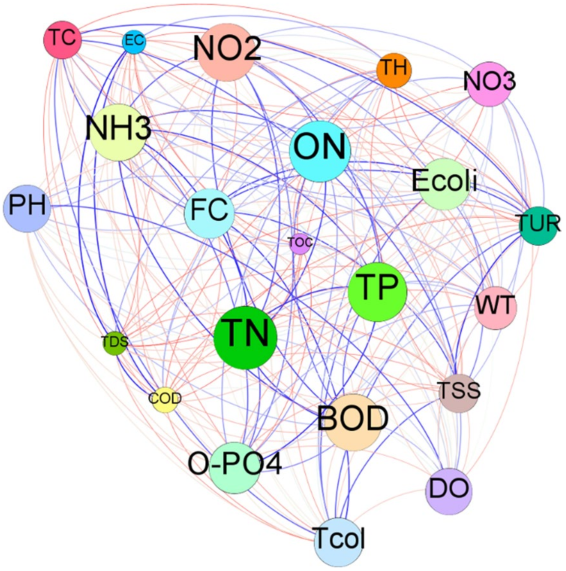


Fig. 7 Network analysis of water quality parameters based on a correlation matrix of 22 parameters. Red lines represent negative correlations, blue lines represent positive correlations, and the sphere size indicates parameter relevance; larger spheres denote greater correlation value

Excess nutrients promote the accelerated growth of phytoplankton and other species of aquatic flora, causing disturbances in the balance of the aquatic ecosystem (Wang & Zhang, 2020). In the Culiacan River basin, ammonium is related to TN (0.9588), TP (0.8943), NO_2 (0.7872), NO (0.7778), and PO_4 (0.7442). Nitrites are related to TN (0.8346) and TP (0.8045). Organic nitrogen is related to TN (0.8862). Total nitrogen is related to TP (0.9062), and total phosphorus is related to O-PO_4 (0.9238). The high levels of nutrients (nitrogenous and phosphorous compounds) in the Culiacan River are related to agriculture and affect transparency, reduce the entry of sunlight, and increase turbidity (Gudiño-Sosa et al., 2023).

Figure 8 presents the clustering and correlations of the water quality parameters. The conglomeration of water quality variables was obtained using the Ward method with a standardized square Euclidean distance metric. The hierarchical cluster analysis was used to group the water quality parameters based on the value of the correlation. The hierarchical cluster analysis produced four main groups in the Culiacan River basin. The first group consisted of COD, TDS, EC, and TH and is primarily associated with the mineral and ionic composition of the water. In the first group, higher concentrations of total dissolved solids (TDS) and total hardness (TH) occurred when higher chemical oxygen demand (COD) and electrical conductivity (EC) were observed. These relationships can be attributed to the agricultural runoff impact on water quality. The runoff transports organic matter (higher COD) and dissolved fertilizers (higher TDS, TH) to the rivers. Hence, an increase in the water's electrical conductivity (EC) can also be observed due to the entry of dissolved ions (Chen et al., 2022).

The second group is highly related to the presence of nutrients in water since this group is represented by BOD, NH_3, TN, NO_2, ON, TP, and O-PO_4. This group reflects the nutrient load in the water from agricultural runoff and/or wastewater discharges (Li et al., 2022a, 2022b), and can be used as a critical indicator of nutrient pollution in the Culiacan River basin. A third group clustered TOC, pH, DO, NO_3, and WT parameters. This group encompasses parameters that are indicative of the organic matter content and its influence on the water's pH and dissolved oxygen

