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Articles

Quality and potential use of the hydrographic network of north-central Sinaloa, Mexico

Calidad y uso potencial de la red hidrográfica del centro-norte de Sinaloa, México

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Abstract

The ecological quality of the water indicates the stability of the ecosystem and guarantees its convenience of use. The objective was to investigate the water quality index (ICA) and the pertinence of use of the hydrographic network of north-central Sinaloa. Forty surface water samples from different water resources (RH) were collected: Drains (n = 26), rivers (n = 8) and bays (n = 6), including flow intakes (fresh water) and mouth (saltwater). The physicochemical parameters, nutrients, metals, and fecal indicators were evaluated and compared with national standards and under a multivariate and correlation analysis. The ICA was determined only in flow water samples. The RH were differentiated by certain physicochemical parameters (pH, EC, and TDS), nutritional (P and NO_3) and microbiological ($p < 0.05$). The multivariate analysis revealed a particular contamination profile at RH: Fecal indicator and nutriments were identifying as a risk factor. The fecal concentration in the water samples (65 %) exposes the health risk (> 200 MPN · 100 ml^{-1}), and its values showed correlation with the other quality parameters. The flow of all rivers and most of the drains (64 %) present a "good" ICA, which is in line with its relevance for aquatic life and agricultural activity, but not recreational. While the mouth of the RH is relevant for the recreational and aquaculture use. Our findings evidence a similar anthropogenic management of RH and warn about its potential use. In addition, they remark the importance of restoring the water quality to reduce the environmental and health implications.

Keywords: Bays, drains, water quality, rivers, Sinaloa.

Resumen

La calidad ecológica del agua indica la estabilidad del ecosistema y garantiza su conveniencia de uso. El objetivo fue investigar el índice de calidad del agua (ICA) y la pertinencia de uso de la red hidrográfica del centro-norte de Sinaloa. Se recolectaron 40 muestras de agua superficial de diferentes recursos hídricos (RH): drenes (n = 26), ríos (n = 8) y bahías (n = 6), incluyendo tomas de caudal (agua dulce) y desembocadura (agua salada). Los parámetros fisicoquímicos, nutrientes, metales e indicadores fecales fueron evaluados y comparados con los estándares nacionales bajo un análisis multivariado y de correlación. El ICA se determinó solo en las muestras de caudal. Los RH se diferenciaron por ciertos parámetros fisicoquímicos (pH, CE y SDT), nutrimentales (P y NO_3) y microbiológicos ($p < 0.05$). El análisis multivariado reveló un perfil de contaminación particular al RH: indicadores fecales y nutrimentos se identificaron como factores de riesgo. La concentración fecal en las muestras de agua (65 %) expone el riesgo para la salud (> 200 NMP·100 ml^{-1}), y sus valores muestran correlación con los otros parámetros. El caudal de todos los ríos y mayoría de los drenes (64 %) presentan un ICA "bueno", que está en línea con su pertinencia para la vida acuática y actividad agrícola, pero no recreacional. Por el contrario, la desembocadura de los RH es pertinente para uso recreativo y acuícola. Nuestros hallazgos evidencian un manejo antrópico similar de los RH y advierten sobre el uso potencial. Además, indican la importancia de restaurar la calidad del agua para reducir las implicaciones ambientales y de salud.

Palabras clave: bahías, calidad del agua, drenes, ríos, Sinaloa.

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Introduction

Northwest Mexico's water resources with consumptive use are constituted by the surface hydrographic network (52.35 hm^3 per year), and groundwater sources (33 311 hm^3 per year). In 2015, 90.9 % (77.84 thousand hm^3) of the national volume of water concessioned was destined to the primary economic sector (agriculture, livestock, aquaculture, fishing, beekeeping, mining, etc.) and public supply (Conagua, 2016). Particularly, Sinaloa is the federative entity with the largest volume of water concessioned (9 542.1 hm^3) for the primary economic sector generating an annual gross domestic product of up to US$ 1 559 million dollars (Conagua, 2016; INEGI, 2016). The benefits of the production and extraction of raw materials from economic activities are clearly demonstrated, but such intensification has become a source of polluting waste to the aquatic environment, which requires the establishment of assessment, restoration and control strategies (Haenn, Harnish, & Wilk, 2016; Tietenberg & Lewis, 2018).

The inadequate management of wastes and residues that carry pollutants such as heavy metals, nutrients, organic compounds, as well as pathogenic microorganisms, contribute to the alteration of the hydro chemical profile and cause the degradation of the aquatic ecosystem (Nazeer, Hashmi, & Malik, 2104; Ribeiro, Aparecido, Lajarim, & Sergio, 2014; Conagua, 2016). Surface water pollution modifies the natural function of receiving water bodies (bays and estuaries) and impacts the quality and aquatic life of these ecosystems (Kennish, 2002; Subasinghe, Soto, & Jia, 2009). In addition, there is evidence that water-related infectious diseases are a major cause of morbidity and mortality worldwide (OMS, 2022).

In order to assess water quality and define its relevance of use for human activities and for the protection of aquatic life, each country has established institutions and guidelines to monitor this work (Sarkar & Abbasi, 2006). Due to the diversity and variability of physical, chemical and microbiological parameters required by each region, the categorization of water resources in terms of ecological quality and safety is complex. In recent decades, the development of water quality indexes (WQI) based on aggregate functions has made it possible to group and weight parameters to define a level of quality and, consequently, the potential use of water (Sarkar & Abbasi, 2006).

Currently, the WQI called "Canadian Council of Ministers of the Environment", "National Sanitation Foundation", "Oregon", "General Pollution Index" and the "Ved Prakash Index" are some of the main mathematical models used to determine the level of water pollution (Katyal, 2011). In Mexico, the sanitary and ecological quality of water is regulated by a list of various parameters (physical, chemical and microbiological) condensed in official national standards (NOM-001-SEMARNAT-2021) and ecological criteria (CE-CCA-001/89). Recently, Rubio *et al*. (2016) developed an WQI to categorize the level of contamination and recreational safety in aquatic ecosystems.

In Sinaloa, water quality is of special interest due to the intensification of agricultural and aquaculture activities, including recreational activities. In Sinaloa, physicochemical and/or microbiological monitoring studies have been conducted in the El Fuerte river (Rodríguez, González, Trigueros, Ávila, & Arciniega, 2016), Culiacán river and Sinaloa river (Jiménez & Chaidez, 2012; Ruiz-Luna, Hernández-Guzmán, García-de León, & Ramírez-Huerta, 2017). However, it is required to expand the characterization and categorization of the quality parameters of various water resources of Sinaloa that constitute the source for the development of anthropogenic activities.

