Surface water quality in the upstream of the highly contaminated Santiago River (Mexico) during the COVID-19 lockdown

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Abstract

The Santiago River (Jalisco) is a major waterway in western Mexico and has received considerable attention due to its severe pollution. Understanding the impact of reduced human activity on water quality in the Santiago River during the COVID-19 lockdown (April–May 2020) is critical for river management and restoration. However, there has been no published study in this context, presenting a significant knowledge gap. Hence, this study focuses on determining if the nationwide COVID-19 lockdown influenced or improved surface water quality in a 262-km stretch of the Santiago River upstream. Data for 15 water quality parameters collected during the lockdown were compared to levels obtained in 2019 (pre-lockdown), 2021 (unlock), and the previous eleven years (2009–2019). The values of turbidity, BOD, COD, TSS, f. coli, t. coli, nitrate, sulfate, and Pb decreased by 4–36%, while pH, EC, total nitrogen, and As increased by 0.3–21% during the lockdown compared to the pre-lockdown period, indicating a reduction in organic load in the river due to the temporary closure of industrial and commercial activities. An eleven-year comparison estimated a 0–38% decline in pH, TSS, COD, total nitrogen, sulfates, nitrates, and Pb. The unlock-period comparison showed a significant rise of 3–37% in all parameters except As, highlighting the potential repercussions of restoring activity along the Santiago River. Estimated water quality indices demonstrated short-term improvements in river water quality during the lockdown when compared to other time periods investigated. According to factor analysis, the main pollution sources influencing river water quality were untreated household sewage, industrial wastewater, and agricultural effluents. Overall, our analysis showed that the COVID-19-imposed lockdown improved the water quality of the Santiago River, laying the groundwork for local officials to identify pollution sources and better support environmental policies and water quality improvement plans.

Keywords Water pollution · DO · COD · BOD · Factor analysis · WQI

Introduction

Since early 2019, COVID-19 disease, caused by a novel coronavirus (SARS-CoV-2), has spread to over 210 nations, posing a global health disaster. On March 5, 2022, the overall number of confirmed cases had surpassed 445 million, and the death toll had surpassed 5 million globally (WHO 2022). Due to the COVID-19 pandemic, practically all affected countries took drastic steps and implemented voluntary lockdowns to preserve social distance, restrict public meetings, and effectively reduce COVID-19 trends. Mexico is one of the most impacted countries by COVID-19, ranking fourth in terms of mortality toll behind the United States, Brazil, and India. The first COVID-19 case was reported in Mexico on February 27, 2020, and by March 17, 2020, all 32 federal states in Mexico had COVID-19 cases (Mexico

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Health Ministry 2020). Mexican health officials announced a statewide health emergency on March 31, enforcing the first partial lockdown until April 30 (GDF 2020). Following its effectiveness, the government prolonged the limitation by enforcing the second phase of lockdown until May 31, totaling 62 days of lockdown across Mexico during the COVID-19 pandemic. The lockdown measures included restricting large-scale private and public social gatherings, public transit, and even closing schools and suspending industrial activity. With significant restrictions on human mobility and industrial shutdowns, researchers and policymakers take advantage of the opportunity to investigate and comprehend the environmental impact of COVID-19 measures to gain insights for both short- and long-term implementations. A number of publications have documented and offered evidence for the reductions in various forms of pollution and environmental restoration throughout the world. The reduction in regional transportation, along with lower industrial and commercial operations, has resulted in a considerable reduction in various air pollutants across several countries (Kutralam-Muniasamy et al. 2020; Otmani et al. 2020; Nakada and Urban 2020; Gautam 2020).

In recent years, rapid urbanization, industrialization, and a variety of human activities have been highlighted as the main causes of pollution of the aquatic environment (Kumar et al. 2019). River health in urbanized areas is deteriorating as a result of the discharge of non-biodegradable agricultural fertilizers and untreated industrial waste, which has a negative impact on regional ecology and the social economy. Furthermore, recurring anthropogenic activities, together with natural weathering processes, have been demonstrated to progressively affect river water quality (Khan et al. 2016, 2017; Khan and Wen 2021). Consequently, many countries and regions face the threat of limited river access owing to low water quality. Under the COVID-19 lockdown situation, the discharge of harmful industrial pollutants and sewage into rivers is restricted due to reduced human activity. Several regional studies are being conducted to analyze the impact of the COVID-19 lockdown on river water quality around the world. During the lockdown period, Yunus et al. (2020) observed a considerable drop in suspended particulate matter in Vembanad Lake, Kerala (India). Arif et al. (2020) reported a decrease in BOD and COD levels in the Yamuna River during the lockdown period. Due to lockdown, Mukherjee et al. (2020) detected a dramatic decline in the coliform bacterial burden in the Ganges River. According to Dutta et al. DO increased during the lockdown period, whereas BOD, nitrate, faecal coliform, and total coliform decreased. (Dutta et al. 2020). Shukla et al. (2021) noticed a significant decrease in heavy metal concentrations in the Ganga after a few months of lockdown owing to a reduction in industrial wastewater discharge. Qiao et al. (2021)

examined the impacts of the COVID-19 lockdown on the Yangtze River Basin (China) and compared them to the trend of surface water quality from 2000 to 2019. Despite the negative effects of the COVID-19 pandemic, the temporary shutdown had a positive impact on the quality of river water in many parts of the world, leaving imprints for future legislation and environmental planning.

Clearly, research on changing water quality characteristics during the COVID-19 pandemic has become a prominent subject in the field of water sciences. Although current studies have demonstrated that the COVID-19 lockdown in 2020 has an impact on river water quality, there has been no comprehensive study on the assessment of COVID-19 lockdown effects on Mexican rivers. This knowledge gap significantly reduces our understanding of what happens in the Mexican river system when human activities are severely restricted, limiting our potential to take additional pollution control and river management approaches. Many rivers in Mexico have become severely polluted as a result of growing urbanization and a lack of effective pollution management policies (Ochoa and Bürkner 2012). Among them, the Santiago River is one of Mexico's most polluted rivers, with significant water pollution over decades (McCulligh et al. 2007; Rizo-Decelis and Andreo 2016; McCulligh and Vega Fregoso 2019). It is well-known for the pollution of a variety of toxic substances caused by industrial dumping (Ochoa and Bürkner 2012). Therefore, the main aim of this paper is to assess and fully comprehend if Mexico's statewide lockdown would have lowered the pollution load, possibly resulting in an improvement in the water quality in the 262-km stretch of the Santiago River upstream. Toward this end, it compares the concentrations of 15 water quality parameters during the lockdown (April 1–May 31, 2020) to those during the pre-lockdown (April 1–May 31, 2019), unlock (April 1–May 31, 2021), and the same time period in the preceding eleven years. Unlike previous studies, we carried out a detailed comparative investigation that included physiochemical and biological characteristics as well as inorganic contaminants: pH, temperature, conductivity (EC), turbidity, total suspended solids (TSS), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), nitrate, sulfate, faecal coliform (f. coli), total coliform (t. coli), and heavy metals such as arsenic (As) and lead (Pb). Furthermore, factor analysis was used to identify potential sources impacting the river system, and the water quality index was determined to assess the Santiago River's current water quality state. Taking these together, we believe that the findings of this study would shed light on the implications of COVID-19 measures on river water pollution in Mexico and help to examine the changes caused by lockdown in our environmental system.