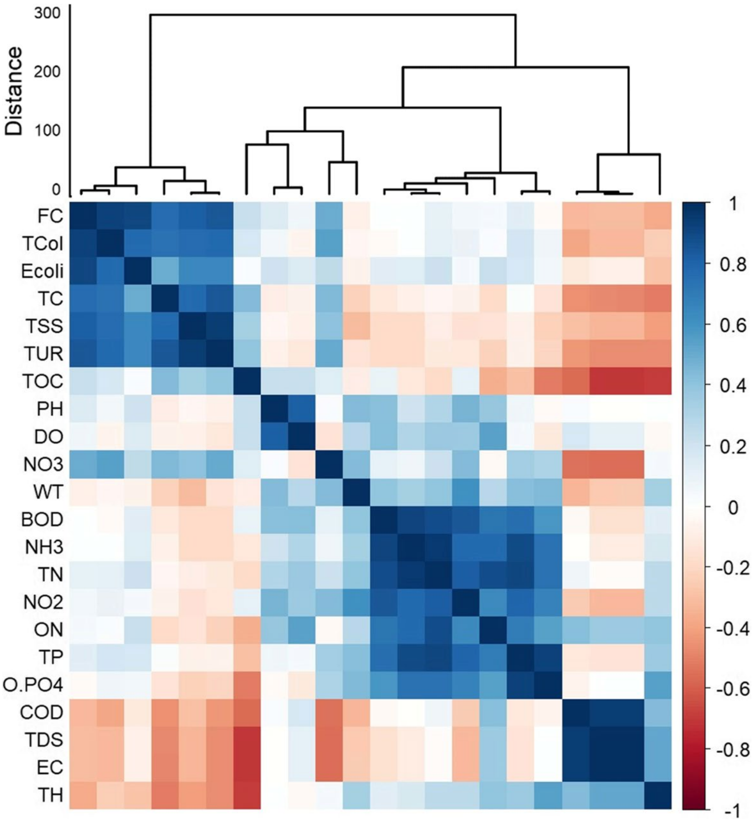


Fig. 8 Pearson correlation and clusters of water quality components. Blue color indicates a positive correlation, while red color indicates a negative correlation

levels. The presence of nitrate (NO_3) in this group also evidences the nitrification processes. Therefore, this cluster can be linked to the effect of aerobic biological activity on the removal of organic matter and nitrogen in the water (Mercado et al., 2024). Finally, a fourth group was formed by FC, TCol, *E. coli*, TC, TSS, and TUR parameters, which can be related to anthropogenic pollution because of inadequate wastewater treatment. These parameters are crucial since they are highly related to public health, as they reflect the presence of pathogens and suspended solids that can affect water clarity and safety (Mehta et al., 2023; Shenbagalakshmi et al., 2023). Despite the hierarchical cluster analysis identified the parameters that were relevant for water quality variation in the Culiacan River basin, few studies have used this methodology. Yang and Zhou (2023) conducted a hierarchical clustering analysis and identified patterns and differences in the water quality variables of the Yangtze River.

Principal component analysis

Figure 9 shows the PCA using the water quality parameters in the Culiacan River basin. This statistical analysis identified the principal variables (components) that best represent the variance in the water quality data. Through PCA, the most influential water quality parameters were identified from 22 initial parameters. This analysis also identifies groups of water quality variables that are linked to each other (Loaiza et al., 2021). In the Culiacan River basin, four principal components (PC) accounted for 85% of the cumulative variance, suggesting that these components represent most of the variability present in the data. Principal component 1 (PC1) showed that turbidity and true color (TC) observed the most variability (31.3%). Turbidity and TC can be associated with the presence of suspended and dissolved materials that affect the clarity and appearance of the water

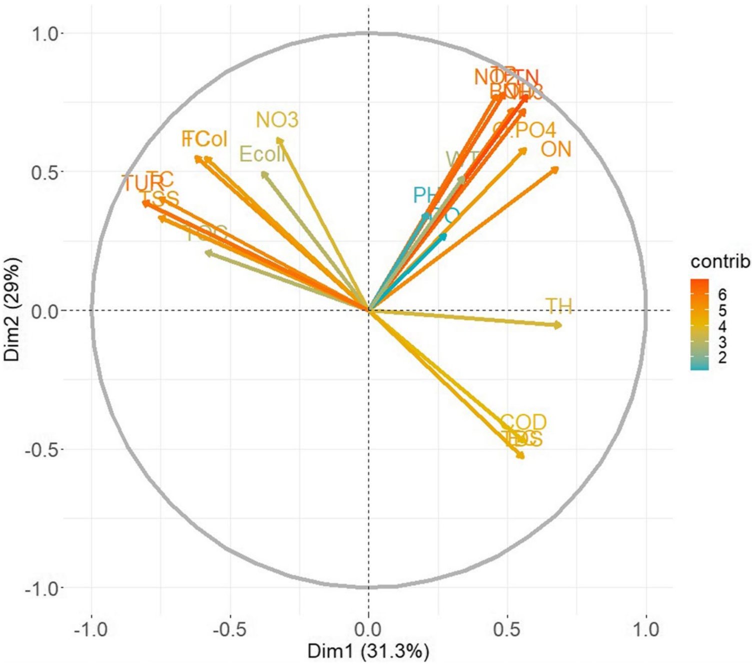


Fig. 9 Biplot of PCA for water quality parameters. The first two components explain 60.3% of the variance. Vectors show variability and linear correlations between these principal components

