Water Air Soil Pollut (2024) 235:260
https://doi.org/10.1007/s11270-024-07050-3

Assessing the Physicochemical and Microbiological Condition of Surface Waters in Urabá-Colombia: Impact of Human Activities and Agro-Industry

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Received: 1 August 2023 / Accepted: 20 March 2024 / Published online: 13 April 2024

Abstract Water resources in the Urabá region of Colombia, one of the most significant banana-producing areas for global consumption, are confronted with substantial challenges due to agro-industrial activities, population growth, untreated wastewater discharge, and excessive groundwater usage. This study aims to comprehensively evaluate the physicochemical and microbiological characteristics of surface waters in Urabá, delving into the influence of agro-industrial activities and human interventions on water quality. The evaluation includes a correlation analysis of multiple water quality parameters measured in ten significant rivers of the region. The findings reveal overall water pollution, potentially associated with the lack of wastewater treatment systems in nearby communities and indicate potential seawater intrusion due to groundwater overexploitation from human and agricultural activities. Among the studied rivers, the Apartadó River exhibits the poorest water quality, while the León River demonstrates better conditions, benefiting from less human interference and natural ecosystems.

Keywords Water quality assessment · Surface water · Water pollution · Urabá-Colombia · Agro-industry · Seawater intrusion

1 Introduction

Colombia is one of the countries with the highest freshwater availability in the world, with three times more water potential than other South American countries and six times more than the average world water availability (Gualdrón-Durán, 2016). Despite its status as one of the most abundant natural resources in the Antioquia department, water is grappling with limitations in availability due to the dual challenges of population and industry growth. These factors not only contribute to an increasing demand for water but also lead to heightened pollutant discharges into surface and ground waters, adversely affecting the overall quality and availability of water from these sources (Evans et al., 2019; Nitasha & Sanjiv, 2015; Vallejo Toro et al., 2016).

Several studies are being conducted worldwide to assess water quality in different sources, evaluating physicochemical and microbiological parameters such as temperature, pH, dissolved oxygen, turbidity, nitrogen, phosphate, Chemical oxygen demand,

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biological demand of oxygen, total dissolved solids, total coliforms, *Escherichia coli (E. coli)*, and others. These studies reveal that, in general, these parameters can exhibit significant variations, even due to seasonal factors (Brainwood et al., 2004; Gupta et al., 2017; Şener et al., 2017). Similarly, studies on surface water sources show how human activities, including pollution from specific industries, domestic wastewater, and various agricultural practices, have a discernible impact on water quality (Dalla Vecchia et al., 2015; Derfoufi et al., 2019).

Regarding the use of this resource, the economic activity that demands the most water is agriculture, which accounts for more than 70% of the world's freshwater withdrawals from rivers, lakes, and aquifers. For countries with low income (GNI Gross National Income less than US $1005) or lower-middle income (from US$1006 to US$3955), this value corresponds to 82% (Galvis et al., 2018). In addition, contamination can be triggered if agricultural products are mishandled and the purification and disposal processes are not carried out technically and responsibly (Barragán et al., 2020; Lans-Ceballos et al., 2018; Wu et al., 2018).

In the Urabá region, this resource is mainly oriented towards agricultural activities such as cultivation and export of bananas and plantains. The region also has intensive production of oil palm, cocoa, corn, rice, cassava, plantain, avocado, and mango, as well as cattle, buffalo, sheep, goats, pigs, and horses (Corporación para el Desarrollo Sostenible del Urabá—CORPOURABÁ 2016, 2019; Pemberthy et al., 2021).

Currently, the expansion of plantain and banana monoculture plantations in Urabá is leading to the overexploitation of the region's aquifer and surface waters. This has a direct impact on water quality in the area due to the continuous discharge of pesticide and fertilizer residues from fruit production processes. These pollutants are introduced into the waters through infiltration or runoff, further exacerbating the situation. In addition, the lack of wastewater treatment systems means that domestic and non-domestic discharges are also made directly into rivers, which causes the degradation of the quality of surface water bodies (CORANTIOQUIA and Tecnológico de Antioquia 2011; Instituto de Hidrología, Meteorología y Estudios Ambientales—IDEAM, 2019; Pemberthy et al. 2021).

While there is a diversity of research on the coastal ecosystem of the Gulf of Urabá, specific studies addressing water quality in the region's rivers are lacking. For example, Pemberthy et al., (2020, 2021) focused their study on investigating the presence of emerging pollutants, including pharmaceuticals and traces of metals such as Cr, Pb, and Hg, in seawater in the coastal area of Urabá's Gulf. This research sheds light on contamination sources in coastal waters but does not address potential pollution in the region's rivers. Similarly, Yanes et al. (2019) introduced a novel methodology for ecological risk assessments in the coastal areas of the Department of Antioquia. However, their study primarily examined mangroves and beaches, overlooking river ecosystems.

As a result of these various human activities that degrade water quality in the region, it becomes essential to monitor the physicochemical and microbiological parameters in water bodies. This monitoring is necessary for assessing the impacts of these activities, promoting responsible water use, and ensuring environmental sustainability and human health protection (Haque et al., 2018). Analyzing these parameters not only provides indicators of the dynamics and ecological stability of the system but also serves as evidence of the presence of pollutants (Evans et al., 2019; Gualdrón-Durán, 2016), This, in turn, can guide the development of strategies for mitigating and preventing water pollution in the future.

It is crucial to acknowledge that the interplay among these variables can fluctuate depending on the unique conditions in the Urabá region of Antioquia. A thorough examination of the gathered data is essential to grasp the specific connections within the region and to understand how water quality might be influenced by human activities and agro-industry.

The variables under scrutiny in this investigation are deemed essential indicators, providing comprehensive insights into the chemical, physical, and microbiological makeup of the water. In addition to identifying potential effects of human activities and agribusiness on water bodies, the collective assessment fosters a more holistic comprehension of water quality.

Consequently, the aim of this study is to evaluate the physicochemical and microbiological features of surface waters in the Urabá region. It involves conducting an exploratory and comprehensive examination of the principal rivers in connection with their agricultural and population contexts. The assessment seeks to explore correlations between these characteristics and various factors, including cultivation areas, elevation, geology, proximity to communities, and distance from the sea.

Furthermore, the study endeavors to provide an initial assessment of water quality for agro-industrial purposes through the evaluation and correlation study of physicochemical and microbiological parameters.