Study area

The Santiago River basin is located in central-west Mexico (23° 24′ 36″ and 20° 18′ 03″ N, 101° 16′ 48″ and 105° 28′ 12″ W) and is part of the Lerma-Chapala-Santiago hydrological basin. The Santiago River, one of Mexico's longest rivers, originates at Chapala Lake in Jalisco state and flows 475 km through six states, including Durango, Zacatecas, Aguascalientes, Guanajuato, Jalisco, and Nayarit, before flowing into the Pacific Ocean. Its principal tributary is the Lerma River, which receives various wastewater discharges from the heavily populated urban region of the State of Mexico and nearby cities (Fig. 1). It also draws water from numerous other rivers, including the Verde, Juchipila, Bolaos, and Zula, which join at several points. The

delimitation of the study area was considered from the origin of the Santiago River (Chapala Lake) and up to the border of Jalisco before entering the state of Nayarit (Fig. 1a). The climate in this river basin is dry and warm, with a mean temperature of 19.3 °C and a precipitation rate of 736 mm year^{-1} (SEMADET 2016) (Fig. 1c). The river basin is geologically bordered on the NW-NE by the Sierra Madre Occidental and on the SE-NE by the Trans-Mexican Volcanic Belt. Cenozoic extrusive igneous rocks of the Tertiary age predominate in this basin, with a minor proportion of Tertiary and Quaternary alluvial deposits (Ferrari et al. 2012). This basin also contains Cretaceous Mesozoic sedimentary strata to a lesser extent (Ferrari et al. 2012). The Santiago River runs across Jalisco, passing through Ocotlán, Poncitlán, Atequiza, Atotonilquillo, Juanacatlán, El Salto, Tonalá, and other
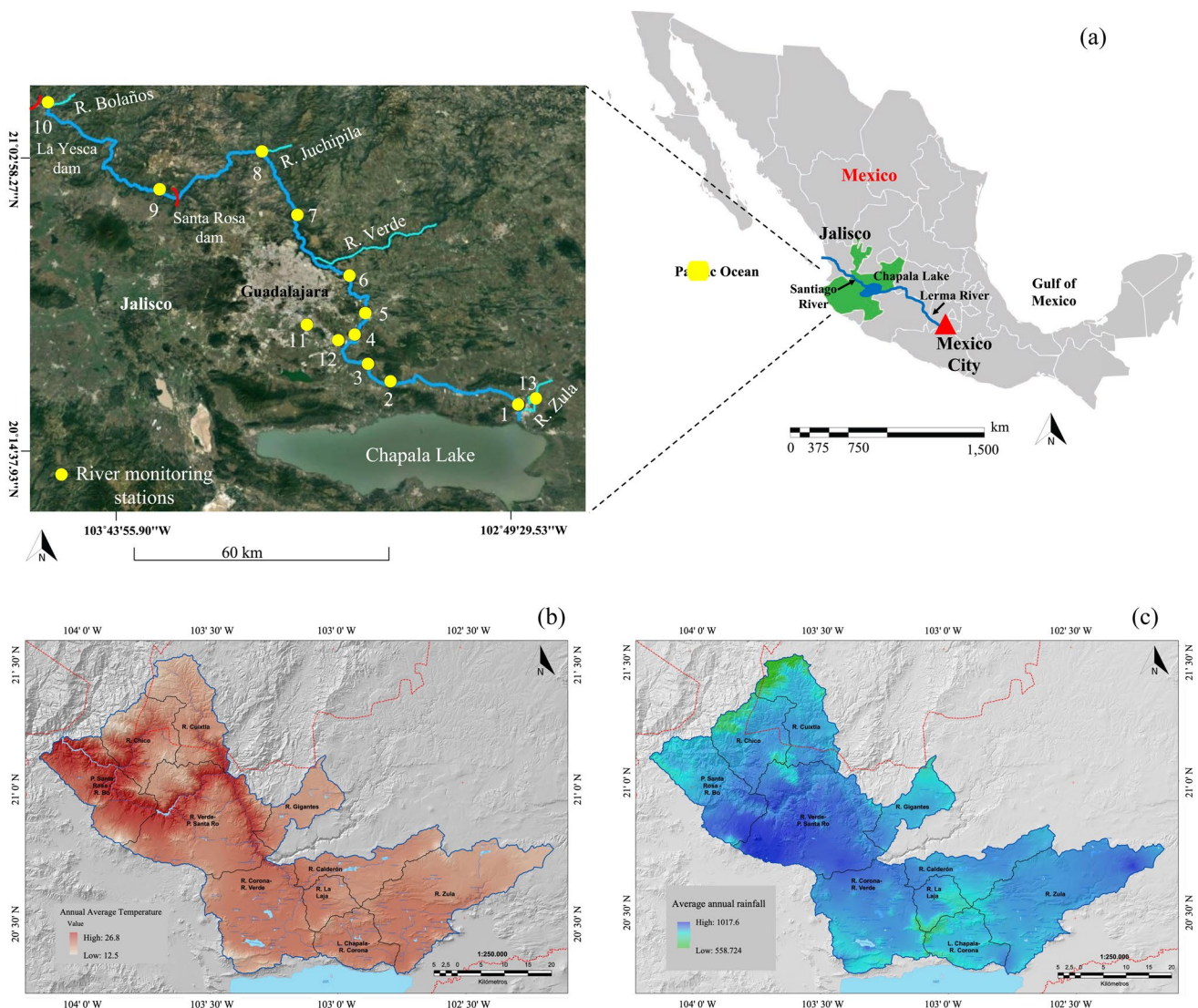

Fig. 1 Map depicting **a** the 13 sampling locations, and **b** the average annual temperature and **c** average annual rainfall of the Santiago River Basin in Jalisco (Mexico). **b, c** Modified from SEMADET (2016)

municipalities. The population of the Santiago River basin is estimated to be 7.5 million people, with 4.8 million centered in Guadalajara City (INEGI 2015). It was previously a tourist attraction and a source of pure drinking water for about 70–80% of the water demands of Guadalajara (Von Bertrab 2003; Ochoa and Bürkner 2012; Rizo-Decelis and Andreo 2016; McCulligh and Vega Fregoso 2019). The rapid growth of this metropolis's population (10 times in 65 years), combined with urbanization, industrialization, insufficient land-use planning, and untreated effluent, has affected the water quality of the Santiago River. Through the El Ahogado and Arroyo Seco channels, it receives discharges from over 300 enterprises in the Ocotlán-El Salto and Guadalajara industrial corridors, including aluminum, plastic, paper, chemical and petrochemical, automotive, food, and drinks (McCulligh et al. 2007; McCulligh and Vega Fregoso 2019).