(Mercado et al., 2024). This high variability in turbidity and TC is linked to seasonal patterns, particularly the rainy season. Heavy rains cause runoff from the surrounding land, carrying soil, sediment, and other particulate matter into the rivers, increasing turbidity. While turbidity is caused by particles, true color is often attributed to dissolved organic matter (DOM). However, rainfall also promotes the entrance of organic matter from the land into the water, leading to higher concentrations of DOM and a change in TC.

PC2 also showed a high variation (29%) and highlighted the influence of NO_2, TP, and TN on the water quality. These parameters are critical since high nutrient loads (variation) can lead to excessive algae growth and water quality deterioration. The high variation of these contaminants can also be explained by runoff from intensive agricultural areas. PC3 reflected a high variation (13.7%) of *E. coli*, TOC, TDS, and EC. This component suggests a combination of natural and human-induced influences. While wastewater treatment plant discharges or industrial discharges can contribute significant variations in *E. coli*, TOC, TDS, and EC, seasonal variations (rainy and dry seasons) can also influence the increase and decrease of these water quality parameters. PC4 showed a significant variation (10.7%) of TOC, O-PO_4, and DO. This high variation is linked to the biological productivity and decomposition processes in the rivers. This component evidenced that an eutrophication process has a great influence on water quality behavior in the Culiacan River basin since nutrient enrichment leads to excessive algae growth, reducing oxygen levels when algae die and decompose. Upstream the Humaya River, Loaiza et al. (2021) reported that 26% of the data variation is associated with water nutrients NO_3^-, NO_2^-, and TP, indicating that agricultural activities could lead to the Adolfo Lopez Mateos Reservoir's eutrophication. These findings confirmed the impact of anthropogenic activities on water quality in the study area.

Integrated water quality index

The modified Integrated Water Quality Index (IWQI) was used to qualitatively assess water contamination. BOD, COD, FC, TN, TP, and TSS were used to determine the IWQI. Table 2 presents the IWQI classification and Table 3 shows the results of the IWQI considering the classification of the samples. Figure 10a shows the sites showing the highest values of IWQI. At these locations, the highest counts of fecal coliforms, organic matter, and nutrients were found. Therefore, IWQI was used to identify the

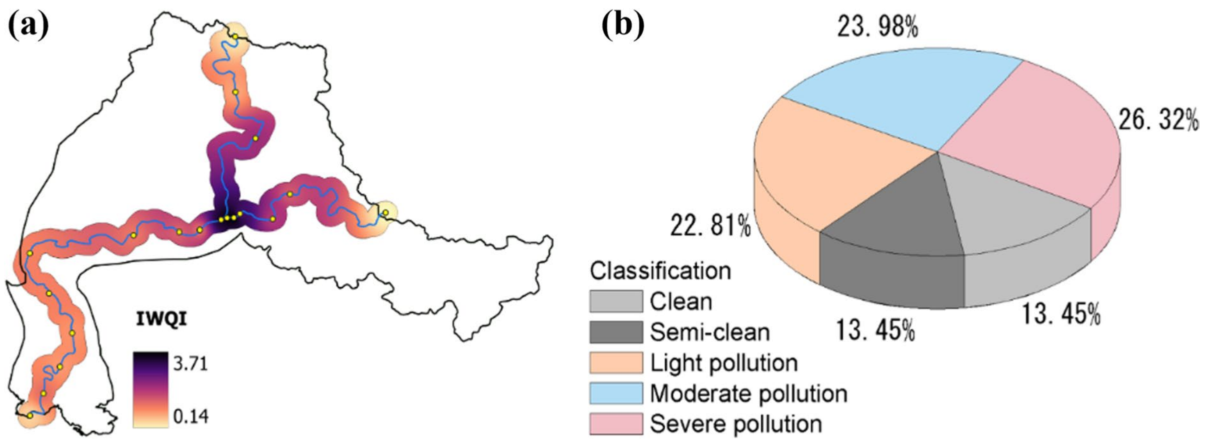


Fig. 10 IWQI results in the Culiacan River basin. **a** Spatial behavior and **b** classification percentages