The objectives of this study were (i) to investigate a panel of quality parameters (physicochemical, nutrients, metals, and microbiological) in surface water samples from rivers, drains, and bays in the north-central region of Sinaloa with respect to national standards that determine suitability for use, and (ii) to determine the WQI.

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Materials y methods

Sampling

The state of Sinaloa has a territorial extension of 58,092 km^2 and extends between the foothills of the Sierra Madre Occidental and the Pacific Ocean coast. Sinaloa's surface hydrographic network comes from the Pacific and Gulf of California slopes, and it also has eleven rivers that supply water to its dams and other bodies of water. The drains, rivers, bays and estuaries are the main sources of water that supply the region's economic activities. Five cities in the state of Sinaloa were selected for this study, including Ahome (001), Angostura (002), Guasave (011), Culiacán (015) and Navolato (018). The selection of these cities was due to the accessibility of sampling and because they reflect the real characteristics of the surface water of the hydrographic network under study: a) they are wastewater discharge bodies; b) they have towns and/or develop some anthropogenic activity adjacent to the water resources, and c) their flow is discharged on the coast. During spring 2017, 40 surface water samples were collected from drains (n = 26), rivers (n = 8), and bays (n = 6). Rivers and drains were sampled at the flow level (n = 18) and at their mouth (n = 16) in the coastal zone to evaluate the behavior of parameters according to the nature of the water. The flow samples correspond to fresh water, and the mouth of rivers and drains into the sea represented estuaries (mixture of fresh and salt water). Table 1 describes the details of the identification code (ID), sampling and location (north and west) of the sampling points. Only flow samples were taken in the Los Mochis and Capomitos drains because they converge with other drains. The geographic location of the sampling points in Sinaloa, Mexico, are illustrated in Figure 1. Briefly, for the surface water sampling of the selected water resources, a 5 l sample of water (30 cm depth) was collected in disinfected plastic drums, which were identified and transferred to the laboratory for analysis in less than 24 h.

Table 1. Coordinates and identification (ID) of sampling sites.

City	Source	Name	Confluence (N/O) ID	Estuary (N/O) ID
001	Bay	Jitzamury	Not applicable	26°09'42.1"/109°16'45.1"[1]
001	River	El Fuerte	25°56'32.0"/109°16'01.1"[2]	25°49'46.8"/109°25'03.9"[3]
001	Drain	Juárez	25°42'58.6"/109°07´19.7"[4]	25°42'12.0"/109°08'47.8"[5]
001	Drain	Los Mochis	25°39'37.8"/109°02'31.2"[6]	Not applicable
001	Drain	Mochicahui	25°39'30.4"/109°02'06.2"[7]	25°38'25.3"/109°02'09.8"[8]
001	Drain	Navobampo	25°34'54.8"/108°48'10.1"[9]	25°32'52.9"/108°47'53.9"[10]
011	Drain	Guasave	25°23'03.6"/108°34'34.0"[11]	25°22'43.3"/108°37'44.0"[12]
011	Bay	Pitahaya	Not applicable	25°18'32.7"/108°32'05.1"[13]
011	River	Sinaloa	25°22'20.0"/108°25'25.5"[14]	25°17'03.1"/108°29'42.1"[15]
011	Drain	San Rafael	25°21'58.6"/108°20'38.8"[16]	25°19'05.0"/108°21'57.5"[17]

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City	Source	Name	Confluence (N/O) ID	Estuary (N/O) ID
002	River	Évora	25°13′46.1″/108°11′26.7″[18]	25°10′45′.2″/108°14′21.5″[19]
002	Drain	Playón	25°13′14.4″/108°09.22.3″[20]	25°10′09.4″/108°13′03.7″[21]
002	Bay	Santa María	Not applicable	25°11′17.1″/108°11′35.7″[22]
002	Drain	Reforma	25°07′01.0″/108°04′13.6″[23]	25°04′41.6″/108°04′30.9″[24]
002	Drain	Palmitas	25°04′18.9″/107°58′49.0″[25]	24°59′31.6″/108°00′38.4″[26]
018	Drain	M.Derecha	24°52′12.4″/107°48′50.5″[27]	24°52′08.0″/107°59′06.0″[28]
018	Bay	Santa María	Not applicable	24°46′14.0″/107°56′15.7″[29]
015	River	Culiacán	24°37′43.1″/107°39.39.2″[30]	24°29′39.0″/107°43′58.5″[31]
018	Drain	Caimanero	24°34′27.0″/107°36′45.0″[32]	24°30′08.2″/107°38′10.9″[33]
015	Drain	Chiricahueto	24°35′57.6″/107°29′02.9″[34]	24°31′40.7″/107°32′12.2″[35]
015	Drain	Capomitos	24°34′21.7″/107°27′46.0″[36]	Not applicable
015	Drain	Higueras	24°25′08.3″/107°24′12.3″[37]	24°23′36.5″/107°28′31.7″[38]
015	Bay	Evanito	Not applicable	24°19′51.1″/107°29′07.8″[39]
015	Bay	Palancas	Not applicable	24°24′30.3″/107°28′38.4″[40]

ID: The numbers indicated in the right margin of the coordinates correspond to the sampling sites represented in Figure 1.