Methodology

Sampling sites, data acquisition, and analyses

Due to the exacerbating contamination problem, the Jalisco State Water Commission (CEA) has launched monthly monitoring campaigns at 13 locations along the river's course since 2009 to study and record the physical, chemical, and biological characteristics of river waters. The sampling sites are located along a 265-km stretch of the Santiago River upstream from Chapala Lake in the state of Jalisco between 20°20′ 48.94″ N and 21°11′ 24.38″ N and 102°46′ 45.8″ W and 104°04′ 22.99″ W (Fig. 1 and Table 1). The sampling sites (1–10) are situated along the river's course, with sites 4–7 located in the metropolitan area. The sample sites 11 and 12 correspond to the El Ahogado canal, whereas site 13 corresponds

to the Zula River. CEA collects monthly water samples in triplicate at each site and analyzes them in laboratories recognized by the Mexican Accreditation Entity (EMA) in compliance with the national official Mexican Standard Norm NMX–EC–717025–IMNC–2006 (Supplementary Material Table S1). In this study, monthly water quality datasets for 13 sample locations upstream of the Santiago River were obtained from the Jalisco State Water Commission (http://www.ceaja lisco.gob.mx/contenido/datosabiertos/) between April and May 2009–2021, representing approximately 5070 individual data points. Accordingly, datasets for 15 parameters including physiochemical (pH, EC, temperature, turbidity, TSS, DO, BOD, COD, nitrate, sulfate, and TN), biological (f. coli and t. coli) and heavy metals (As and Pb) were obtained. Initially, we validated all the datasets downloaded in Excel files for zero and no-detects. Following the recommendations of the US Environmental Protection Agency, all values recorded as zero or no-detects were later changed to the half value of the indicated detection limit (Croghan and Egeghy 2003). The processed data were then used to examine the water quality at all thirteen sites for four different time periods: pre-lockdown (April–May 2019), lockdown (April–May 2020), and unlock period (April–May 2021), as well as during the same interval of the previous eleven years (2009–2019). The comparison between the pre-lockdown and lockdown periods was performed to determine the changes in river water quality caused by the temporary shutdown of anthropogenic activities during the lockdown period. The lockdown and unlock periods were compared to provide a clear picture of how anthropogenic activities impact river quality. Furthermore, the lockdown values were compared to eleven-year data to estimate the short-term impacts of the temporary shutdown during the COVID-19 pandemic and to understand its evolution over a decadal timeframe.

Water quality index

The surface water quality of the Santiago River was evaluated through the Water Quality Index (WQI) proposed by Horton (1965) and developed by Brown et al. (1970) and Cude (2001) which can provide a simple indicator of water quality for drinking purposes based on few important parameters. For this purpose, 8 parameters namely: pH, EC, DO, BOD, COD, nitrate, sulfate, and TSS were used for the calculation of WQI by the following equations:

$$Q_i = \frac{(M_i - l_i)}{(S_i - l_i)} \times 100,$$

$$W_i = \frac{k}{S_i},$$

Table 1 Coordinates of sampling locations along the Santiago River (Jalisco), Mexico

Sites	Geographic coordinates
Sampling Site 1	20°20′48.94″ N, 102°46′45.8″ W
Sampling Site 2	20°23′58.8″ N, 103°05′26.23″ W
Sampling Site 3	20°26′31.21″ N, 103°08′37.73″ W
Sampling Site 4	20°30′46.17″ N, 103°10′28.41″ W
Sampling Site 5	20°34′15.73″ N, 103°08′50.22″ W
Sampling Site 6	20°40′05.84″ N, 103°11′13.81″ W
Sampling Site 7	20°50′20.75″ N, 103°19′44.3″ W
Sampling Site 8	21°02′18.08″ N, 103°25′33.73″ W
Sampling Site 9	20°54′43.58″ N, 103°42′43.07″ W
Sampling Site 10	21°11′24.38″ N, 104°04′22.99″ W
Sampling Site 11	20°32′16.17″ N, 103°17′48.13″ W
Sampling Site 12	20°29′52.33″ N, 103°13′00.2″ W
Sampling Site 13	20°20′40.38″ N, 102°46′29.16″ W

$$WQI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i},$$

where,

Q_i = sub-index of the ith parameter

M_i = monitored value of the parameter

l_i = ideal value; the ideal value for pH = 7, DO = 14.6 mg/L, and for other parameters it was considered equal to zero (Tripaty and Sahu 2005; Chowdhury et al. 2012; Ewaid and Abed 2017).

S_i = standard value of the ith parameter; the values recommended by Mexican Standard Norm (2015) and World Health Organization (WHO 2011).

W_i = unit weightage of the ith parameter, calculated by the value inversely proportional to the standard value (S_i) mentioned by Mexican Standard Norm (2015) and WHO (2011)

n = number of parameters included

Based on the calculated WQI, the category of water quality types is recognized as follows: excellent (0–25), good (26–50), poor (51–75), very poor (76–100) and unsuitable for drinking (> 100).

Statistics

For carrying out the statistical analysis of the data obtained, Statistica software version 8.0 was used. Factor analysis (FA) was performed using normalized variables for 15 parameters, and an eigenvalue of greater than 1 was taken as a criterion for the extraction of the factors required for explaining the sources of variance in the data. Statistical analysis of water quality parameters in this study was conducted to see the interrelationship between different variables, to identify probable sources to explain the contamination status of the Santiago River, and to observe the influence of restricted human activities on water quality during the COVID-19 lockdown. In addition, we performed correlation tests ($p < 0.05$, 0.01, and 0.001) for the lockdown period to determine the relationship between the water quality parameters.