1.1 Study Context

The Urabá region is located in the northwestern part of Antioquia-Colombia (see Fig. 1). It is bordered to the north and northwest by the Caribbean Sea (Atlantic Ocean), where the Gulf of Urabá is located; to the east by the department of Córdoba and the western region; to the south by the department of Chocó, the southwestern and western regions; and to the west by the department of Chocó. It has an area of 11,664 km^2 (representing 18.6% of the total area of the department). The height ranges from 0 to 3200 m above sea level (Camacho Rojas, 2014) (see also Fig. 2(c)). Its average temperature is 28.0 °C, and the relative humidity is about 85.9%, corresponding to a tropical rainforest's climate characteristics. The intertropical convergence zone determines the region's climate, characterized by an average annual rainfall ranging from 2100 to 3800 mm in the north–south direction. A rainy season from April to November and a dry season between December and March also characterize this region (Campillo et al., 2021).

This region is composed of 11 municipalities classified into three zones: Northern (Arboletes, Necoclí, San Juan de Urabá, and San Pedro de Urabá), Central (Turbo, Apartadó, Carepa, Chigorodó, and Mutatá), and the Middle Atrato zone (Murindó and Vigía del Fuerte) as illustrated in Fig. 1 (Corporación para el Desarrollo Sostenible del Urabá—CORPOURABÁ 2016).

Serranía del Abibe is the primary supply reserve and the main provider of ecosystem services in

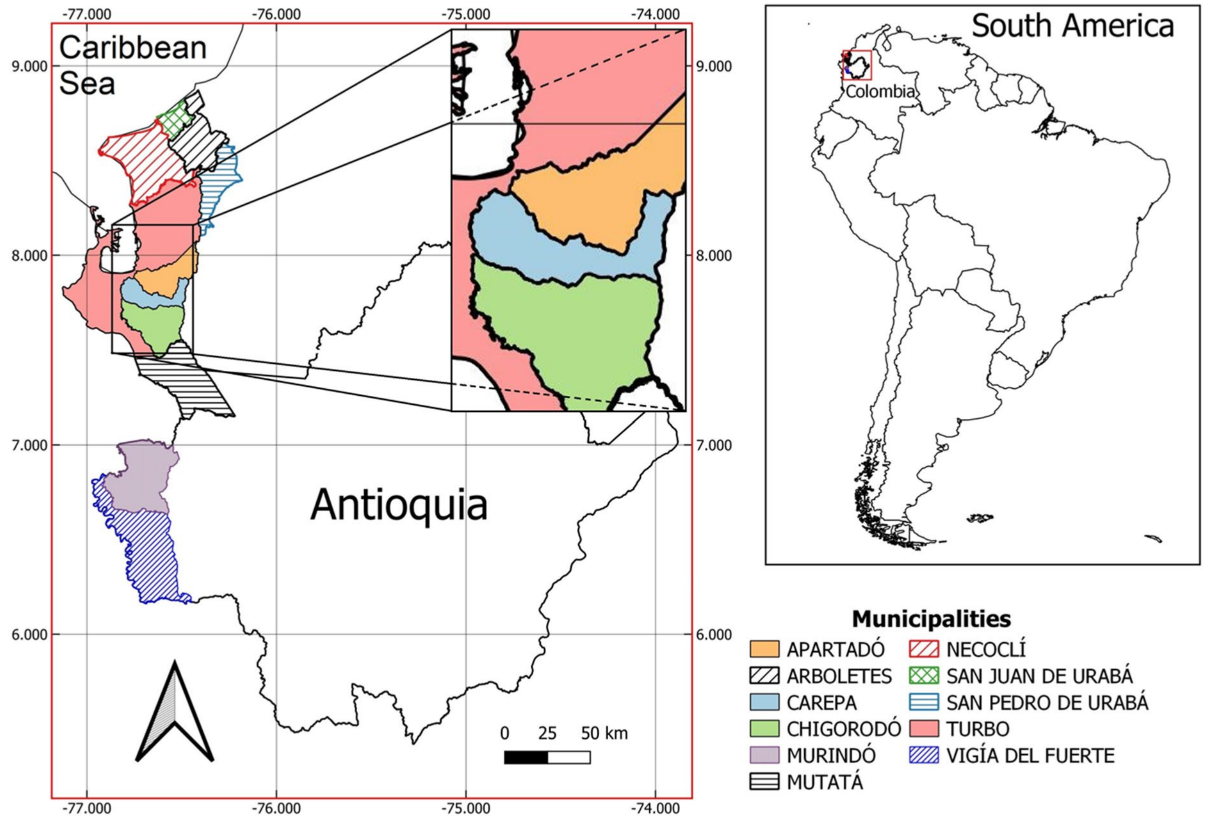


Fig. 1 Municipal delimitation of the Urabá region and the study area — source: The authors