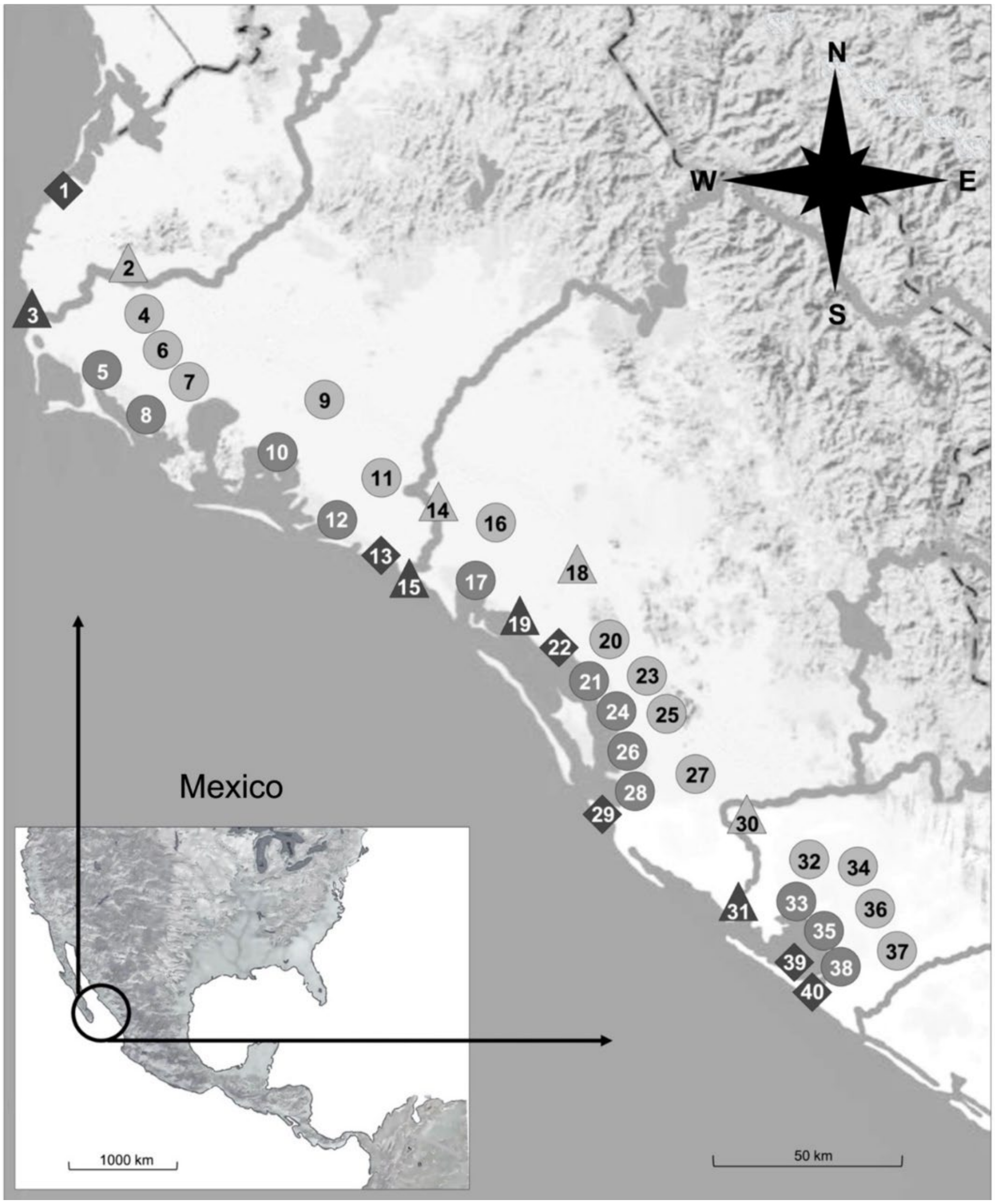

Figure 1. Map of the study area showing the sampling sites. The correspondence of the numbers (ID) with the sampling sites is described in Table 1.

Evaluation of parameters

The surface water quality panel consisted of 23 parameters distributed in the following categories: physicochemical (*n* = 10), nutrients (*n* = 4), heavy metals (*n* = 8) and fecal microorganisms (*n* = 1). The panel of quality parameters was determined according to the methodologies described in the national regulations (NOM and NMX) as indicated in each test or using multiparametric probes. Physicochemical parameters included biochemical oxygen demand (BOD) (NMX-AA-028-SCFI-2001), chemical oxygen demand (COD) (NMX-AA-03/02-SCFI-2011), suspended solids (SS) (NMX-AA-004-SCFI-2013), total suspended solids (TSS) and total dissolved solids (TDS) (NMX-AA-34-SCFI-2015). Electrical conductivity (EC), pH, temperature (T), dissolved oxygen (DO) and turbidity (Tur) were determined on site using Hach-HQ40D and Hanna-HI9829 multiparameter probes. The determination of SS, BOD and COD was omitted in samples from the mouth (drains and rivers) and bays due to the salty nature of the water. For nutrients, the concentration of NO3 (NMX-AA-079-SCFI-2001), NO_2 (NMX-AA-099-2006), P and PO_4 (NMX-AA-029-SCFI-2001) was determined. Heavy metals (As, Cd, Cu, Cr, Hg, Ni, Pb and Zn) were analyzed using the method described in NMX-AA-

051-SCFI-2016. The fecal coliform (FC) concentration was estimated with the most probable number in 100 ml (MPN/100 ml) protocol described in NMX-AA-042-1987. The tests were performed per triplicate.

Water regulatory compliance

The water quality compliance of the hydrographic network of north-central Sinaloa was determined by evaluating the quality panel determined in the water samples with the specifications described by national standards (NOM-001-SEMARNAT-2021, CE-CCA-001/89). For turbidity, the limit specified by international standards (EPA, 1986) was used. In addition, regulatory compliance with water quality parameters was analyzed by means of a multivariate analysis (hierarchical grouping based on Euclidean distance) to identify the parameters that represent the risk factors of the water resource contamination profile.

Relevant water use

The pertinence of surface water use in the hydrographic network of north-central Sinaloa was determined by comparing the values obtained from the quality panel with the specifications described by national regulations (NOM-001-SEMARNAT-2021, CE-CCA-001/89). A group of specific parameters are used for categorization relevant to aquatic life (pH, T, DO, TSS, SS, BOD, P, PO_4, NO_3 and NO_2), and agricultural (pH, T, TSS, SS, BOD, P and FC), aquaculture (pH, T, Tur, DO, NO_3, NO_2, and P) and recreational (Tur, pH, T, TSS, FC) activities. Given the nature of surface water, flow and bay/estuary samples were considered for agricultural and aquaculture use, respectively. The degree of relevance was calculated as an index of the number of parameters met for each category.

Calculation of the water quality index

The water quality index (WQI) in water samples from river flow and drains (n = 18) was defined using the methodology proposed by Rubio *et al*. (2016). Water samples from bays or outfall were excluded from the analysis due to the influence of salinity on the WQI value (DEQ, 2016). The WQI was calculated considering three factors: specific gravity (*wi*) and optimum level of the quality parameter (*pi*), and a water appearance constant (*k*). The *wi* factor was assigned to each parameter according to its relevance in defining water quality (1-4), where 4 represents the highest level and 1 the lowest. Each parameter was assigned a value of *pi*, with a value of 1 if it complied with the permissible limit proposed by national (NOM-001-SEMARNAT-2021, CE-CCA-001/89) and/or international (EPA, 1986) regulations, and a value of 2 if it exceeded the limit. The constant (*k*) was assigned by visual inspection of water turbidity during sampling: 0.5 (very turbid), 0.75 (turbid) and 1.0 (clear). Once the values for *wi*, *pi* and *k* were assigned, the WQI was calculated with Equation (1). The values for classifying the WQI were excellent (2.9-3.3), good (2.5-2.8), fair (1.9-2.4) and poor (1.3-1.8):

$$WQI = \sum_{i=n} \frac{w_i p_i}{p_i k} \quad (1)$$

Statistical analysis

To establish the relationship between the quality parameters with water resources and the nature of water (fresh and salt), the Kruskal-Wallis nonparametric test was used. A Pearson correlation and multivariate cluster analysis of observations was employed to classify the evaluated parameters by nature of water according to their similarity. A value of $p \leq 0.05$ was considered statistically significant (Minitab 16).