Results and discussion

Physiochemical characteristics

Figure 2 depicts the observed trends of physiochemical and biological parameters as well as heavy metals for the four periods (pre-lockdown, lockdown, unlock, and eleven-year trend) at various locations along the Santiago River. Table 2 provides a summary of the range, average value, and measured variables in river water samples during the lockdown, pre-lockdown, and unlock periods, as well as the Mexican Standard Norm (2015). Box and Whisker plots (Fig. 3) displays the comparative changes pattern of individual parameters during the pre-lockdown, lockdown, and unlock phases. The range of pH was similar in pre-lockdown (7.1–9.4) and lockdown (6.6–9.1), with narrow variations observed during the unlock period (6.7–8.1) (Figs. 2 and 3). Only a marginal increase of 0.30% and a decrease of 1.16% were noted during lockdown in relation to the pre-lockdown and eleven-year trend (Table 2). Owing to the smaller variations between pre-lockdown and lockdown along the river course, data on pH serves much less in identifying possible pollution sources and does not generate essential information on water quality. Similarly, the average water temperature during pre-lockdown, lockdown, and unlock was 21, 22, and 24 °C, respectively. The modest temperature difference could be related to the temperature of the atmosphere and weather conditions. Precipitation has a significant impact on river water quality, either improving it by diluting pollutants or degrading it by increasing loadings of different pollutants such as TSS, nutrients, and microorganisms (e.g., *E. coli*) during storm events and heavy rainfall. Since the study period falls during the summer dry season (March and April), precipitation has no dilution or enhancement impact on the pollutant levels of the Santiago River, indicating that meteorological conditions had no influence on the observed changes in the Santiago River's surface water quality, and the reduction in pollution levels is primarily attributable to industry shutdown during lockdown.

As shown in Fig. 2, high levels of EC were observed in all the sites, with an increase of 2.76% during the lockdown period compared to the pre-lockdown period (Table 2 and Fig. 3). Similarly, the EC values showed a slight escalation of 2.43% between lockdown and the eleven-year trend (Table 3). The reasons can be found when analyzing the changes in EC levels registered among the sampling sites. For instance, we observed a 3.76% increase in the metropolitan area (sites 4–7), indicating the augmentation of household waste and waste disposal in the metropolitan area. More importantly, a decline of 5.56% in EC values was noted during the lockdown in the sampling sites located at El Ahogado canal (11 and 12), which are greatly and usually affected by nearly 157 industrial wastewater discharges (Arellano-Aguilar et al. 2012; Ochoa and Bürkner 2012; McCulligh and Vega Fregoso 2019). In contrast, with the restoration of industrial activities, the same sampling sites 11 and 12 demonstrated a 3% increase in the unlock period. Thus, the positive reduction (5.56%) in EC values during lockdown, notably at sites 11 and 12, clearly indicates that lockdown procedures have resulted in a significant reduction in industrial discharges of untreated wastewater near the El Ahogado canal.

Fig. 2 Levels of 15 water quality parameters in the Santiago River at each sampling location during the pre-lockdown, lockdown, unlock, and 2009–2019 periods

Table 2 Analytical data of water quality parameters during the pre-lockdown, lockdown, and unlock periods in the Santiago River upstream

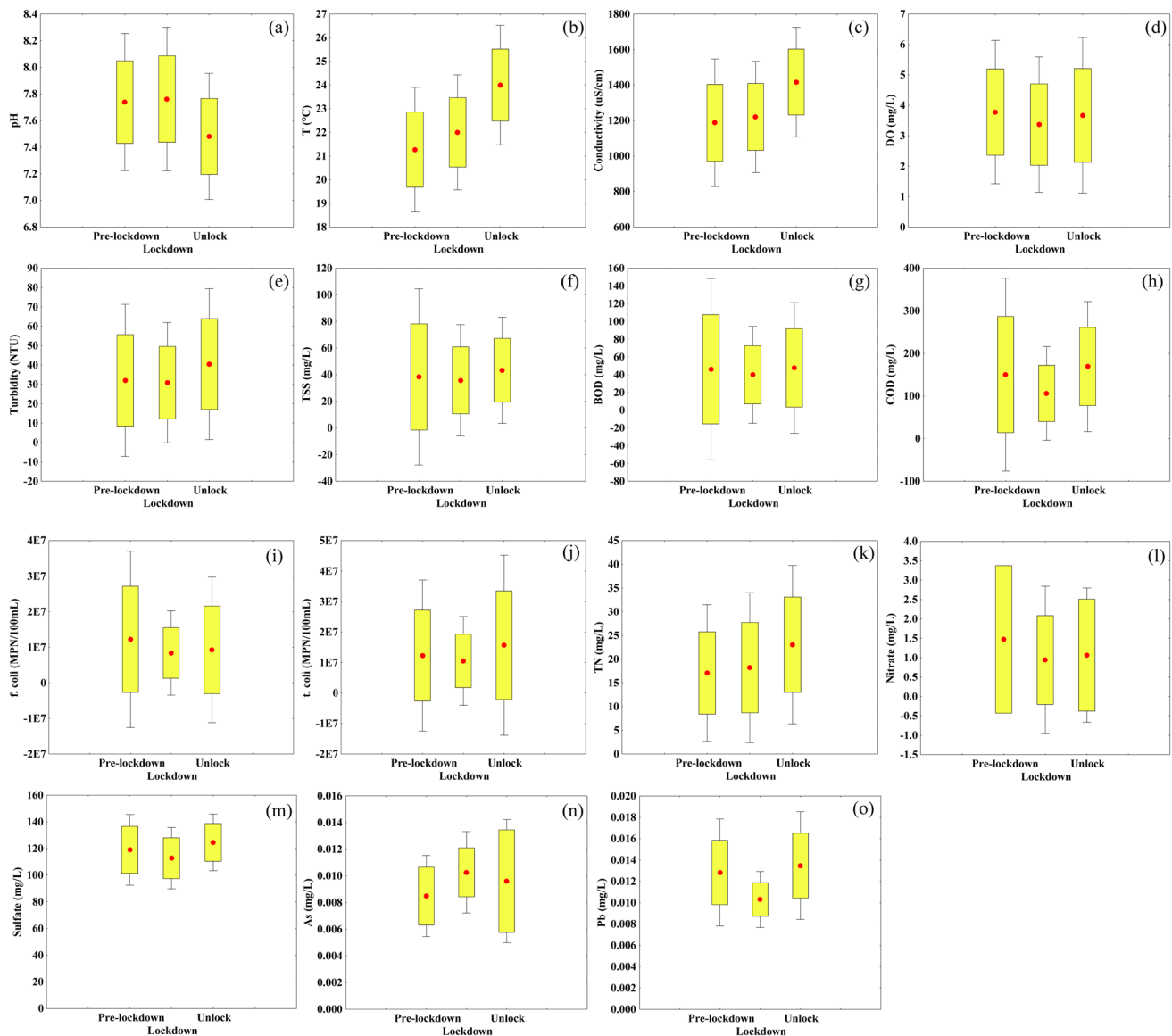| Stations	Parameters	Pre-lockdown			Lockdown			Unlock			Relative change (%)		Mexican permissible limits
		Min	Max	Average	Min	Max	Average	Min	Max	Average	Pre-lockdown vs lockdown	Lockdown vs unlock	
1	pH	7.1	9.4	7.738	6.6	9.1	7.762	6.85	8.1	7.48	+0.30	+3.61	6.5–8.5
2	Temperature (°C)	19.5	26	21.3	19.5	27.5	22	19.5	28	24	+3.18	+8.33	–
3	Conductivity (uS/cm)	408	1745	1187.308	852	1957	1220.077	668.5	1691.5	1416.769	+2.76	+13.88	–
4	DO (mg/L)	0.08	8.95	3.778	0.02	6.98	3.368	0.005	7.48	3.669	–10.84	+8.20	5
5	Turbidity (NTU)	5.4	140	32.062	5	117.5	30.934	3.7	142.5	40.509	–3.53	+23.63	3
6	TSS (mg/L)	7	370	38.385	7	245	35.769	7	114.385	43.356	–6.81	+17.49	50
7	BOD (mg/L)	2.03	425	46.208	2.09	183.61	39.866	3.465	132.45	47.664	–13.72	+16.36	30
8	COD (mg/L)	16.52	997.78	150.355	19.68	388.6	106.028	38.6	553.485	169.29	–29.48	+37.37	40
9	f. coli (MPN/100 mL)	90	110,000,000	12,238,289	40	46,000,000	8,422,265	588	55,215,000	9,282,692	–31.18	+9	1000
10	t. coli (MPN/100 mL)	230	110,000,000	12,296,617	70	46,000,000	10,545,466	588	87,000,000	15,694,646	–14.24	+33	–
11	Total nitrogen (mg/L)	0.96	69.74	17.095	0.42	52.95	18.211	2.98	42.98	23.053	+6.52	+21.00	–
12	Nitrate (mg/L)	0.28	4.58	1.472	0.15	7.08	0.940	0.14	2.62	1.067	–36.11	+11.87	10
13	Sulfate (mg/L)	49.77	144.505	119.021	55.51	155.655	112.764	74.21	154.055	124.595	–5.25	+9.49	250
14	As (mg/L)	0.005	0.0148	0.0084	0.0053	0.0146	0.0102	0.0026	0.0143	0.0096	+20.98	–6.42	0.01
15	Pb (mg/L)	0.0072	0.0378	0.0128	0.008	0.0141	0.0102	0.004	0.021	0.0134	–19.76	+23.60	0.01