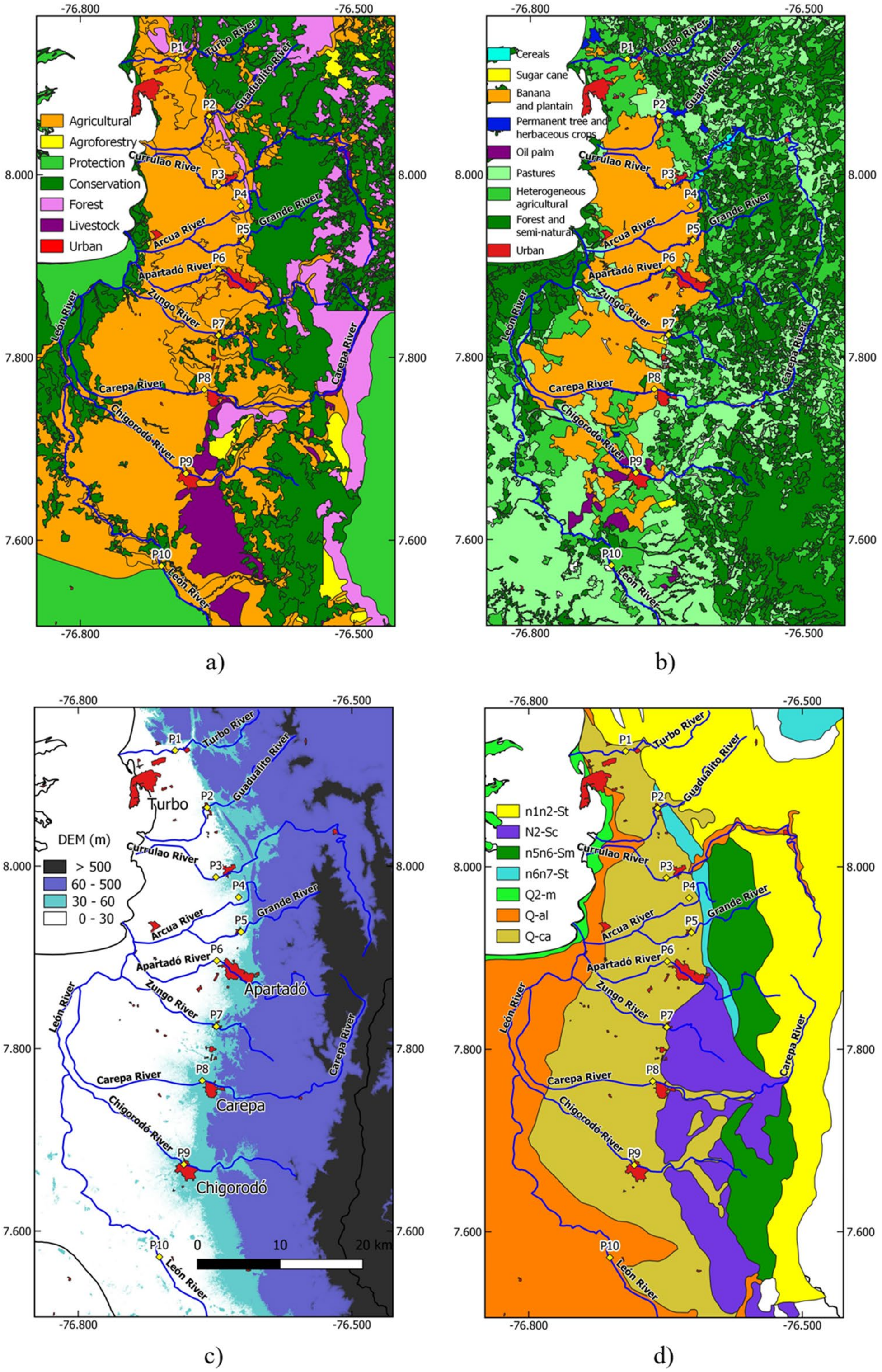


Fig. 2 Maps of the Urabá region: a) Soil Purpose (2017), b) Agricultural Activity (2018), c) Digital Elevation Model (DEM) and d) Geology (2015). The river sampling is labeled as P1 to P10. — source: The authors *(Instituto de Hidrología, Meteorología y Estudios Ambientales*—IDEAM, 2018*; Instituto Geográfico Agustín* Codazzi-IGAC, 2012*)*

the Urabá region. The Turbo, Currulao, Apartadó, Carepa, Chigorodó and Mutatá rivers originate there. These rivers are the leading water suppliers for the towns and cities of the region. The León River basin is also identified, which runs through the municipalities of Mutatá, Chigorodó, Carepa, Apartadó, and Turbo, flowing directly into the Gulf of Urabá. It is also a maritime route for exporting bananas abroad. (Corporación para el Desarrollo Sostenible del Urabá—CORPOURABÁ 2016).

The study area was delimited to Turbo, Apartadó, Carepa, and Chigorodó municipalities (see Fig. 1), considering the Turbo, Guadualito, Currulao, Arcua, Grande, Apartadó, Zungo, Carepa, Chigorodó, and León rivers the Urabá region that constitutes the León River basin, as is shown in Fig. 3. The spatial distribution of conservation, protection, production, and urban areas is shown in Fig. 2(a), where agriculture and livestock farming are the main sectors of economic activity. Furthermore, Figs. 2(b) and 2(c) show that banana and plantain are the dominant crops in the study area and that practically all the productive activity is carried out in soil with an elevation below 60 m.a.s.l. (meters above sea level). On the other hand, Fig. 2(d) shows the geological map of the region. Here, it can be observed that practically all urban areas are settled in Q-ca (Quaternary-Pleistocene-Holocene-colluvium and alluvium: alluvial fans and colluvial deposits), while all the agricultural and livestock activities take place both in Q-ca and in Q-al (Quaternary-Pleistocene-Holocene-alluvium: Floodplain and alluvial deposits).

2 Materials and Method

As illustrated in Fig. 3 and Table 1 below, the study area was delimited by taking a sampling point in each of the León, Chigorodó, Carepa, Zungo, Apartadó, Grande, Arcua, Currulao, Guadualito, and Turbo Rivers of the Urabá region. The recommendations of the American Water Works Association, as outlined in the 23rd edition of the Standard Methods publication, were followed for collecting, preserving, and managing water samples from each river, where the parameters assessed, including the units and analysis methods used were listed in Table 2 (Baird et al., 2017). To analyze the physicochemical and microbiological parameters, sterile 500-mL polyethylene and 250-mL glass containers were employed. These containers were submerged approximately 30 cm below the water surface at a minimum of three points around each selected location in any given river, with the aim of calculating average values. These samples were then duly labeled, sealed, and transported to the laboratory of the University of Antioquia—Apartadó campus at a temperature of approximately 4.0 °C. The ambient temperature was measured at each sampling point, and the physicochemical variables of water samples were measured with a multiparametric probe: water temperature, pH, dissolved oxygen, and conductivity.

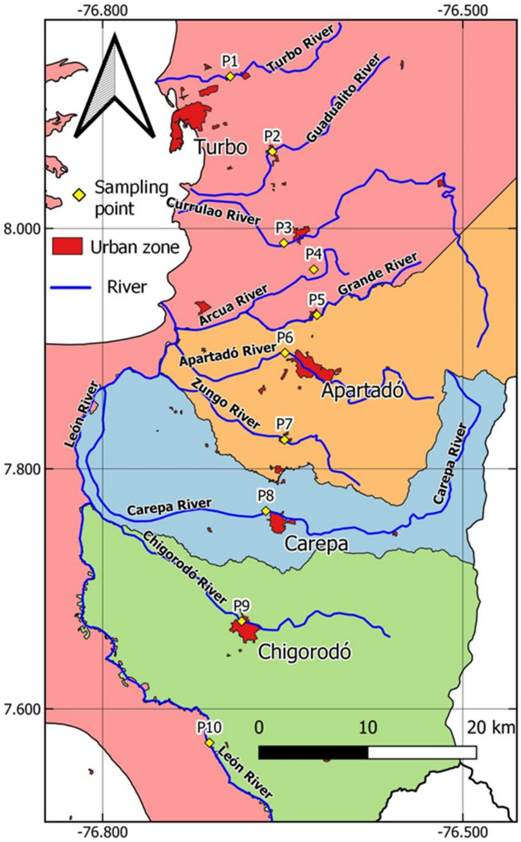


Fig. 3 The Urabá region: Sampling points and rivers map in the study area (P1 to P10). The largest red areas represent the urban spots of the municipal centers, while the remaining ones represent other populated centers — source: The authors

Spatial trends in the measurements of rivers water's physicochemical and microbiological parameters were graphically examined with Quantum Geographic Information System (QGIS) version 3.22.5.