Results

Evaluation of water quality parameters

Table 2, Table 3, and Table 4 summarize the water quality parameters of water samples from rivers (flow), drains (flow), bays and estuaries (mouths of drains and rivers) of the hydrographic network of north-central Sinaloa. The descriptive statistics (μ and %CV) of the quality panel of the water samples show the diversity of their nature. The quality of the water resources was differentiated by certain physicochemical (pH, EC and TDS), nutritional (P and NO_3) and microbiological (FC) parameters ($p < 0.05$), and their values alert about the alteration of water quality. The metals evaluated did not represent a relevant pollutant agent for the water samples analyzed.

Table 2. Physicochemical, nutritional, and microbiological characterization of river flow.

ID	pH	T	EC	Tur	DO	TDS	TSS	SS	BOD	COD	NO3	NO2	PO4	P	FC
2	7.6	29	1 204	3	1.0	1 088	20	0.1	1.0	30	0.4	0.02	0.25	0.35	930
14	8.1	30	1 124	21	0.1	904	20	0.1	5.0	30	6.5	0.03	0.25	0.25	430
18	8.0	33	37 600	21	5.4	1 512	64	0.2	2.3	30	4.4	0.15	0.25	0.25	430
30	8.0	31	5 770	40	6.0	528	20	0.1	3.0	30	0.3	0.02	0.25	0.36	23
μ	7.9	31	11 424	21	3.1	1 008	31	0.1	2.8	30	2.9	0.06	0.25	0.30	453
%CV	3	6	154	71	96	41	71	40	59	0	106	115	0	20	82

ID: Site identification number (Table 1); μ: Arithmetic mean; %CV: Coefficient of variation; magnitudes: T (ºC), EC (μS cm-1), TUR (FNU), DO (mg·l-1), TDS (mg·l-1), TSS (mg·l-1), SS (mg·l-1), BOD (mg·l-1), COD (mg·l-1), NO3 (mg·l-1), NO2 (mg·l-1), PO4 (mg·l-1), P (mg·l-1), FC (MPN·100 ml-1).

Table 3. Physicochemical, nutritional, and microbiological characterization of the drainage flow.

ID	pH	T	EC	Tur	DO	TDS	TSS	SS	BOD	COD	NO_3	NO_2	PO_4	P	FC
4	7.3	25	16 840	25	6.4	15 992	20	0.1	3.0	100	0.1	0.06	0.30	0.35	240 000
6	7.5	31	6 320	56	0.4	5 501	57	0.3	14.0	95	0.1	0.86	0.62	1.83	4 300
7	8.0	31	5 740	38	0.6	5 028	0.4	0.3	3.0	39	1.2	0.28	0.48	0.80	240 000
9	7.1	26	15 870	18	0.6	4 641	215	1.0	8.0	27	5.8	0.54	0.25	0.38	15 000
11	7.6	28	10 300	39	0.5	7 464	31	0.1	4.2	40	0.7	0.13	0.40	0.65	93 000
16	7.6	30	4 100	85	0.2	2 960	80	0.1	6.1	31	5.4	0.13	0.25	0.27	2 400
20	7.8	30	40 300	134	3.6	3 230	130	0.3	4.4	33	4.9	0.09	0.25	0.32	9 300
23	7.9	22	3 300	33	3.0	2 672	20	0.1	3.8	30	0.5	0.01	0.25	0.34	4 300
25[a]	7.6	30	3 090	23	4.1	2 220	20	0.2	6.5	30	2.2	0.01	0.25	0.54	4 300
34	7.2	25	801	125	1.8	1 276	220	2.0	78.0	171	0.1	0.01	2.52	4.63	930 000
36	7.4	24	3 150	69	5.1	2664	20	0.1	9.0	33	2.1	0.28	0.32	0.55	2 400
37	7.8	26	1 020	57	4.6	810	66	0.1	12.0	30	4.0	0.01	0.27	0.41	9 300
27	7.8	26	9 670	101	1.6	861	79	0.2	14.0	43	0.7	1.48	0.85	1.67	150 000
32[b]	8.0	29	2 570	124	3.6	1891	121	0.3	12.0	40	0.6	0.02	0.25	0.89	2 400
μ	7.6	27	8 791	66	2.6	4086	77	0.4	12.7	53	2.0	0.28	0.51	0.97	121 907
%CV	4	10	118	62	79	96	92	141	151	78	104	152	116	119	204

ID: Site identification number (Table 1); μ: Arithmetic mean; %CV: Coefficient of variation; magnitudes: T (ºC), EC (μS cm^{-1}), TUR (FNU), DO ($mg \cdot L^{-1}$), TDS ($mg \cdot l^{-1}$), TSS ($mg \cdot l^{-1}$), SS ($mg \cdot l^{-1}$), BOD ($mg \cdot l^{-1}$), COD ($mg \cdot l^{-1}$), NO_3 ($mg \cdot l^{-1}$), NO_2 ($mg \cdot l^{-1}$), PO_4 ($mg \cdot l^{-1}$), P ($mg \cdot l^{-1}$), FC ($MPN \cdot 100\ ml^{-1}$); [a]As (0.005 $mg \cdot L^{-1}$), [b]As (0.021 $mg \cdot l^{-1}$).

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Table 4. Physicochemical, nutritional, and microbiological characterization of water from bays and river mouths and drains (estuaries).

