CONSERVATION PROJECT OF MARINE RESOURCES IN CENTRAL AMERICA

COROZAL BAY WILDLIFE SANCTUARY, BELIZE

TRANSBOUNDARY INTEGRAL DIAGNOSIS ON THE WATER QUALITY OF THE CHETUMAL/COROZAL BAY SYSTEM IN THE PERIOD 2017-2018

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1.- INTRODUCTION

The human activities that are developed around the aquatic systems of the Reserva Estatal Santuario del Manatí Bahía de Chetumal (RESMBCH), constitute a determining factor in the quality of its waters. Therefore, the analysis of chemical and physical constituents are useful indicators to assess their condition in relation to stress factors that may have a natural or anthropogenic origin, such as nutrient enrichment or the presence of chemical contaminants. El Colegio de la Frontera Sur (ECOSUR) carried out a "Diagnosis of the Chetumal Bay Water Quality ", using its own databases of water quality parameters, as well as data from monitoring programs of the Secretaría de Marina, and the Secretaría de Salud of the Quintana Roo State; which indicated a decrease in water quality in the bay over a period of 10 years (2005-2015). As a result, the development of a permanent water quality monitoring program was proposed, in order to determine the spatial and temporal variability of the indicators, to take actions of cleaning, conservation and management.

Based on this proposal, in 2017 and 2018 ECOSUR conducted the water quality monitoring and the training of RESMBCH staff, with the main objective of strengthening the capacities of the Instituto de la Biodiversidad y Áreas Naturales Protegidas (IBANQROO) of the Quintana Roo State, with financial support from the Conservation Project of Marine Resources in Central America; administered by MAR FUND and financed by the Government of Germany through the German Development Bank (KFW).

Additionally, since Chetumal Bay is an aquatic system shared between Mexico and Belize, in 2017 and 2018 ECOSUR also worked in coordination with Sarteneja Alliance for Conservation and Development (SACD) staff to conduct water quality monitoring at Corozal Bay; which included the training of some of its members, with the aim of strengthening their technical capacities. These activities were also supported by the Conservation Project of Marine Resources in Central America.

The results of the water quality assessment for 2017 and 2018 in Bahía Chetumal / Corozal indicated that poor water quality was maintained mainly in sites close to human settlements, especially during the dry and rainy seasons; in addition to a condition of organic enrichment in the central region of the system, associated mainly with natural processes of mineralization of organic matter, produced in the extensive wetlands that are located in the communication channel with the Caribbean Sea (Álvarez, 2019).

Among the objectives of the 2018 monitoring, the elaboration of a water quality integral diagnosis of these protected natural areas of Mexico and Belize was included. The document will be useful in making decisions for conservation, protection and clean-up actions of this cross-border system. The diagnosis is presented below.

2.- STUDY AREA

The Reserva Estatal Santuario del Manatí Bahía Chetumal (RESMBCH), includes the water bodies of the Guerrero, Salada and Chile Verde lagoons, and the Chetumal Bay estuary system. The Chetumal Bay has an approximate surface of 2,560 km^2, where the northern part forms a shallow basin with depths ranging from 2 to 5 m; in which there are several freshwater inlets such as the Hondo River, small streams and underground springs (Carrillo et al., 2009).

The Corozal Bay Wildlife Sanctuary (CBWS) is located south of Bahía Chetumal, and is part of the cross-border estuarine system shared between the countries of Mexico and Belize. Corozal Bay covers an approximate area of 720 km^2 and is mainly shallow (less than 2 m deep), although in the communication channel with the Caribbean Sea, it can reach up to 5 m deep. The system also has several surface freshwater inputs, including New River and Progreso Lagoon, as well as groundwater discharges along its coastline (SACD, 2009).

The integral diagnosis of the behavior of the water quality indicators was made by analyzing the Chetumal and Corozal Bays as a single estuarine system. So the monitoring sites have a continuous numbering. Thus, the Chetumal/Corozal System (hereinafter referred to as) comprises sites 1 to 32 (Fig.1 and Table 1).