Table 1 Sampling points of the evaluated water bodies — source: The authors

Sample point	Location	Coordinates		
		Latitude	Longitude	Altitude (m)
P1	Turbo River	8.1266660	-76.6936676	21.4
P2	Guadualito River	8.0641056	-76.6585601	28.6
P3	Currulao River	7.9878032	-76.6490078	23.4
P4	Arcua River	7.9658303	-76.6240585	25.1
P5	Grande River	7.9278369	-76.6214059	27.6
P6	Apartadó River	7.8962484	-76.6480077	24.7
P7	Zungo River	7.8241638	-76.6484759	39.3
P8	Carepa River	7.7647969	-76.6639725	31.3
P9	Chigorodó River	7.6729423	-76.6841424	34.0
P10	León River	7.5716390	-76.7110000	16.6

Table 2 Physicochemical and microbiological parameters evaluated in the different surface water samples — source: The authors

Parameters	Units	Methods
Ambient temperature	°C	Thermometric
Water temperature	°C	
Biochemical oxygen demand (BOD_5)	mg/L	Membrane Electrode
Dissolved oxygen (DO)	mg/L	
pH	pH units	Electrometrical
Conductivity	μS/cm	
Ammonia nitrogen (NH_3-N)	mg/L	Colorimetric
Orthophosphates (PO_4-P)	mg/L	
Total coliforms	MPN/100 mL	Defined substrate
Escherichia coli *(E. coli)*	MPN/100 mL	
Chemical oxygen demand (COD)	mg/L	Closed-colorimetric reflux
Viable heterotrophs	CFU/100 mL	Membrane filtration

In addition to estimating the distance parameter, defined as the distance from the sampling point to the mouth of the river in the sea, from the layer of rivers shown in Fig. 3.

A Shapiro–Wilk test was used to verify the normality assumption for each parameter. Since the results revealed non-normal distributions, Spearman's Rho matrix and the Mann–Whitney U test (non-parametric statistical analysis) were calculated to assess the strength of association between parameters at sampling sites. The statistical significance was set in these analyses at 0.001, 0.01 and 0.05. The analyses were performed with Python along with the Seaborn and Scipy libraries. To see more details of these analyses, please refer to the source code at (Aristizábal-Tique et al., 2024).

3 Results

The following results were obtained from the analysis of physicochemical and microbiological parameters monitored during sunny, partly cloudy, and cloudy days in a dry season. At some sampling points, solids, and turbidity were observed in surface waters, directly related to the presence of decomposing organic matter and hydrogen sulfide.

The distance from the test point to the mouth of the river in the sea and the population of the urban centers show heterogeneous values, ranging from around 6 km to 50 km and from 4000 hab. to 100,000 habs., respectively (Departamento Administrativo Nacional de Estadística -DANE 2018; Gobernación de Antioquia, 2023).

Table 3 displays the results obtained from the river monitoring. The average ambient temperature recorded was 28.9 °C, while the average water temperature was 27.6 °C. Dissolved oxygen (DO) levels ranged from 6.73 to 8.00 mg/L, except for the Apartadó river, which exhibited extremely low DO levels of 0.03 mg/L. The pH values ranged from 7.1 to 8.2, indicating an alkaline tendency.

On the other hand, nutrient concentrations, specifically ammonia nitrogen (NH3-N) and orthophosphate (PO4-P), were found to exceed the reference standards (refer to Table 4). Furthermore, for sampling points P1 to P6, the surface water bodies exhibited BOD_5 and COD values surpassing the recommended limits established in resolution 0631 of 2015 (see Table 4). Notably, the Apartadó river (P6) presented the highest values among the sample points.

Regarding the microbiological parameters, values above 1600 MPN/100 mL were found for total coliforms. In addition, the minimum value of 540 MPN/100 mL was observed for *E. coli*. However, some bodies presented values higher than 1600 MPN/100 mL. For viable heterotrophs, values above 20.0×10^4 CFU/ mL were obtained in most of the samples (TNTC too numerous to count, values above 20.0×10^4 CFU/ mL) (see Table 4).

From a visual and qualitative approach, spatial variation of pH, conductivity, DO, BOD_5, COD, PO_4-P, NH_3-N, *E. Coli*, and Heterotrophs are presented in Fig. 4. Here, the pH values recorded correspond to values between 7.1 and 8.2, considered neutral to slightly alkaline, with the highest values for the Turbo and Guadalito Rivers (8.2) and the lowest for the Chigorodó River (7.1). In Fig. 4, conductivity showed differences among all the points measured, with values ranging from 169 to 847 µS/cm, showing a tendency to decrease from north to south; in addition, a decrease is observed from the sampling point closest to the farthest from the sea.

The DO showed similar values at all points, except for the Apartadó River, which was significantly lower. Apartadó is the urban area with the largest population. The BOD_5 results varied among the points, with values ranging from 46.2 to 241.7 mg/L. There was a trend towards higher BOD_5 in the north of the region and lower in the south, with the highest value being in the Apartadó river (241.7 mg/L) and the lowest in the Carepa river (46.2 mg/L). The same trend was evident in the COD measurement, where the highest value

Table 3 Monitoring results for the physicochemical parameters in the different surface water samples — source: The authors

Sample point *	Ambient Temp. (°C)	Water Temp. (°C)	DO (mg/L)	pH	Conductivity (µS/cm)	Ammonia nitrogen (NH_3-N) (mg/L)	Ortho phosphate (PO_4-P) (mg/L)	COD (mg/L)	BOD_5 (mg/L)
P1	26.6	27.4	7.71	8.2	847	7.6	0.108	287.1	220.0
P2	28.1	27.3	7.62	8.2	774	6.8	0.128	239.0	215.0
P3	30.4	28.8	7.55	7.9	714	8.0	0.131	255.6	191.7
P4	29.8	26.7	7.36	8.0	464	7.9	0.193	209.7	188.3
P5	28.0	27.4	7.62	7.9	428	8.3	0.136	176.7	154.3
P6	30.8	28.6	0.03	7.5	579	17.7	0.316	324.5	241.7
P7	29.9	27.8	8.00	7.7	305	8.5	0.070	151.3	113.3
P8	30.1	27.5	7.04	7.9	428	15.1	0.085	90.0	46.2
P9	27.1	26.7	7.74	7.1	186	11.3	0.090	121.9	120.0
P10	28.0	27.8	6.73	7.5	169	7.9	0.126	104.5	78.3