Table 2 IWQI classification table of surface water samples from the Culiacan River basin

Range	Type	Classification	
≤0.20	I	Clean	⬜
0.21-0.40	II	Semi-clean	⬛
0.41-1.00	III	Slightly polluted	🟧
1.01-2.0	IV	Moderately polluted	🟦
≥2.01	V	Severely polluted	🟥

Table 3 IWQI results of surface water samples from the Culiacan River basin

Site	2012	2013	2014	2015	2016	2017	2018	2019	2020
1	0.054	0.17	0.15	0.11	0.15	0.09	0.22	0.16	0.06
2	2.944	1.00	1.85	1.17	2.31	2.1	0.87	0.38	1.11
3	0.697	0.55	1.41	1.95	8.40	1.98	0.82	0.89	0.74
4	4.127	2.85	2.22	1.04	2.54	5.55	2.23	1.53	3.86
5	0.338	9.07	2.52	4.66	2.18	2.35	7.88	3.01	1.71
6	4.098	2.29	2.17	2.56	2.16	7.69	2.14	7.36	2.66
7	0.244	1.03	2.14	8.27	1.92	3.73	0.77	0.32	0.90
8	0.217	0.81	1.81	1.42	0.77	1.05	0.55	0.21	0.32
9	0.115	0.42	0.01	0.40	0.08	0.34	0.32	0.12	0.22
10	0.816	1.45	1.36	4.48	2.51	8.29	1.99	5.29	4.21
11	0.426	1.18	1.54	2.38	1.32	0.82	1.23	2.33	0.17
12	0.121	3.25	2.51	3.04	0.99	1.58	0.83	0.24	0.36
13	4.118	0.69	1.25	1.12	0.79	1.41	1.14	0.29	0.12
14	1.078	0.96	2.29	1.79	1.71	0.75	0.48	0.33	0.36
16	0.921	0.97	1.73	0.94	1.66	1.34	0.56	0.65	0.98
15	0.398	0.98	1.38	1.31	1.70	0.67	1.17	0.32	0.82
17	0.161	1.11	1.04	1.68	0.38	0.57	0.99	0.24	1.45
18	4.269	1.23	0.80	0.32	0.93	0.47	0.80	0.17	2.08
19	0.321	0.50	0.15	0.12	0.33	0.07	0.14	0.14	0.11

source of pollution. The highest values were found in the confluence of the Humaya and Tamazula Rivers, where the urbanization is located. Figure 10b shows that severe contamination was found in most of the samples (26.32%), while 13.45% of the samples evidenced good water quality. According to IWQI, the surface waters of the Culiacan River basin are not suitable for direct contact or human consumption.

This methodology was also used by Solihu and Bilewu (2022) who evaluated the impacts of anthropogenic activities on the water quality of the Asa River (Kwara, Nigeria) for agricultural use.

Water quality index

The WQI is a direct measure of water quality related to its use. FC, BOD, NO_3, OPO_4, pH, DO, TDS, WT, and Turb were used to determine the WQI. These parameters met the safe irrigation standards set by Mexican regulations (see Table 1), except for FC, which exceeded the permissible limit in most samples. Table 4 WQI shows the classification, range, and type, and Table 5 evaluates water quality based on 22 parameters analyzed from 2012 to 2020. WQI values were highly dependent on FC since its concentration was very variable, mainly in the rainy season. Figure 11a shows that the best water quality conditions were upstream at the sampling points located downstream of the outlets of the dams. A large variation in the water quality conditions is observed when approaching the urban area. The poorest water quality condition is observed at point 12, where Culiacan downtown is located. A slight improvement in the water quality conditions is observed in the Culiacan River downstream of the urban area. According to Fig. 11b, 94.74% of the samples presented a fair quality while 5.26% presented a good quality. Mnyango et al. (2022) recommend the possible uses of water based on WQI classification. Surface waters classified as type 2 (good) could be used for domestic, irrigation, and industrial purposes. Surface waters classified as type 3 (fair) could be used for irrigation and industry, considering previous water treatment for those specific purposes.