Fig. 3 Box and whisker plot shows phase wise fluctuation of individual parameters between the pre-lockdown, lockdown, and unlock periods. **a** pH, **b** temperature, **c** conductivity, **d** DO, **e** turbidity, **f** TSS, **g** BOD, **h** COD, **i** f. coli, **j** t. coli, **k** total nitrogen, **l** nitrate, **m** sulfate, **n** As, and **o** Pb

The BOD and COD values were considerably diminished during the lockdown in comparison to their respective pre-lockdown and unlock periods (Table 2 and Fig. 3). When compared to pre-lockdown, their mean concentrations were reduced by 13.72% and 29.48% in the lockdown period. More notably, the sampling sites 11 and 12, located in the metropolitan area and the El Ahogado canal, displayed significant reductions of 20% and 32%, respectively, in COD. Despite the reduced levels of BOD and COD, nearly 30–76% of sampling sites exceeded the permissible limits of the Mexican Standard Norm (BOD = 30 mg/L; COD = 40 mg/L). In relation to the eleven-year trend, BOD increased by 19% and COD decreased by 14.66% during the lockdown. There

has been an increment of 6.52% and a decrement of 7.77% in TN values during the lockdown in relation to the pre-lockdown period and the eleven-year trend (Tables 2 and 3). Generally, TN and BOD concentrations express the state of organic load, whereas COD levels reflect the trends of chemical contamination in a river system. As shown in Table 4, the significant correlations among BOD *vs* COD ($r^2 = 0.95$) and TN ($r^2 = 0.87$) indicate a common source of origin. In the Santiago River, the organic and chemical loads mainly come from: (1) untreated gray water flow, (2) runoff from agricultural areas that carries excesses of nitrogen and phosphorous fertilizers and various agrochemicals (insecticides, fungicides, pesticides, etc.); and (3) industrial wastewater

Table 3 Relative change in water quality parameters of Santiago River between the lockdown and eleven-year data

Stations	Parameters	2009–2019	2020	Change (%)
1	pH	7.853	7.762	− 1.16
2	Temperature (°C)	24.47	22	− 10.09
3	Conductivity (uS/cm)	1191.111	1220.077	+ 2.43
4	DO (mg/L)	3.114	3.368	+ 8.16
5	Turbidity (NTU)	38.93	30.93	− 20.54
6	TSS (mg/L)	51.813	35.769	− 30.97
7	BOD (mg/L)	33.500	39.866	+ 19.00
8	COD (mg/L)	124.236	106.028	− 14.66
9	f. coli (MPN/100 mL)	2,512,287	8,422,265	+ 235.24
10	t. coli (MPN/100 mL)	3,047,798	10,545,466	+ 246.00
11	TN (mg/L)	19.745	18.211	− 7.77
12	Nitrate (mg/L)	0.935	0.940	NC
13	Sulfate (mg/L)	114.221	112.764	− 1.27
14	As (mg/L)	0.007	0.010	+ 42.86
15	Pb (mg/L)	0.016	0.010	− 37.50

NC: no change

discharges, such as the stillage produced during the manufacture of beverages such as tequila and other industries that discharge organic waste into this river (McCulligh et al. 2007; Rizo-Decelis and Andreo 2016; McCulligh and Vega Fregoso 2019). From our results, it is clear that the diminished industrial activities during lockdown must have resulted in a notable level of reductions in BOD and COD, whereas agricultural activities that remained active might

have contributed largely to increased TN levels. However, after the lockdown restrictions were lifted, anthropogenic activities in the Santiago River basin took their pace, leading to an increase in BOD (16.36%), COD (37.37%), and TN (21%) levels in the unlock period (Fig. 3).