* The table presents the average values of three points around each selected point in any river

Table 4 Results obtained for the microbiological, distance and population parameters for the sample sites — source: The authors

Sample point *	Viable heterotrophs (CFU/mL)	Total coliforms (MPN/100 mL)	*E. coli* (MPN/100 mL)	Distance (m)	Population (hab.)
P1	3.4×10^4	> 1600	540	6595.6	4033
P2	5.7×10^4	> 1600	920	9747.4	10,955
P3	TNTC	> 1600	> 1600	10,783.6	23,344
P4	TNTC	> 1600	920	15,754.4	9682
P5	TNTC	> 1600	1600	15,562.0	7490
P6	TNTC	> 1600	1600	15,194.3	98,454
P7	15.0×10^4	> 1600	735	19,587.1	9093
P8	TNTC	> 1600	> 1600	34,983.3	33,009
P9	TNTC	> 1600	> 1600	40,356.1	47,046
P10	5.7×10^4	> 1600	1000	53,325.7	4597

* The table presents the average values of three points around each selected point in any river

was in the Apartadó River (324.5 mg/L), and the lowest was in the Carepa River (90.0 mg/L). The concentrations of PO_4-P and NH_3-N were significantly different among the evaluated rivers; the Apartadó River was the one that presented the highest concentrations in both cases (0.316 mg/L, 17.7 mg/L, respectively). Considering the microbiological parameters, the Turbo, Guadualito, Zungo, and León Rivers presented lower values of *E. Coli* and viable heterotrophs, while the remaining showed very high values.

Figure 5 shows the Spearman's Rho matrix, where several expected and significant relationships can be observed, where the geomorphological (Altitude and Distance from the test point to the mouth of the river in the sea) and population parameters are correlated with the physicochemical and microbiological parameters of water (ammonia nitrogen, conductivity, pH, etc.). Many strong and significant correlations are identified between the distance measurements and the physicochemical parameters (conductivity, pH, BOD5, COD). In contrast, more moderate correlations are identified between the population measurements and the microbiological parameters (E. coli, Viable heterotrophs) and ammoniacal nitrogen.

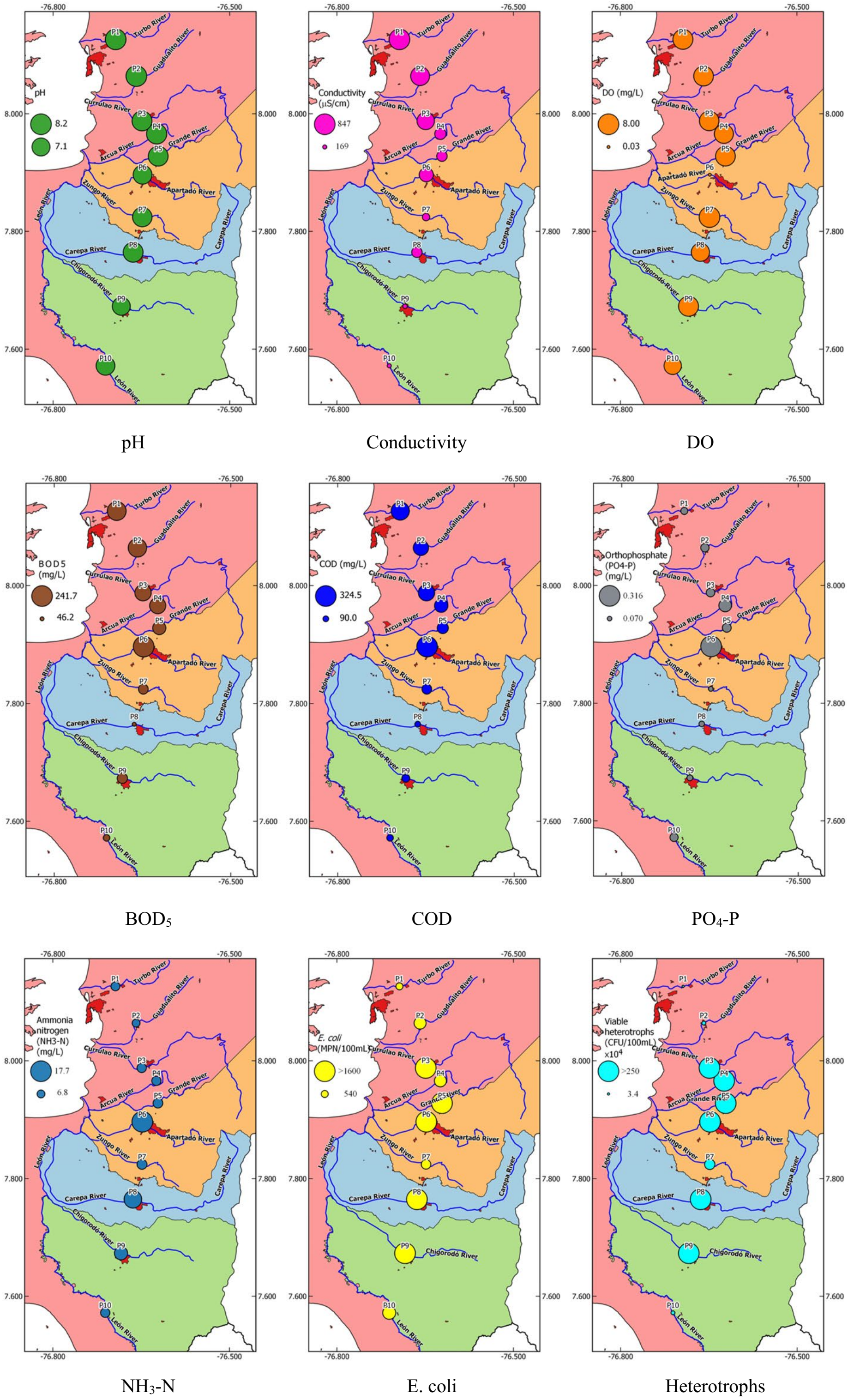
4 Discussion

Considering the water quality parameters based on Colombian standards and norms, the results of the samplings have indicated that water quality conditions, in general, fall far from the recommended limits for agricultural activities. The water quality criteria considered in this study are based on the regulations and parameters presented in Table 5. Below, we will assess the main results concerning the measured parameters.

Regarding the DO, the results show that, except for the Apartadó River, all the sampled rivers showed an ideal DO concentration with values above 5.0 mg/L. These DO levels indicate a good water quality and a healthy ecosystem (Carvalho et al., 2021; Instituto de Hidrología, Meteorología y Estudios Ambientales—IDEAM, 2019; Peirce et al., 1998).