Comparison between WQI and IWQI

In this study, the results obtained agree with those mentioned by Rajkumar et al (2022), who suggested that IWQI is stricter than WQI. They mention that the WQI method should not be used as a pollution

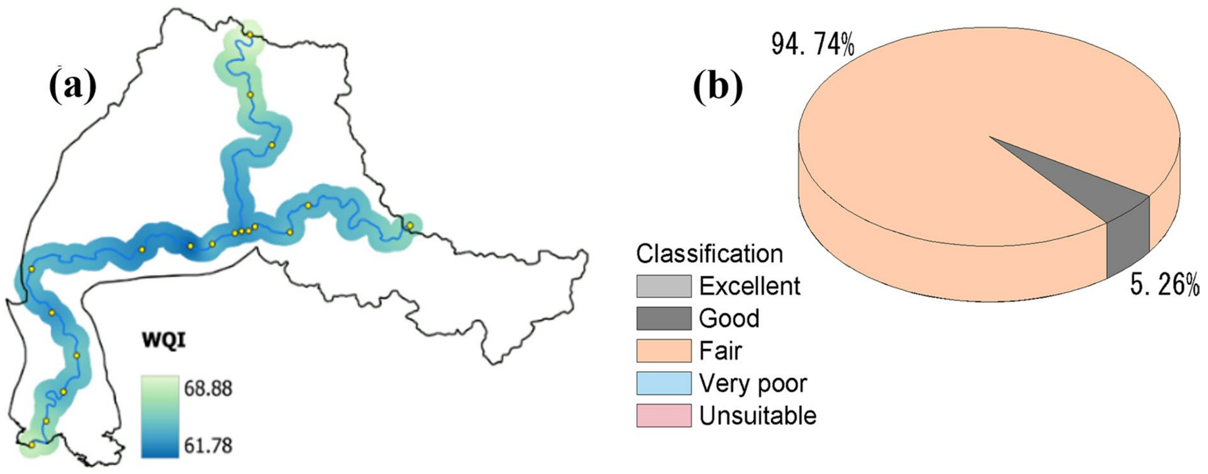


Fig. 11 WQI results in the Culiacan River basin. **a** Spatial behavior and **b** classification percentages

Table 4 WQI classification, range, and type

Range	Type	Classification	
91-100	I	Excellent	⬜
71-90	II	Good	⬛
51-70	III	Fair	🟧
26-50	IV	Very poor	🟦
0-25	V	Unsuitable	🟥