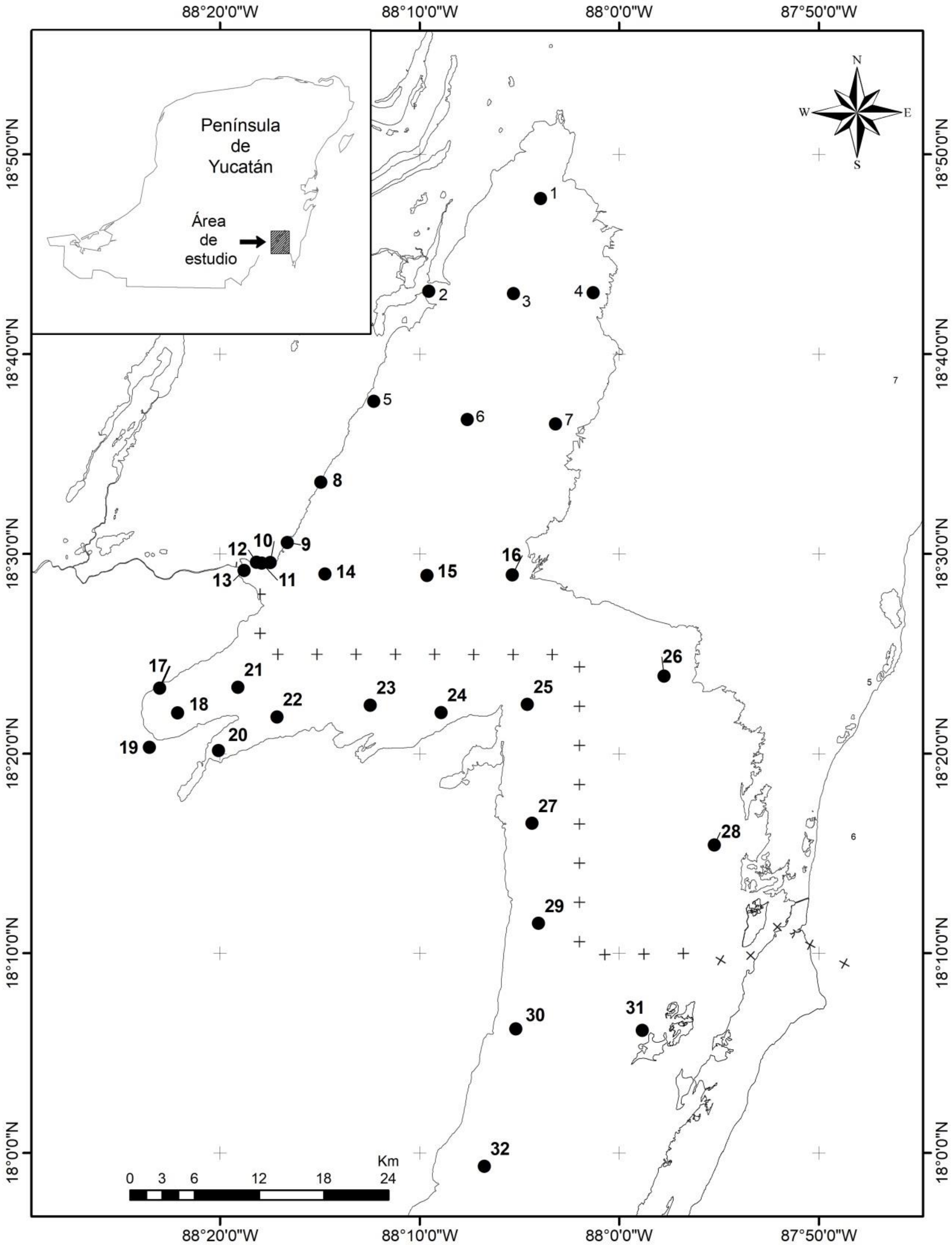

Fig. 1.- Map with the 32 monitoring sites of the Chetumal/Corozal System, for the 2017-2018 monitoring period.