Although these DO values would be expected to find low values of COD and BOD_5, this was not what was observed in all measured rivers; for example, the COD values of the Apartadó, Arcua, Currulao, Guadualito, and Turbo rivers exceed the maximum values allowed by the standard, as does the BOD5. Therefore, it is possible to have high DO levels in a river water sample despite a high COD and BOD_5 if there are other factors contributing to the oxygenation of the water, like as aeration from natural processes like wave action or waterfalls, photosynthesis by aquatic plants, water temperature, atmospheric oxygen exchange and the presence of oxygen-producing organisms (Ma et al., 2021; Radwan et al., 2003).

The very low DO value measured in the Apartadó River is striking (0.03 mg/ L); this value can be related to the high values of BOD_5 and COD: 241.7 mg/L and 324.5 mg/L, respectively. BOD is a measure of the amount of oxygen consumed by microorganisms in the water as they decompose

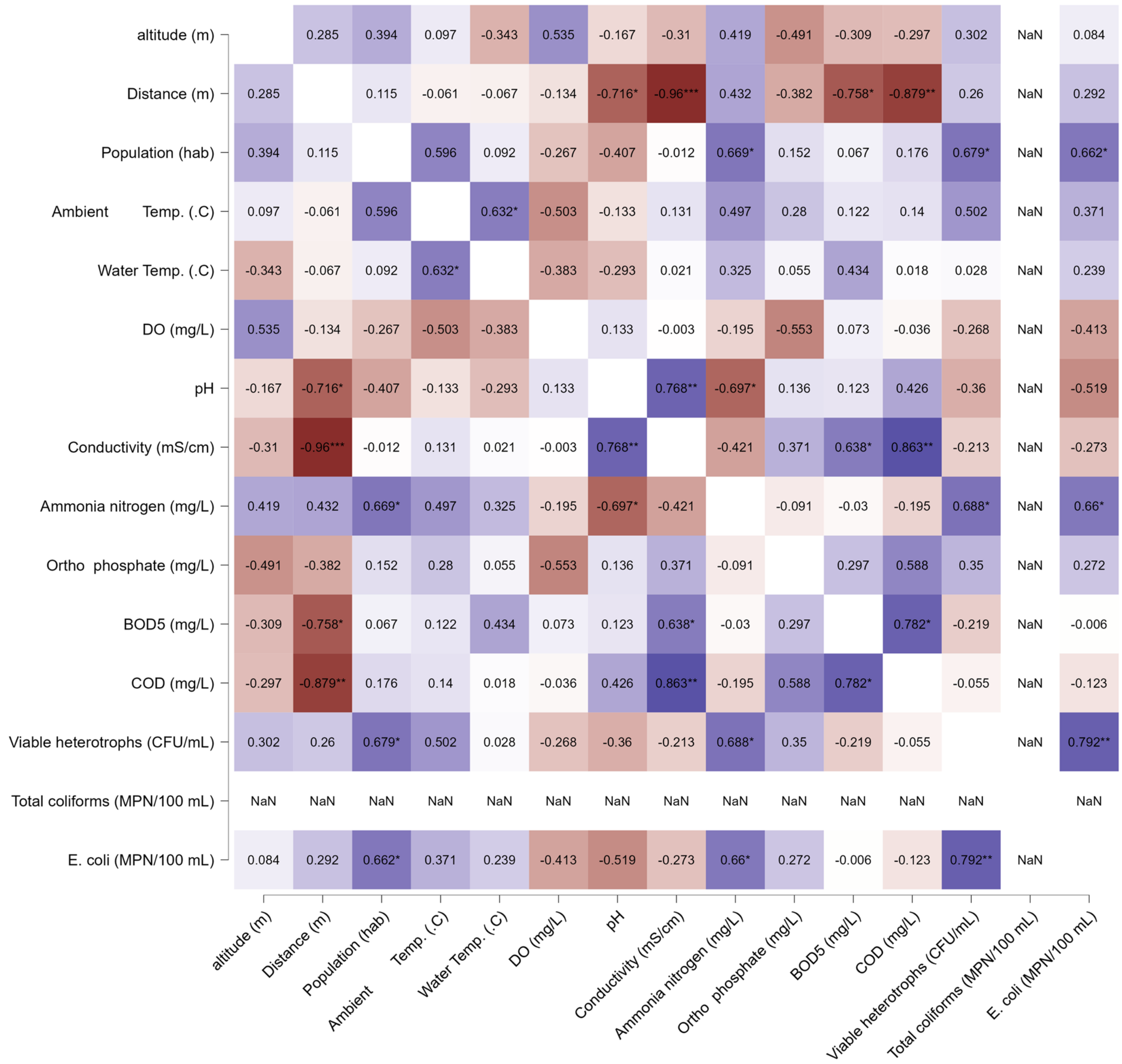


pH Conductivity DO

BOD_5 COD PO_4-P

NH_3-N E. coli Heterotrophs

Fig. 4 Characterization of parameters measured in the sampling points — source: The authors



	altitude (m)	Distance (m)	Population (hab)	Ambient Temp. (.C)	Water Temp. (.C)	DO (mg/L)	pH	Conductivity (mS/cm)	Ammonia nitrogen (mg/L)	Ortho phosphate (mg/L)	BOD5 (mg/L)	COD (mg/L)	Viable heterotrophs (CFU/mL)	Total coliforms (MPN/100 mL)	E. coli (MPN/100 mL)
altitude (m)		0.285	0.394	0.097	-0.343	0.535	-0.167	-0.31	0.419	-0.491	-0.309	-0.297	0.302	NaN	0.084
Distance (m)	0.285		0.115	-0.061	-0.067	-0.134	-0.716*	-0.96***	0.432	-0.382	-0.758*	-0.879**	0.26	NaN	0.292
Population (hab)	0.394	0.115		0.596	0.092	-0.267	-0.407	-0.012	0.669*	0.152	0.067	0.176	0.679*	NaN	0.662*
Ambient Temp. (.C)	0.097	-0.061	0.596		0.632*	-0.503	-0.133	0.131	0.497	0.28	0.122	0.14	0.502	NaN	0.371
Water Temp. (.C)	-0.343	-0.067	0.092	0.632*		-0.383	-0.293	0.021	0.325	0.055	0.434	0.018	0.028	NaN	0.239
DO (mg/L)	0.535	-0.134	-0.267	-0.503	-0.383		0.133	-0.003	-0.195	-0.553	0.073	-0.036	-0.268	NaN	-0.413
pH	-0.167	-0.716*	-0.407	-0.133	-0.293	0.133		0.768**	-0.697*	0.136	0.123	0.426	-0.36	NaN	-0.519
Conductivity (mS/cm)	-0.31	-0.96***	-0.012	0.131	0.021	-0.003	0.768**		-0.421	0.371	0.638*	0.863**	-0.213	NaN	-0.273
Ammonia nitrogen (mg/L)	0.419	0.432	0.669*	0.497	0.325	-0.195	-0.697*	-0.421		-0.091	-0.03	-0.195	0.688*	NaN	0.66*
Ortho phosphate (mg/L)	-0.491	-0.382	0.152	0.28	0.055	-0.553	0.136	0.371	-0.091		0.297	0.588	0.35	NaN	0.272
BOD5 (mg/L)	-0.309	-0.758*	0.067	0.122	0.434	0.073	0.123	0.638*	-0.03	0.297		0.782*	-0.219	NaN	-0.006
COD (mg/L)	-0.297	-0.879**	0.176	0.14	0.018	-0.036	0.426	0.863**	-0.195	0.588	0.782*		-0.055	NaN	-0.123
Viable heterotrophs (CFU/mL)	0.302	0.26	0.679*	0.502	0.028	-0.268	-0.36	-0.213	0.688*	0.35	-0.219	-0.055		NaN	0.792**
Total coliforms (MPN/100 mL)	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN		NaN
E. coli (MPN/100 mL)	0.084	0.292	0.662*	0.371	0.239	-0.413	-0.519	-0.273	0.66*	0.272	-0.006	-0.123	0.792**	NaN	