The DO concentrations remained below 5 mg/L which does not meet the permissible limits in the majority of the sampling sites for all the assessment periods (pre-lockdown, lockdown, unlock, and eleven-year trend) (Fig. 2). DO values declined by 10.84% in lockdown with respect to pre-lockdown but increased by 8.20% in the unlock period and 8.16% compared to the eleven-year trend (Tables 2 and 3). The low DO values suggest poor water quality and, as a result, a lack of oxygen in the water, which has a negative impact on aquatic life. A maximum range (4–93%) of decreased DO levels was observed in the sampling sites located in metropolitan areas characterized by increased BOD levels. The correlation analysis demonstrated a negative relationship between DO and BOD ($r^2 = − 0.59$) signifying that the higher rate of bacterial decomposition of organic matter in the surface waters may have increased the demand for oxygen for their metabolic activities (Susilowati et al. 2018) and consequently reduced the DO levels. Thus, the reductions in DO levels during the lockdown in the majority of the sites may be explained by the increment in BOD levels in those sites for the same period.

The turbidity for all the assessment periods (pre-lockdown, lockdown, unlock, and eleven-year trend) presented higher orders of magnitude (approximately 10 times) with respect to the permissible limits of 3 NTU set by the Mexican Standard Norm (2015) (Fig. 2, Tables 2 and 3). Nonetheless, the lockdown seems to have lowered turbidity. Turbidity

Table 4 Correlation between water quality parameters during the lockdown period in the Santiago River (Jalisco), Mexico

Parameters	Temp	pH	EC	DO	Turb	TSS	BOD	COD	f. coli	t. coli	Nitrate	Sulfate	TN	As	Pb
Temp	1.00														
pH	0.79[*†]	1.00													
EC	–	–	1.00												
DO	–	0.74[*†]	–	1.00											
Turb	–	–	0.59[*]	− 0.62[*]	1.00										
TSS	–	–	–	–	0.59[*]	1.00									
BOD	–	–	0.67[*]	− 0.59[*]	0.80[*†‡]	0.80[*†]	1.00								
COD	–	–	0.61[*]	− 0.59[*]	0.63[*]	0.82[*†‡]	0.95[*†‡]	1.00							
f. coli	–	–	–	–	–	–	–	0.62[*]	1.00						
t. coli	–	–	0.61[*]	–	–	–	0.73[*†]	0.78[*†]	0.95[*†‡]	1.00					
Nitrate	–	–	–	–	–	–	–	–	–	–	1.00				
Sulfate	–	–	0.87[*†‡]	–	–	–	–	–	–	–	–	1.00			
TN	–	–	0.80[*†]	–	–	0.73[*†]	0.87[*†‡]	0.88[*†‡]	0.73[*†]	0.85[*†‡]	–	–	1.00		
As	0.61	–	–	–	–	–	–	–	–	–	–	–	–	1.00	
Pb	–	–	–	–	–	0.88[*†‡]	0.77[*†]	0.83[*†‡]	–	0.61[*]	–	–	0.85[*†‡]	–	1.00

$p < 0.05$[*]; 0.01[†]; 0.001[‡]

values decreased by 3.53% compared to the pre-lockdown levels and by 20.54% compared to the eleven-year trend. Turbidity levels for the unlock period, on the other hand, increased dramatically by 23.63% due to the lifting of lockdown restrictions. The correlation analysis showed a strong positive association of turbidity with TSS ($r^2 = 0.59$), BOD ($r^2 = 0.80$), and COD ($r^2 = 0.63$), implying that a decrease in TSS, BOD, and COD levels in river water quality during the lockdown period due to a halt in industrial activities directly contributed to lower turbidity values. The lockdown of 2020 also lowered TSS values by 6.81% and 30.97%, respectively, relative to the pre-lockdown and eleven-year trend (Fig. 2). The strong relationship of TSS with BOD ($r^2 = 0.80$), COD ($r^2 = 0.82$) and Pb ($r^2 = 0.88$) signifies that the decrease in TSS during the lockdown period may be associated with lower BOD, COD, and Pb values due to attenuated industrial activities. Additionally, the TSS values for pre-lockdown, lockdown, and unlock periods remained below the Mexican standard limits of 50 mg/L. The lockdown also significantly reduced nitrate and sulfate levels in the Santiago River by 36.11% and 5.25%, compared to the pre-lockdown period (Table 2 and Fig. 3). While nitrate and sulfate increased by 9–11% between the lockdown and unlock periods, this indicates that industrial operations were reduced or suspended throughout the lockdown period. Furthermore, the average concentrations of nitrate and sulfate are 0.940 and 112.764, respectively, which are below the Mexican standard limits and do not appear to be exceeded even during pre-lockdown and unlock periods. The correlation analysis for both nitrate and sulfate indicated no relationships with other water quality measures, implying additional sources of origin, notably from extensive livestock activities in the Santiago River basin (Guzmán-Colis et al. 2011; Rizo-Decelis and Andreo 2016) and industrial wastewater discharges.

Biological parameters

The trend of f. coli and t. coli counts in Santiago River water at the 13 sampling sites for all the study periods is shown in Fig. 2. The monitored concentrations of f. coli in water samples ranged between 40 and 46,000,000 MPN/100 mL during the lockdown period, whereas they ranged from 90 to 110,000,000 MPN/100 mL in the pre-lockdown period (Table 2). During the lockdown and pre-lockdown periods, t. coli counts ranged between 70 to 46,000,000 MPN/100 mL and 230–110,000,000 MPN/100 mL. The results reveal that lockdown restrictions drastically reduced f. coli and t. coli concentrations by 31.18% and 14.24%, respectively. In particular, a significant reduction of 20% of coliform bacteria (f. coli and t. coli) was recorded in the sites located at El Ahogado canal. The fall in microbial loads (f. coli and t. coli) may be due to the shutting down of industries, hotels, restaurants, community halls, malls, and food stalls, together

with reduced waste disposal in the river (Yunus et al. 2020; Selvam et al. 2020). It is further confirmed by the strong positive associations of coliform bacteria with industrial organic pollutants such as BOD ($r^2 = -0.73$) and COD ($r^2 = 0.62$; 0.78). In the unlock period, the microbial loads increased drastically (f. coli: 588—55,215,000 MPN/100 mL; t. coli: 588—87,000,000 MPN/100 mL), indicating the negative impacts of anthropogenic activities owing to lockdown lifting or non-lockdown in the river basin. Nonetheless, the microbial values in the Santiago River exceeded the Mexican standard limits during all the periods (pre-lockdown, lockdown, and unlock), pointing out the potential health threats from water-borne diseases and the immediate need for coliform management in the study area.