Table 5 WQI results of surface water samples from the Culiacan River basin

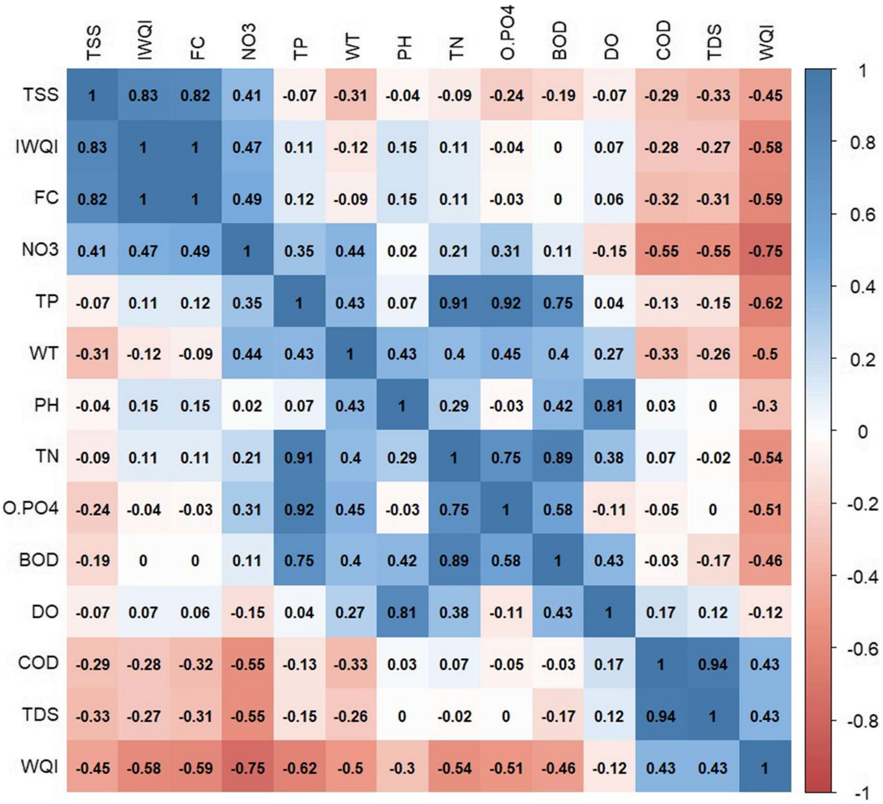
Site	2012	2013	2014	2015	2016	2017	2018	2019	2020
1	71	64	66	66	67	66	63	64	67
2	62	64	62	67	64	66	64	66	64
3	66	64	61	67	66	67	64	65	62
4	60	63	60	65	66	66	64	68	63
5	64	60	63	63	66	65	63	67	59
6	60	61	60	66	64	62	64	64	62
7	62	64	64	65	67	62	66	69	63
8	71	65	64	66	69	66	69	71	60
9	70	72	72	70	69	63	62	71	71
10	62	60	65	64	65	63	64	67	63
11	62	62	60	64	66	65	65	68	69
12	65	57	59	57	64	63	66	65	60
13	58	64	59	63	63	64	64	66	64
14	63	65	62	64	64	65	67	69	62
16	61	62	62	65	62	64	65	67	62
15	63	64	66	65	65	67	67	65	64
17	63	65	64	62	65	66	64	67	63
18	65	70	66	63	66	68	63	69	65
19	68	68	67	71	66	71	66	70	66

indicator since it does not strictly adhere to the regulatory quality criteria. In this study, the IWQI classified 26.32% of the samples as severely polluted, 23.98% as moderately polluted, 22.8% as slightly polluted, 13.45% as semi-clean, and 13.45% as clean. According to IWQI, a surface water sample is classified as "clean" when no chemical parameter exceeds its acceptable limit. The WQI showed that 94.74% of the samples presented a fair water quality. This result confirms that the surface waters of the Culiacan River Basin are considered suitable for agricultural irrigation based on these standards (FAO, 2021).

Figure 12 shows the Pearson correlation between WQI and IWQI indices with the parameters used in their calculation. This analysis was carried out to identify the parameters that highly influenced the indices' variations. It is important to note that a higher WQI value indicates better water quality, whereas for IWQI, a higher value indicates poorer water quality. Therefore, negative correlations between both indices are observed. IWQI exhibited a strong correlation with TSS (1.00), FC (0.83), and NO_3 (0.47). On the other hand, WQI shows a high correlation with NO_3 (0.75), TP (0.62), and FC (0.59). According to these results, IWQI is highly influenced by runoff and untreated wastewater effluents, while WQI is mostly influenced by agricultural activities. It is noteworthy that NO_3 and FC showed a high influence on the IWQI and WQI variations. When the WQI and IWQI indices were correlated, both parameters were identified as the variables that most influenced these indices' variations. These results are relevant since the most important water quality parameters that influence water quality variations in the Culiacan River basin were identified. Understanding these correlations is fundamental for developing effective water management strategies, focusing on water quality parameters that show the highest variation. Lv et al. (2023) also correlated the WQI with the water quality parameters and demonstrated that TP showed the most significant influence on the Pearl River, China. This methodology contributes to a more comprehensive understanding of the factors influencing water quality for the development of more effective strategies for the management and protection of water resources.

Conclusions

The study provides an in-depth description of the behavior of the Humaya, Tamazula, and Culiacan Rivers located in a tropical region. The present study demonstrated the vulnerability of these surface water bodies to anthropogenic activities and hydrological characteristics of the study area. The temporal analysis of the water quality parameters showed a high variation in water quality conditions between the rainy and dry seasons. The sampling site 12 showed a higher concentration and variation of water nutrients