Source	ID	pH	T	EC	Tur	DO	TDS	TSS	NO_3	NO_2	PO_4	P	FC
River	3	8.0	28	48 600	11	1.5	42 227	20	0.1	0.01	0.25	0.25	3
River	15	8.0	33	52 570	8	1.6	46 040	20	0.2	0.02	0.25	0.25	93
River	19	8.0	30	16 330	63	3.3	12 379	49	3.3	0.63	0.25	0.36	93
River	31	8.0	31	49 770	10	1.8	38 408	20	0.1	0.01	0.25	0.25	3
Drain	5	7.1	26	15 870	18	0.5	15 992	12	0.2	0.06	0.35	0.60	9 300
Drain	8	7.5	26	4 000	41	5.4	3 431	29	0.4	0.10	1.61	4.97	9 300
Drain	10	8.1	30	25 630	64	0.4	18 680	128	3.3	0.21	0.25	0.25	2 400
Drain	12	7.6	29	32 900	15	0.5	32 056	20	0.3	0.06	0.25	0.25	23
Drain	17	7.8	24	12 360	31	4.1	11 156	20	2.7	0.01	0.25	0.25	2 400
Drain	21	8.1	26	46 100	53	3.0	37 016	20	0.5	0.01	0.25	0.25	430
Drain	24	8.1	30	57 380	136	3.9	42 940	144	0.1	0.13	0.25	0.41	3
Drain	26	8.1	22	4 750	46	6.5	6 706.3	42	0.5	1.33	0.25	0.34	2 400
Drain	35	7.5	26	1 436	47	6.4	2 702.9	37	2.9	1.47	0.81	1.28	15 000
Drain	28	7.8	28	34 900	13	1.9	31 932	20	0.5	0.96	0.25	0.37	120
Drain	33	8.4	32	6 750	152	1.9	62 488	52	0.1	0.04	0.25	0.25	3
Drain	38	8.2	31	19 780	62	3.3	16 554	58	0.1	0.02	0.25	0.33	430
Bay	1	7.7	31	68 200	120	1.5	84 404	20	0.1	0.01	0.25	0.25	3
Bay	13	7.8	30	40 300	11	1.5	37 936	20	0.1	0.02	0.25	0.25	3
Bay	22	8.0	28	18 740	138	3.7	13 694	150	2.9	0.02	0.25	0.67	23
Bay	29	8.1	31	17 100	23	1.6	53 858	21	0.1	0.03	0.25	0.28	540
Bay	39	8.1	30	31 860	32	4.4	54 198	63	0.1	0.04	0.25	0.25	120
Bay	40[a]	8.6	34	42 690	95	3.9	32 206	154	0.1	0.02	0.25	0.52	3
μ		7.9	29	29 455	54	2.8	31 682	51	0.9	0.23	0.34	0.58	1 940
%CV		4	10	65	85	63	66	93	143	187	90	172	205

ID: Site identification number (Table 1); μ: Arithmetic mean; %CV: Coefficient of variation; magnitudes: T (°C), EC (μS cm^{-1}), TUR (FNU), DO ($mg \cdot l^{-1}$), TDS ($mg \cdot l^{-1}$), TSS ($mg \cdot l^{-1}$), NO_3 ($mg \cdot l^{-1}$), NO_2 ($mg \cdot l^{-1}$), PO_4 ($mg \cdot l^{-1}$), P ($mg \cdot l^{-1}$), FC (MPN·100 ml^{-1}), [a]Cu (0.3 $mg \cdot l^{-1}$).

The correlation matrix of the significant water quality parameters is presented in Figure 2. The interaction between the parameters was dependent on the type of water (flow and estuaries/bays). FC was identified as a common factor strongly associated with the other parameters (physicochemical and nutrients) in both water types, whose relationship is positive in the flow and mainly negative in the mouth.

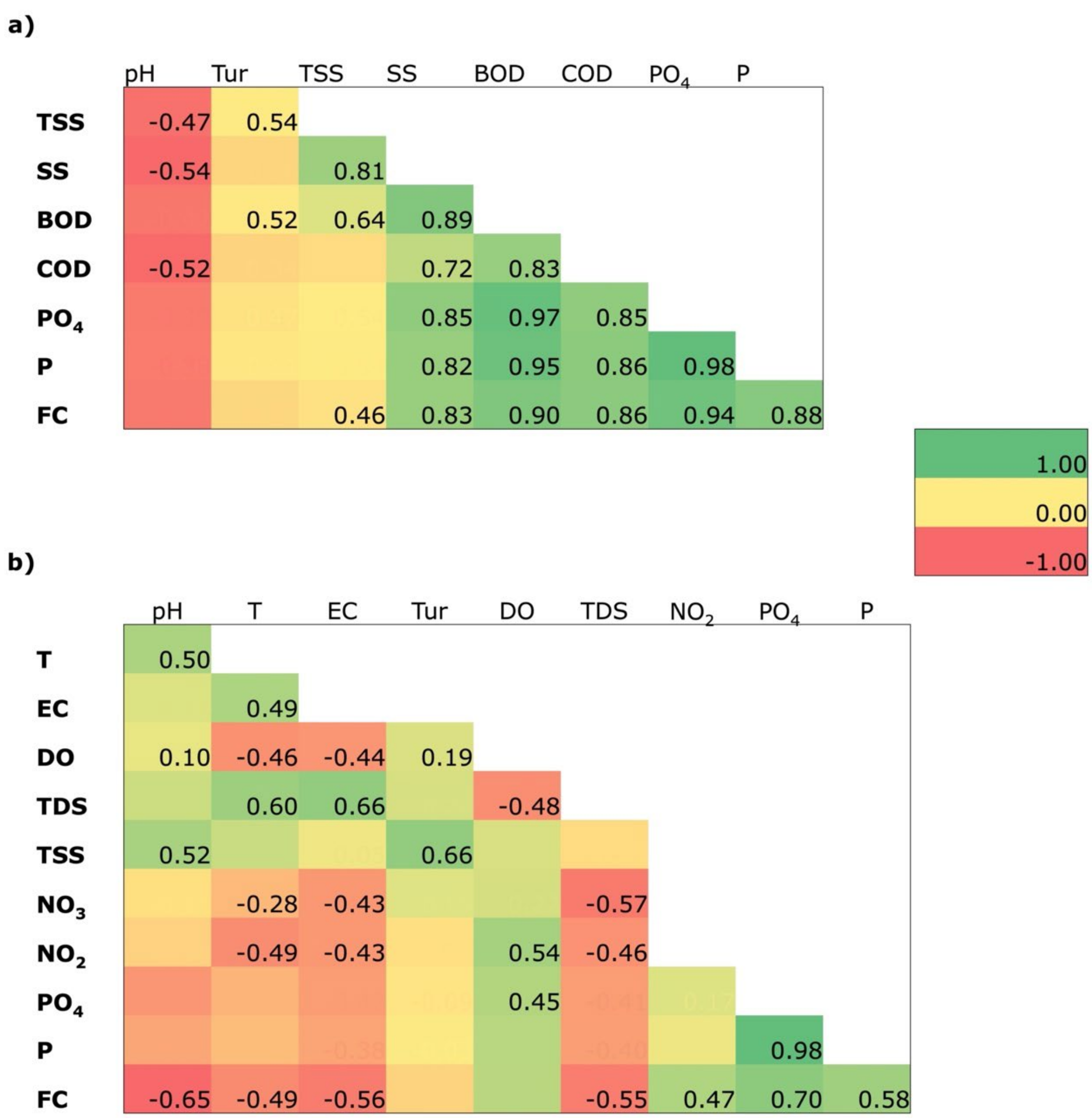

Figure 2. Correlation coefficients of water quality parameters of flow (a) and mouth (b) of the hydrographic network of north-central Sinaloa. The figure shows the significant parameters ($p < 0.05$) and the intensity of coloration the relationship index.