Fig. 5 Spearman's rank correlation matrix (Spearman's Rho matrix). *P*-value: * $p<0.05$, ** $p<0.01$, ***$p<0.001$ — source: The authors

organic matter, therefore, a high BOD indicates a high level of organic pollution in the water; on the other hand, the COD is a measure of the amount of oxygen required to oxidize organic and inorganic matter in water, and it represents the amount of pollutants or organic compounds present in the water that can be oxidized. High COD levels suggest a higher concentration of organic matter, such as sewage, industrial waste, or agricultural runoff, which can deplete oxygen levels in the water when it decomposes (Li & Liu, 2019; Peirce et al., 1998; Rao et al., 2023). Thus, it can be concluded that the Apartadó River is the most polluted and with the worst conditions. These results are linked to the fact that this river crosses one of the region's main urban areas, the municipality of Apartadó, and can be explained by the presence of a high organic load from domestic wastewater discharges that reach the water source without any treatment or decrease in the organic load pollutant (Corporación para el

Table 5 Quality criteria according to Colombian regulations and other sources — source: The authors

Parameters	MINAMBIENTE (Resolution 631 of 2015, 2015)	(Instituto de Hidrología, Meteorología y Estudios Ambientales—IDEAM, 2019)	(Roldán-Pérez & Ramírez-Restrepo, 2008)	(Corporación para el Desarrollo Sostenible del Urabá—CORPOURABÁ 2019)
Temperature	–	–	24.0 °C–32.0 °C	0 °C–30.0 °C
DO	–	> 3.0 mg/L	–	> 2.0–5.0 mg/L
pH	6.0–9.0	–	–	6.0–8.0
Conductivity	–	–	< 50 µS/cm, 500–2000 µS/cm	–
Ammonia nitrogen	–	< 3.3 mg/L	–	–
Orthophosphate	–	–	0.001–0.002 mg/L	–
BOD_5	90 mg/L	–	–	–
COD	180 mg/L	–	–	–
Total coliforms	–	–	< 1600 MPN/100 mL	–
E. coli	–	–	1000 MPN/100 mL	–

– : The reference does not mention the parameter maximum allowed value

Desarrollo Sostenible del Urabá—CORPOURABÁ, 2019).

Figure 4 show that points P1 to P6 exhibits the highest BOD_5 and COD values. These points are the closest to the sea, and, as shown in Fig. 5, there is a high correlation between the values of these parameters and the distance to the sea. These results could be explained by the phenomenon of seawater intrusion which can introduce organic matter and nutrients, which lead to increased microbial activity and elevated BOD_5 and COD levels. This, in turn, can result in decreased dissolved oxygen concentrations, potentially affecting aquatic life and overall water quality in affected river systems (Chithra et al., 2021).

In general, the high COD and BOD_5 values obtained for some of the rivers measured could be explained by the presence of biodegradable organic matter from agricultural and livestock activities in the region and by the excess of fertilizers that reach the water bodies through infiltration or runoff (Resolution 631 of 2015, 2015).

Regarding the ammonia nitrogen result for the water bodies assessed, all of them exceeded the reference concentration of < 3.3 mg/L suggested by the National Water Study (Instituto de Hidrología, Meteorología y Estudios Ambientales—IDEAM, 2019). High ammonia nitrogen levels in rivers indicate water pollution, specifically from excess ammonia (NH3) or its ionized form, ammonium (NH4 +). The elevated ammonia nitrogen levels found in the measured rivers could have several causes, including discharge of untreated or inadequately treated wastewater from industries or municipalities; agricultural runoff, especially from excessive use of nitrogen-based fertilizers; ammonia is also released from animal waste, particularly in areas with intensive livestock farming (Jiang et al., 2022). As shown in Fig. 5, there is a direct correlation between the size of the population and the concentration of ammonia nitrogen, which demonstrates the influence of human activities on the river's pollution.

The ammonia nitrogen levels affect the balance of the aquatic ecosystem, decreasing DO in the water as evidenced in the values measured in the Apartadó River, which presented the highest ammonia nitrogen concentration and the lowest DO levels. This relationship is explained because ammonia in water can undergo a process called nitrification, where certain bacteria convert it first to nitrite (NO2-) and then to nitrate (NO3-). This nitrification process is aerobic, meaning it requires dissolved oxygen to occur. As a result, when there are elevated ammonia levels in rivers, the nitrification process may consume significant amounts of dissolved oxygen, leading to decreased oxygen levels in the water (Dunnette & Avedovech, 1983).

Similarly, the concentration of orthophosphates was high for all the rivers evaluated. These values are associated with ecosystems heavily intervened by anthropogenic activities. Currently, the industrial and agricultural activities of the Urabá region contribute to nitrogen and phosphorus in the water. For this reason, the high values of these nutrients are associated with the use of agrochemicals in the region for the production of bananas and plantains and with the decomposition of organic matter from domestic and non-domestic wastewater discharges (Gualdrón-Durán, 2016; Roldán-Pérez & Ramírez-Restrepo, 2008).