	TSS	IWQI	FC	NO3	TP	WT	PH	TN	O.PO4	BOD	DO	COD	TDS	WQI
TSS	1	0.83	0.82	0.41	-0.07	-0.31	-0.04	-0.09	-0.24	-0.19	-0.07	-0.29	-0.33	-0.45
IWQI	0.83	1	1	0.47	0.11	-0.12	0.15	0.11	-0.04	0	0.07	-0.28	-0.27	-0.58
FC	0.82	1	1	0.49	0.12	-0.09	0.15	0.11	-0.03	0	0.06	-0.32	-0.31	-0.59
NO3	0.41	0.47	0.49	1	0.35	0.44	0.02	0.21	0.31	0.11	-0.15	-0.55	-0.55	-0.75
TP	-0.07	0.11	0.12	0.35	1	0.43	0.07	0.91	0.92	0.75	0.04	-0.13	-0.15	-0.62
WT	-0.31	-0.12	-0.09	0.44	0.43	1	0.43	0.4	0.45	0.4	0.27	-0.33	-0.26	-0.5
PH	-0.04	0.15	0.15	0.02	0.07	0.43	1	0.29	-0.03	0.42	0.81	0.03	0	-0.3
TN	-0.09	0.11	0.11	0.21	0.91	0.4	0.29	1	0.75	0.89	0.38	0.07	-0.02	-0.54
O.PO4	-0.24	-0.04	-0.03	0.31	0.92	0.45	-0.03	0.75	1	0.58	-0.11	-0.05	0	-0.51
BOD	-0.19	0	0	0.11	0.75	0.4	0.42	0.89	0.58	1	0.43	-0.03	-0.17	-0.46
DO	-0.07	0.07	0.06	-0.15	0.04	0.27	0.81	0.38	-0.11	0.43	1	0.17	0.12	-0.12
COD	-0.29	-0.28	-0.32	-0.55	-0.13	-0.33	0.03	0.07	-0.05	-0.03	0.17	1	0.94	0.43
TDS	-0.33	-0.27	-0.31	-0.55	-0.15	-0.26	0	-0.02	0	-0.17	0.12	0.94	1	0.43
WQI	-0.45	-0.58	-0.59	-0.75	-0.62	-0.5	-0.3	-0.54	-0.51	-0.46	-0.12	0.43	0.43	1

Fig. 12 Pearson correlation of water quality parameters used for the calculation of WQI and IWQI indices. Blue color indicates a positive correlation, while red color indicates a negative correlation

(TP, TN, BOD, and COD) and fecal bacteria possibly because it is in the agricultural area. The spatial analysis also demonstrated a deterioration of the water quality conditions at the sampling sites located in the urban area. IWQI evidenced that 73.1% of the samples can be classified as severely polluted, moderately polluted, or slightly polluted. Significant correlations were observed between water quality parameters, indicating positive and negative relationships that reflect the complex interactions within the water quality ecosystem. These strong correlations suggest opportunities to develop mathematical models for simulating river water quality conditions, particularly to develop useful tools for various hydrological and climate change scenarios.

IWQI and WQI identified that TSS, NO_3, and FC were the parameters that showed a high influence on the water quality variation, where the runoff, agricultural activities, and untreated wastewater effluents were identified as the most important drivers of surface water pollution of the Culiacan River basin. To mitigate the influence of the anthropogenic activities on surface waters in the Culiacan River Basin, continuous monitoring of the activities close to the study area must be instaurated since the urban infrastructure is advancing rapidly and the surface water contamination is evident, which not only affects the ecosystems but also makes water unsuitable for other uses such as agriculture.

Study limitations and future work

Due to financial limitations, this study presents results from a 6-month sampling period in the Culiacan River. Further research is needed to capture seasonal variations in a shorter sampling period to achieve a more comprehensive understanding. Although the study examined 22 water quality parameters, future research should also include emerging contaminants like microplastics and pharmaceuticals because of their growing importance in water quality assessment. Besides, future studies should use predictive models to assess the water quality of the Culiacan River basin under different hydrological and climate scenarios and forecast potential water quality changes.

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Author contributions Yaneth A. Bustos-Terrones: conceptualization; writing—original draft; writing—review and editing; visualization; investigation. Juan G. Loaiza: software; writing—review and editing; resources. Jesús Gabriel Rangel-Peraza: methodology; resources; writing—review and editing. Ma. Neftalí Rojas-Valencia: visualization; writing—review and editing; formal analysis. All authors reviewed the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Confict of interests The authors declare no competing interests.

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