Regulatory compliance

Of the 23 parameters evaluated, 12 (52.1 %) were outside the specifications according to the regulatory criteria, with the main parameters exceeded among the water samples (*n* = 40) being: DO (*n* = 33), P (*n* = 27), NO_3 (*n* = 22), FC (*n* = 20), T (*n* = 19), NO_2 (*n* = 18) and TDS (*n* = 18). The multivariate analysis points out the parameters identified as risk factors for water quality of the flow and mouth of the Sinaloa hydrographic network (Figure 3). A high similarity of the water quality disturbance profile was observed between the samples of flow (74 %) and mouth (84 %), which reflects the similarity of anthropogenic management and pollution sources that impact the water quality of the region's water resources. Nutrients (P, PO_4, NO_3, NO_2) and fecal indicators were identified as the main risk factors in the water samples, whose correlation with the physicochemical parameters is shown in Figure 2.

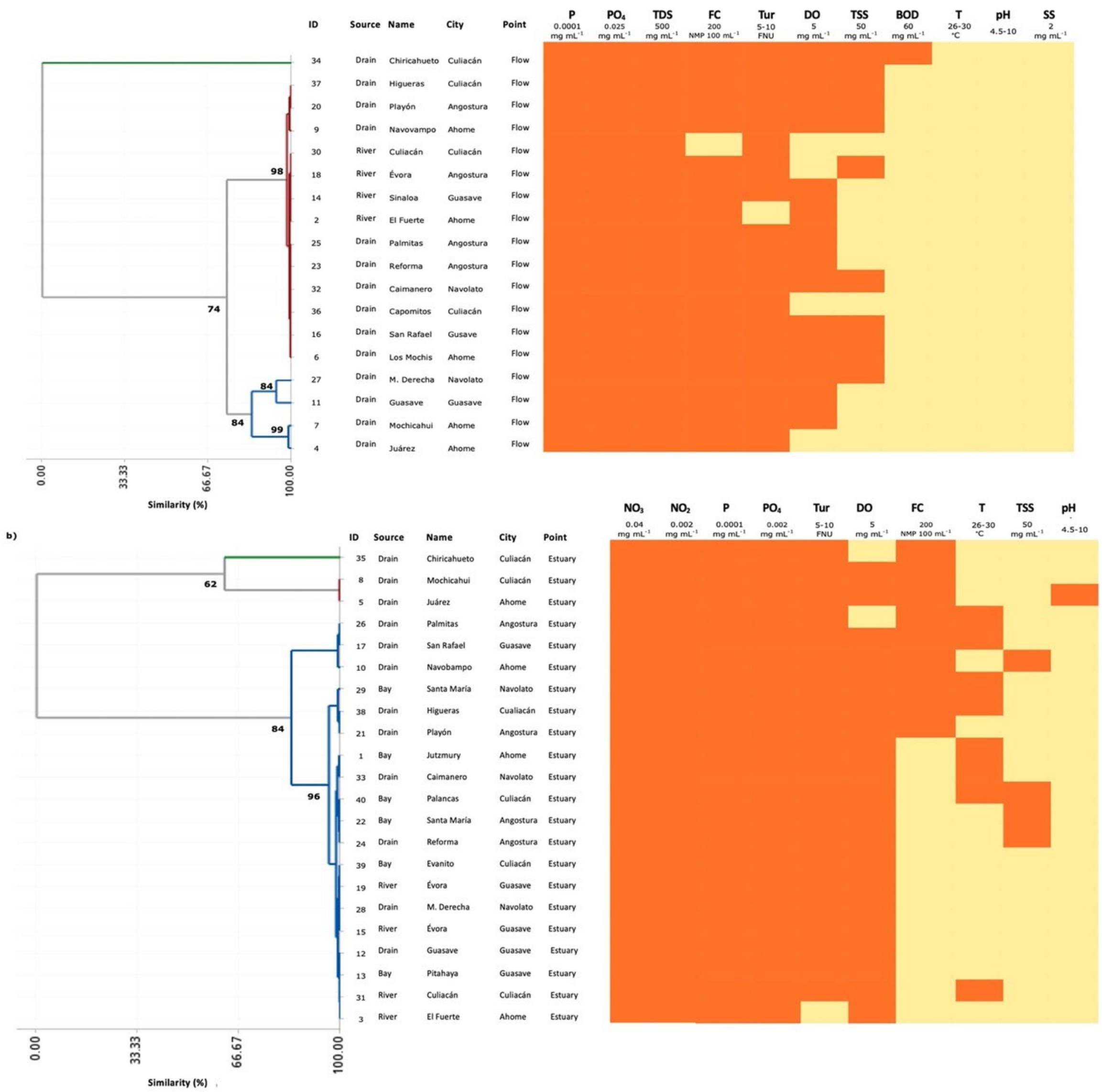

Figure 3. Cluster of ecological quality profile of flow (a) and mouth (b) samples of the Sinaloa hydrographic network according to their concordance with national (CE-CCA-001/89; NOM-001-SEMARNAT-2021) and international (EPA, 1986) standards. The level of regulatory

compliance is indicated by orange (non-compliant) and yellow (compliant). The limits are specified for each parameter.

Relevant use and WQI

The suitability and WQI of the water resources are explained in Figure 4. The WQI allowed classifying with "good quality" the flow of 100 % (*n* = 4) and 64 % (*n* = 14) of the rivers and drains, respectively. The categorization of water uses relevance indicated that the majority (> 60 %) of river and drainage flows allow aquatic life (56-78 % relevance) and agricultural activities (67-87 % relevance). However, recreational activities should be avoided in river and drainage flows. This classification did not always coincide with the determined WQI. As for estuaries/bays, recreational and aquaculture activities can be carried out in the assessed sites with a relevance of 60-100 %. However, the quality conditions do not allow aquatic life in any of the evaluated sites.