Metals

The concentrations of As and Pb showed significant variations in the lockdown period with respect to the pre-lockdown and eleven-year trends (Fig. 3; Tables 2 and 3). When we look at the As levels, they increased from 0.008 mg/L in pre-lockdown to 0.010 mg/L during the lockdown, accounting for a 20.98% increment. Likewise, the As levels increased by 42% in the lockdown period compared to the eleven-year trend. In the lockdown period, As presented no correlations with other water quality parameters, suggesting its unique source origin in the Santiago River. The elevated concentrations of As in the Santiago River have been previously attributed to industrial wastewater discharges (Arellano-Aguilar et al. 2012; Ochoa and Bürkner 2012; McCulligh and Vega Fregoso 2019), and even with decreased industrial activity during the COVID-19 outbreak, the As levels were higher in this study. The reason may be the low levels of suspended particles during the lockdown period that would aid in the retention of As in sediments from the above water column through binding or co-precipitation (Smedley and Kinniburgh 2002; Rubinos et al. 2003; Barral-Fraga et al. 2020). Similarly, an increased trend of As (42.86%) with decreased TSS (30.97%) was observed between lockdown and the eleven-year trend. In contrast, a maximum decrease of 24.52% was noticed in the case of Pb during the lockdown. The sample sites 11 and 12 located in the El Ahogado canal receiving industrial waste from the Guadalajara metropolitan area presented higher levels of Pb with 0.21 mg/L and 0.19 mg/L, respectively, during pre-lockdown and drastically reduced to 0.014 mg/L and 0.013 mg/L, respectively, in lockdown, reflecting the influence of restricted industrial activities. More importantly, Pb was found to be positively correlated with industrial pollutants such as BOD ($r^2 = 0.77$), and COD ($r^2 = 0.83$), as shown in Table 4. In addition, 8 out of 13 sites registered sharp reductions ranging from 5 to 70% in Pb levels. Likewise, the eleven-year trend when compared with the lockdown period

revealed a 13.78% reduction in Pb. Furthermore, according to the Mexican Standard Norm (2015), the maximum allowable limit for As and Pb is 0.01 mg/L. In pre-lockdown, 3 sites displayed As levels above the permissible limits, whereas 6 sites exceeded the limits during lockdown (Fig. 2). The exceedances of Pb levels were recorded in 9 and 4 sites during the pre-lockdown and lockdown periods, respectively. Sample sites 2–4 had higher values (0.012–0.020 mg/L) than permissible levels before lockdown but decreased below the limits (0.006–0.01 mg/L) during the lockdown.

Factor analysis

Factor analysis (FA) was performed on the normalized dataset (15 parameters) for both the pre-lockdown and lockdown periods to understand their compositional pattern, interrelationship between the parameters, and identify the factors influencing each one. The eigenvalues, the percentage of variance, and the cumulative percentage of variance are presented in Supplementary Material Table S2. The results of factor analysis loadings for the study period are presented in Fig. 4a, b.

Three factors contributed to 100.00% and 80.24% of the total variance in the dataset of pre-lockdown and lockdown periods. In the case of pre-lockdown (Fig. 4a), Factor 1 exhibited 70.94% of total variance with strong positive loadings of TSS, BOD, COD, f. coli, and t. coli. This factor may be termed the "organic pollution factor," and it represents impacts from point sources such as industrial effluent and home wastewater. The El Ahogado canal (sites 11 and 12),

as well as the lower sections of the Verde River (station 7) and Zula River (station 13), are the principal hotspots for major events of urban and industrial wastewater discharges from NE Guadalajara city and surrounding regions. Factor 2 exhibited 18.79% of total variance with negative loadings on pH, DO, and As. This factor may be termed the "metal pollution factor," and it indicates that pH and DO seem to favor the enrichment of As in the dissolved phase. It also indicates that the pollutants in the water consumed a significant quantity of oxygen. Finally, Factor 3 exhibited 10.27% of total variance with negative loadings on EC, turbidity, and TN and a positive loading on sulfate. The relationship between these variables could be termed the "inorganic pollution factor," indicating their inflow mainly from agricultural and municipal effluents. Furthermore, the absence of association of nitrate loadings in the components identified suggests the presence of non-point source pollution, which includes decomposed organic waste and livestock activities from agricultural regions in the river basin.

When compared to pre-lockdown, the lockdown period showed significant variations in the factor loadings (Fig. 4b). Factor 1, which explained 48.39% of the total variance, had strong positive loadings of TSS, BOD, COD, sulfate, TN, and Pb. This factor is known as a "mixed pollution factor," and it is defined as a type of mixed pollution that consists of point sources such as industrial waste and non-point sources associated with agricultural activities. Factor 2 (18.36% of the total variance) showed negative loadings for pH, temperature, and DO. Unlike in pre-lockdown, Factor 3 (13.49% of the total variance) termed "pathogenic pollution factor"
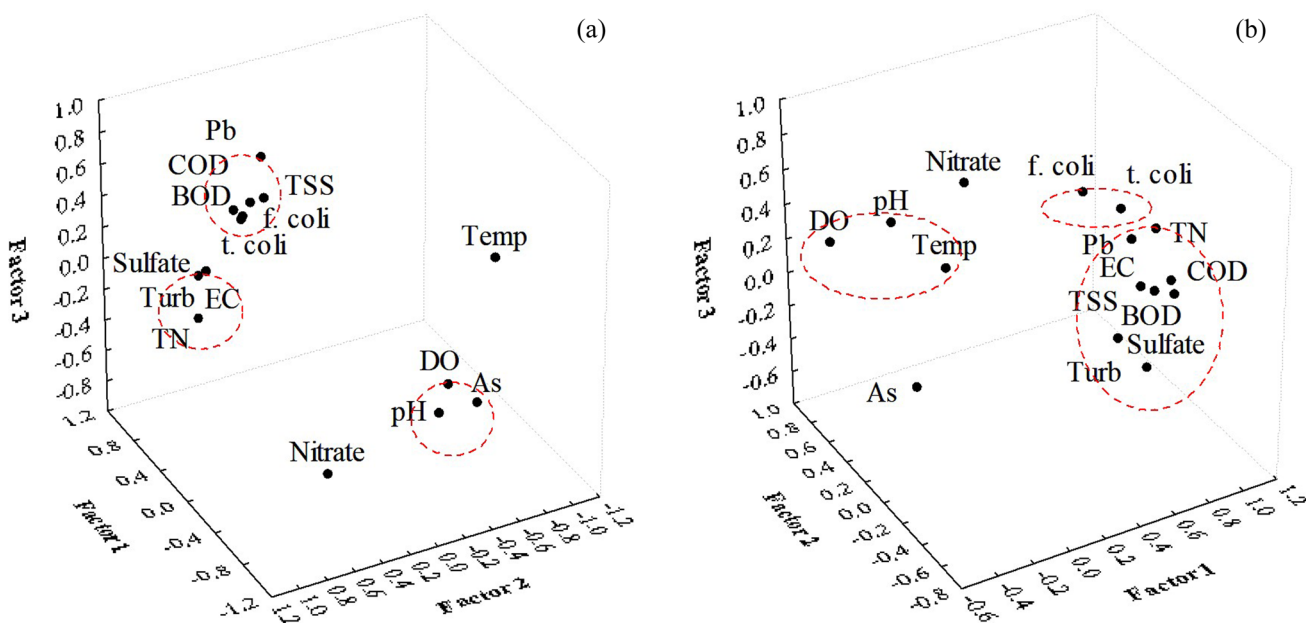