In the present study, the microbiological results obtained for the water bodies reported high viable heterotroph > 2000 (TNTC) and total coliforms > 1600 MPN/100 mL values. These results could be explained owing to the close location of the rivers to a source of organic matter. The concentration of *E. coli* was between 530 and > 1600 MPN/100 mL, which denotes the existence of domestic wastewater discharges without any treatment. As shown in Fig. 5, there is a direct correlation between the size of the population and the concentration of *E. coli* and viable heterotroph, which demonstrates once again the influence of anthropogenic activities on the contamination of rivers. Considering that the values in the bacteriological quality of the water vary according to the use of this resource (Roldán-Pérez & Ramírez-Restrepo, 2008), some of the water bodies assessed may be used for agricultural activities since they do not exceed the values of 5000 MPN/100 mL in total coliforms (Ministerio de Ambiente y Desarrollo Sostenible - MADS, 2015a, 2015b). However, some water bodies, such as the Chigorodó, Carepa, Apartadó, and Currulao rivers, exceed the permissible values for fecal coliforms of 1000 MPN/100 mL.

These strong correlations between the population size variable and the measured parameters can be attributed to human activities that contribute to water pollution through various means, such as wastewater discharge, agriculture, and industrial activities. These activities release pollutants which have an impact on water quality and consequently influence the measured values of water quality parameters. The size of the population living near the assessed rivers is directly related to the volume of wastewater produced and discharged into these water bodies. The region experiences high population density in the surrounding municipalities of Apartadó, Carepa, Mutatá, and Chigorodó, as well as significant agro-industrial development, and the absence of wastewater treatment plants. These factors collectively contribute to the increased pollutant load in the water bodies and the observed correlations with water quality parameters. (Corporación para el Desarrollo Sostenible del Urabá—CORPOURABÁ 2019). Notably, the Apartadó River, which passes through the largest population center in the region, the municipality of Apartadó, exhibits the most affected water quality parameters associated with contamination resulting from human activities. However, it is worth noting that within the studied hydrological system, the León River, located in the southern part of the region, exhibited the best water quality conditions. This can be attributed to its greater distance from heavily populated areas and the coast, as well as its location in a less intervened ecosystem.

Concerning Conductivity, which indicates the presence of ionized salts such as chlorides, sodium ions, carbonate, etc. (Gualdrón-Durán, 2016), typical conductivity values, as indicated by (Roldán-Pérez & Ramírez-Restrepo, 2008), are less than 50 µS/cm in waters with low ionic content and range from 500 to 2000 µS/cm in highly mineralized waters. The study found higher conductivity values in rivers closer to the coast (Turbo, Guadualito, Currulao) with a decreasing tendency from north to south, indicating the presence of highly mineralized and salty waters. On the other hand, Spearman's correlation analysis revealed a strong and statistically significant inverse relationship ($p < 0.001$) between Conductivity values and proximity to the coast mouth, with a coefficient of -0.96. Similar strong correlations were found for pH (-0.716), BOD5 (-0.758), and COD (-0.879). These findings suggest that the phenomenon of seawater intrusion in the coastal zone may be responsible for these results (Maliva, 2020), which can be attributed to overexploitation of groundwater by human and agricultural activities in the Urabá region, especially by the banana agro-industry (Muñoz Mora et al., 1997; Villegas et al., 2018). The salinization of groundwater caused by the phenomenon of seawater intrusion is widely recognized as one of the main environmental problems in coastal regions worldwide. Overexploitation of water resources is considered a major contributing factor to this phenomenon, as it triggers piezometric inversion that enables the flow of groundwater from the coast inland. Additionally, studies have demonstrated the association between urban development and salinization of coastal aquifers due to water resource overexploitation (Kazakis et al., 2019; Muñoz Mora et al., 1997; Shalev, 2021).

Regarding pH, values between 7.1 and 8.2 were registered, indicating an alkaline condition in the waters. The presence of alkaline pH suggests the possible occurrence of substances such as carbonates and phosphates in the river basin or runoff from agricultural fields, where they are used to modify the pH of agricultural soils. Additionally, it is important to consider the possibility of seawater intrusion as a contributing factor to the alkaline pH in the coastal areas. Seawater intrusion can introduce high salinity levels to the freshwater bodies, which may affect the pH balance and conductivity of the water. The study found a high and significant correlation between pH and conductivity (0.768, $p<0.01$), indicating that changes in salinity due to seawater intrusion may influence pH levels.

5 Conclusions

This study aimed to comprehensively assess surface water quality in Colombia's Urabá region, considering physico-chemical, population, and agro-industrial factors. The analysis of the ten main rivers revealed significant variations, with notable correlations of conductivity, pH, BOD5, and COD with coastal distance. These correlations indicate potential seawater intrusion, possibly associated with overexploitation of aquifers and surface waters.

Rivers located near major populations, particularly the Apartadó, exhibited poor water quality due to inadequate sanitation, posing ecological risks in the absence of wastewater systems. In contrast, the León River showcased superior water quality, benefiting from more natural conditions.

The findings from our study underscore the importance of continuous monitoring for safeguarding water resources in high-risk areas. Community engagement and education emerge as crucial factors for ensuring sustainability in agro-industrial processes. Implementing measures to control anthropogenic impacts, such as reducing water consumption, is deemed essential. For agribusiness, adopting a combination of sustainable practices and effective management proves key to promoting better water quality while maintaining productivity.

Author Contributions Victor Hugo Aristizabal-Tique: Supervision, investigation, conceptualization, methodology, formal analysis, visualization, writing-reviewing and editing, funding acquisition; Diana Maryory Gómez-Gallego: Investigation, writing—original draft, writing-reviewing and editing; Ivis Tatiana Ramos-Hernández: Resources, data Curation, writing—original draft; Yamilet Arcos-Arango: Supervision, investigation, conceptualization, methodology, writing-reviewing and editing; Diana Nayibe Polanco-Echeverry: Resources, data Curation, writing-reviewing and editing, funding acquisition; Francisco Javier Vélez-Hoyos: Investigation, conceptualization, methodology, writing—original draft, writing-reviewing and editing, funding acquisition, project administration. All authors read and approved the final manuscript.

Funding Open Access funding provided by Colombia Consortium. This work was supported by the *Universidad Cooperativa de Colombia* under the Projects in Alliance (Grant numbers INV2391 and INV2399); and *Universidad de Antioquia* through the Dirección de Regionalización y Escuela de Microbiología.

Data availability Source Code: https://doi.org/https://doi.org/10.24433/CO.8303479.v1.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication The paper is submitted with the consent of all listed authors.

Competing Interests The authors declare no competing interests.

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