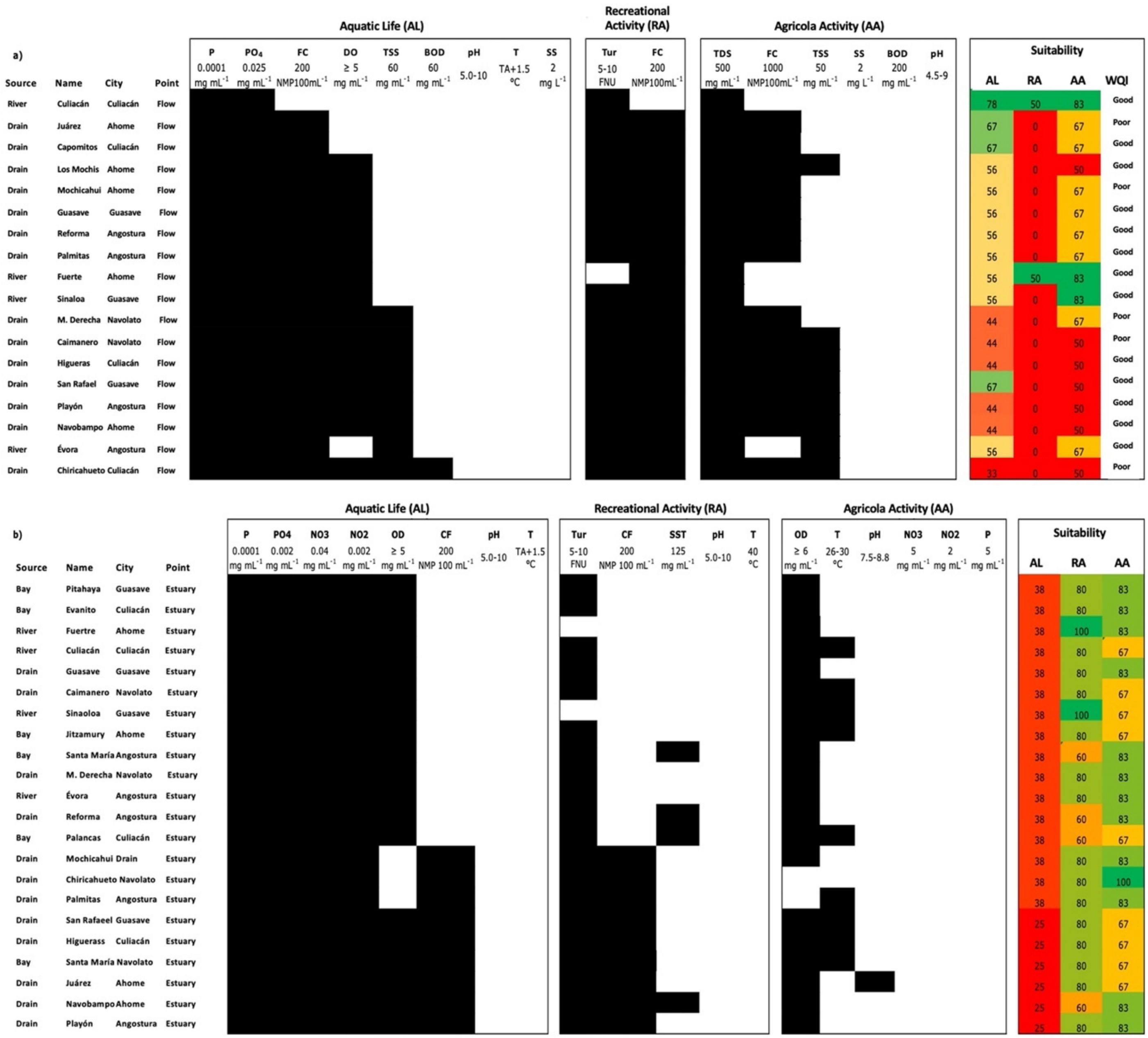

Figure 4. Quality index and pertinence of use of the hydrographic network of Sinaloa. Compliance with the quality parameters in the water

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samples of the flow (a) and mouth/bays (b) is described. The color black and white indicates compliance and non-compliance of the parameters with respect to the regulations, respectively. The degree of relevance is identified with a green to red color scale.

Discussion

The benefit of studying the flow and behavior of the various parameters (microbiological, physicochemical, nutritional, and metals) that dictate the quality of water bodies was motivated by the evident alteration of aquatic ecosystems and the potential impact on health and the environment. The results of this study offer a reference of the ecological stability and security of water resources as sources of water in the central-northern region of Sinaloa.

Regarding the determination of nutrients in the water samples, the following order of concentrations was observed: NO_3 (0.05 - 6.52 mg/L) > P (0.25 - 4.97 mg/l) > PO_4 (0.25 - 2.52 mg/l) > NO_2 (0.01 - 1.48 mg/l) (Table 2, Table 3, Table 4). The concentrations of P ($p < 0.025$) and NO_3 ($p < 0.021$) showed statistical association with the type of water resource ($p > 0.05$), indicating that the sources of these nutrients impact rivers, drains and their mouths to different degrees. Eutrophication is the biological response of water bodies to the discharge of compounds rich in phosphorus and nitrogen, leading to pollution and imbalance of the aquatic ecosystem (Brandini *et al*., 2016; Ngatia, Grace III, Moriasi, & Taylor, 2019). The increase of organic matter and algae, as well as the establishment of hypoxic and anoxic conditions are some of the adverse effects of eutrophication of water bodies (Ciobotaru, Marcu, Cimpoeru, Savin, & Ivanov, 2017). Natural processes, agricultural activities, industrial wastes and wastewater are relevant sources of nitrogenous, phosphorus and other compounds, which promote the increase of their concentrations when indiscriminately discharged into water (Lawniczak *et al*., 2016; Ciobotaru *et al*., 2017; Gupta, Pandey, & Hussain, 2017). According to the P content proposed by the Organisation for Economic Co-operation and Development (OECD), the assessed water samples indicate that the hydrographic network presents a level of eutrophication (> 35 $\mu g \cdot l^{-1}$) or hypereutrophication (> 100 $\mu g \cdot l^{-1}$) (Moreno, Quinero, & López, 2010), as a presumable result of anthropogenic practices (agricultural, livestock and aquaculture activities, unregulated human settlements, inadequate management of human and industrial waste and residues), which are being carried out in the Sinaloa region, and the lack of mitigation measures.