Fig. 4 Factor analyses loading **a** pre-lockdown and **b** lockdown

presented strong positive loadings for f. coli and t. coli but no associations with other organic pollutants like BOD and COD. It indicated that they were derived from non-point pollutants such as fertilizers, livestock feces, and sewage discharges rather than industrial waste. Overall, in the FA analysis, the differences observed between pre-lockdown and lockdown clearly demonstrated the positive effects of diminished anthropogenic activities on the water quality parameters. Furthermore, it revealed three main contamination sources in the Santiago River as: (1) wastewater associated with industrial activities; (2) urban and sewage discharges; and (3) agricultural effluents.

Evaluation of water quality using water quality index method

WQI estimation allows for the determination of the impact of individual water quality parameters on overall water quality and its suitability for drinking. WQI was calculated in this study using WHO (2011) and the Mexican Standard Norm (2015). Table 5 summarizes the WQI values of water samples from all 13 sampling sites for each assessment period.

The WQI values calculated for the Santiago River in the eleven-year trend, pre-lockdown, and lockdown were 121.44, 117.51, and 114.06, respectively. The average WQI for the whole period was 117.67, meaning that the Santiago River's quality belongs to the poor category. However, it can be noted that water quality has improved over the last decade, with an overall 6% change over the length of the Santiago River examined, which might be attributed to the COVID-19 lockdown restrictions. The frequency of WQI values varies depending on the sample sites along the Santiago River

(Table 5). The WQI values for water samples from 13 sampling sites ranged from 66.45 to 277.33, with nearly 97% of samples exceeding 100, regardless of the assessment period. The greatest WQI values were 149.77, 277.33, and 181.49 in the eleven-year trend, pre-lockdown, and lockdown, respectively, while the lowest WQI values were 83.75, 75.41, and 66.45. Furthermore, we observed a heterogeneous pattern of change in WQI values in water samples collected from 13 sites between assessment periods (Table 5). When pre-lockdown and lockdown WQI values were compared, 8 of the 13 sites improved by 0.78–45%, with an overall change of 4.5% in the Santiago River, demonstrating the positive effect of reduced industrial and commercial activity. Similarly, when WQI values from the previous eleven years were compared, the lockdown period showed improvements ranging from 6.2 to 26.50% in river waters from the majority of sites (11 out of 13). The sampled sites in the metropolitan area, in particular, improved by 0.65% and 12.62% during the lockdown period compared to pre-lockdown and elevenyear data, respectively. With the temporary suspension of industrial and commercial activity during the lockdown, there was likely less effluent outflow, lowering the amount of pollution in the study area. Thus, the analysis of WQI data shows that river water quality has improved considerably over time. In this respect, the analyzed river water quality parameters, such as pH, EC, DO, BOD, COD, nitrate, sulfate, and TSS, provide indications of water quality change over time for lockdown and non-lockdown periods.

Nonetheless, the results showed that the majority of the river water samples fell into the inappropriate water category (WQI > 100), implying that the water quality of approximately 90% of the entire region has deteriorated significantly, with many of the parameters found to be above

Table 5 Summary of WQI values of water samples at 13 sampling sites for each assessment period

Stations	2009–2019	Classification	2019	Classification	2020	Classification
1	132.62	*****	84.45	*****	101.86	*****
2	87.75	*****	76.00	****	66.45	****
3	92.76	*****	75.41	****	68.51	****
4	100.76	*****	91.71	*****	95.31	*****
5	111.35	*****	97.53	*****	81.53	*****
6	124.72	*****	124.62	*****	128.49	*****
7	149.77	*****	128.79	*****	157.31	*****
8	143.35	*****	114.56	*****	112.11	*****
9	83.75	*****	81.04	*****	94.17	*****
10	111.80	*****	148.14	*****	140.55	*****
11	185.44	*****	277.33	*****	152.81	*****
12	134.41	*****	149.50	*****	181.49	*****
13	120.26	*****	78.60	****	102.19	*****
Overall Santiago River	121.44	*****	117.51	*****	114.06	*****

*****Unsuitable for drinking; ****very poor

permissible limits. It also implies that the water is not suitable without treatment for any domestic activities. Poor water quality can be attributed to industrialization and various human activities such as the inflow of direct sewerage from residential and commercial establishments, a lack of a proper sanitation system, agricultural run-off, direct disposal of untreated effluents from small scale industries and factories, and unabated dumping of solid waste by communities living along the river, among other things. Although the WQI study results indicated significant short-term improvements during the lockdown period, the occurrence of abrupt deterioration and the persistence of pollution in the Santiago River for decades cannot be ignored and demands special attention from government authorities.

Conclusion

In the present study, the impact of two months of COVID-19 lockdown on the water quality of the Santiago River was examined using data from 13 sampling sites between 2009 and 2021 on 15 parameters. In comparison to the eleven-year trend (2009–2019) and pre-lockdown (2019), the data revealed that surface water quality improved in the 2020 lockdown during the months of April and May, owing to a temporary closure of anthropogenic activities along the 262 km upstream stretch of the Santiago River. Importantly, the majority of the variables were reduced in varying proportions during the lockdown period and subsequently increased during the unlock period. Therefore, the changes in water quality between the lockdown (2020) and unlock (2021) periods confirmed and demonstrated that the surface water quality changes seen between the lockdown (2020) and pre-lockdown (2019) were caused by the COVID-19 lockdown. The most noticeable changes include significant declines in BOD, COD, turbidity, nitrate, sulfate, f. coli, t. coli, and TSS levels, as well as better WQI values. It was also noted that the most polluted El Ahogado canal, which receives industrial discharges, appeared to be improving as a direct consequence of the temporary shutdown of companies closer to the urban area during the lockdown period. It is concluded that the COVID-19 lockdown measures helped enhance water quality to some extent throughout the Santiago River's 262-km length. These findings shed light on the possibility of improving water quality in the Santiago River if the impact of anthropogenic activities is reduced. However, WQI analysis indicated that the water is unfit for any use or human consumption, necessitating future monitoring. Overall, the water quality of Mexico's Santiago River is a serious concern, and this study will provide a platform for environmental managers to prioritize regulatory actions and develop viable strategies for adequate water quality management along Mexico's Santiago River.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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