Heavy metals were not identified in the majority (92.5 %) of the surface water samples. Only in three water samples corresponding to drains (n = 2) and estuaries (n = 1) low concentrations of As (0.005 -

0.021 mg-l^{-1}) and Cu (0.300 mg-l^{-1}) were detected (Table 3 and Table 4). Given that the sampling was of surface water, the absence of heavy metals in sediments of the rivers, drains and coast of Sinaloa should not be underestimated. Previously, Frías-Espericueta *et al*. (2014) exposed the latent risk to human and environmental health due to the quantification of heavy metals (Zn, Cd, Cu and Pb) in rivers located in Sinaloa. In addition, there is evidence supporting that heavy metals are stored in sediments (efevre *et al*., 2014; Nazeer *et al*., 2104) and bioaccumulate in native fauna (Copaja *et al*., 2016). Continuous monitoring of heavy metals in the aquatic ecosystem should be carried out as a control measure.

The physicochemical and microbiological profile for the river, drainage and outfall water samples can be seen in Table 2, Table 3 and Table 4. The nature of the water resources was differentiated in terms of FC (p < 0. 004), pH (p < 0.009), EC (p < 0.000), and TDS (p < 0.000), noting that the river and drainage flow samples presented the maximum values (Table 2 and Table 3), which may influence their dispersion towards the coast (Table 4). The FC limit (MPN/100 ml) in the water samples was 23-930 for the rivers, 2 400-930 for the drains and 3-15 for the coast (mouth and bays). The variation and disturbance of the parameters in these samples reflect the intensification of anthropogenic activities taking place near the drains and rivers, which can compromise their nature and safety, and consequently impact the coast through flow. Previously in Sinaloa, the uncontrolled dumping of wastewater and the dragging of urban, agricultural and industrial waste were described as a source of pollutants that promoted the increase of FC, pH, EC, P, TDS, NO_3 in aquatic ecosystems (Escobedo, Hernández, Herrera, Ulloa, & Chiquete, 1999; Muñoz, Menanteau, & Escobedo, 2011).

Pearson's correlation has been used as an index to measure the degree of relationship and dynamics established by quantitative water quality parameters. In this study, we observed that river and drainage flow samples showed a positive degree of correlation between physicochemical parameters (Tur, TSS, SS, BOD, COD), nutrients (PO_4 and P) and FC, except pH (Figure 2). On the contrary, positive and negative interactions of the parameters are observed in the bays/estuaries. The observed behavior can be attributed to the type of water nature. The observed correlations have also been previously reported in the literature for river water (Edokpayi, Odiyo, Popoola, & Msagati, 2018).

National regulations warn about the relevance of the use of water resources belonging to the north-central zone of Sinaloa (Figure 3 and Figure 4). Multivariate analysis reveals that the water quality profile was defined by sampling point (flow and mouth) and type of water resource (Figure 3). This means that, rivers, drains and coastline share a quality profile of their own and denote similarity with risk factors. In this study, it is evident that water resource flows are exposed to pollution from various sources, such as the intensification of anthropogenic activities and the constant discharge of wastewater, which increases the values of the analyzed water quality parameters. The flows of the drains represented the water bodies whose quality is questioned by the highest number of parameters involved as risk factors (Figure 3). Not enough, a capture effect of pollutants attributable to the vegetation of these ecosystems is suggested (Escobedo *et al*., 1999; Muñoz *et al*., 2011). The emergence of out-of-specification parameters in certain samples at the mouth of drains and rivers is alarming (Figure 3) and could be a consequence of the continuous reception of pollutants along the flow (Yang, Xu, Milliman, Yang, & Wu, 2015).

The ecological quality of samples from the mouths and bays of Sinaloa's hydrographic network is determined by sources that increase the concentration of nutrients (Figure 3). Attention should be paid to the high values in these water sources, as the phenomenon of eutrophication could be developing (Lawniczak *et al*., 2016), and that explains why the DO is out of specification (Figure 2). It is documented that the osmotic pressure exerted by seawater salinity suppresses the presence of FC (Rodríguez *et al*., 2016), which could be being observed in this study. However, here it was described that nitrogenous compounds (NO_3 and NO_2) have a positive relationship with FC concentration (Figure 2). Nowadays, the placement of wetlands in water bodies participate as a mechanism for the removal of physicochemical (Maine *et al*., 2016; Cervantes, Londoño, Gutiérrez, & Peñuela, 2017) and microbiological (Hathaway, Hunt, Graves, Bass, & Caldwell, 2011) pollutants that maintain the ecological balance.

The relevance of use of Sinaloa's water resources as a water source has been a controversial feature. Our study reveals the relevance for the development of aquatic life, and that water to supply economic and recreational activities should be taken with caution (Figure 4). It has been reported that water resources in Sinaloa are continuously exposed to exploitation and contamination (Conagua, 2016). Also, the microbiological conditions of the Humaya, Tamazula and Culiacán rivers have been questioned by the detection of *Salmonella spp* (Jiménez & Chaidez, 2012). In contrast, Rodríguez *et al*. (2016) and Ruiz-Luna *et al*. (2017) have reported acceptable physicochemical and microbiological conditions of El Fuerte River, Sinaloa River and Culiacán River water for anthropogenic use. In any case, the assignment of a normative water use is a fact that should be interpreted with caution. The national regulations NOM-001-SEMARNAT-2021 and CE-CCA-001/89 are Mexican regulatory criteria that determine the ecological quality profile that allows inferring the safety and adequate use of water for anthropogenic activities and relevance for the development of aquatic life.

The results of the WQI showed that most of the river and drainage flows (72 %) present good quality, and this is in line with their relevance for aquatic life and agricultural activity. It should be noted that those drains catalogued with "poor quality" WQI are located in the municipalities of Ahome (*n* = 2), Navolato (*n* = 2) and Culiacán (*n* = 1), and these results could be related to the reception of waste from nearby industrial and human activity, and for having the highest demographic rate. The goodness of the WQI equation proposed by Rubio *et al*. (2016), is due to the selection criteria, weighting and compliance of the parameters included according to Mexican legislation and that it considers the apparent contamination level of the water resource during sampling. The calculated WQI gave a first approximation of the level of contamination and potential water use.

Conclusions

These findings propose that the hydrographic network of north-central Sinaloa has similar anthropogenic management, given that each type of water resource shares similarities with the quality and factors that denote the imbalance of these ecosystems. Correlation and multivariate analysis are tools that allow the identification of quality parameters that function as indicators to explain the behavior and nature of water, with the aim of improving quality. The importance of monitoring the quality and safety of the region's hydrographic network is due to the fact that it represents the source of water for supplying economic and recreational activities. Therefore, the relevant authorities are alerted to carry out periodic monitoring of water resources and implement mitigation measures that allow controlled and supervised management of these bodies of water.

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