Table 1.- Geographical position data of the 32 Chetumal/Corozal System sites, for the 2017-2018 monitoring period.

CHETUMAL/COROZAL SYSTEM		
Sites	**Latitude**	**Longitude**
1	18°47'47.84"N	88° 03'56.51"W
2	18°43'09.52"N	88° 09'32.49"W
3	18°43'02.58"N	88° 05'17.83"W
4	18°43'04.53"N	88° 01'18.41"W
5	18°37'38.91"N	88°12'17.72"W
6	18°36'43.70"N	88° 07'36.54"W
7	18°36'30.77"N	88° 03'10.92"W
8	18°33'35.58"N	88°14'56.50"W
9	18°30'34.65"N	88°16'37.51"W
10	18°29'33.79"N	88°17'29.24"W
11	18°29'32.50"N	88°17'54.89"W
12	18°29'34.85"N	88°18'10.42"W
13	18°29'09.97"N	88°18'47.72"W
14	18°28'59.57"N	88°14'44.12"W
15	18°28'55.24"N	88° 09'37.93"W
16	18°28'56.88"N	88° 05'21.16"W
17	18°23'16.34"N	88°23'01.34"W
18	18°22'02.77"N	88°22'07.40"W
19	18°20'18.63"N	88°23'32.18"W
20	18°20'09.44"N	88°20'04.34"W
21	18°23'19.18"N	88°19'05.86"W
22	18°21'49.92"N	88°17'08.86"W
23	18°22'25.46"N	88°12'28.48"W
24	18°22'03.72"N	88°08'55.29"W
25	18°22'28.14"N	88°04'35.80"W
26	18°23'52.91"N	87°57'45.37"W
27	18°16'30.55"N	88°04'22.06"W
28	18°15'25.14"N	87°55'13.39"W
29	18°11'30.01"N	88° 04'2.66"W
30	18°06'13.02"N	88°05'10.25"W
31	18°06'08.74"N	87°58'50.59"W
32	17°59'20.17"N	88°06'45.57"W

3.- INTEGRAL DIAGNOSIS

The integral diagnosis included the analysis of the spatial and temporal behavior of the twelve water quality indicators assessed during 2017-2018. In which the bays of Chetumal and Corozal, were analyzed as a single estuarine system called here as Chetumal/Corozal System.

The indicators analyzed were: 1) the Ecological Criteria of Water Quality (CECAs, for its acronym in Spanish) for the protection of aquatic life of brackish and marine water (SEDUE, 1989), 2) The TRIX Trophic Index (Vollenweider et al., 1998), that evaluates the organic enrichment of a body of water, integrating several parameters evaluated (dissolved inorganic nitrogen and phosphorus, chlorophyll a, dissolved oxygen and water temperature); and 3) The Condition Index based on the determination of reference values per nutrient in each monitoring site (EPA, 1992).

The sources of contamination by human activities were also characterized, and the natural processes that affect the water quality of the system. Finally, there are some conclusions and recommendations that will allow both countries to develop joint actions for the conservation, protection and cleanup of this important transboundary estuarine system.

3.1.- Spatial and temporal behavior of the indicators in relation to the Ecological Water Quality Criteria (EWQCs).

This section describes the spatial and temporal behavior of the water quality indicators in the Chetumal/Corozal System. In addition, the concentrations of nutrients are compared with the Maximum Permissible Limits (LMP) of the Ecological Water Quality Criteria (CECAs) for the protection of aquatic life of brackish and marine water (SEDUE, 1989), which remain in use because they have not received updates by the Ministry of Environment and Natural Resources.

Physicochemical Indicators:

The spatial and temporal behavior of six parameters measured *in situ* with multiparameter probes in the water column is analyzed.

Temperature.-

The measurement of water temperature is very important, because this parameter determines the solubility of dissolved oxygen in the column water that is indispensable for the respiration of aerobic aquatic organisms. In addition to contributing to the aerobic processes of organic matter decomposition, which make available nutrients such as phosphorus and nitrogen, for the primary producers that are the basis of trophic chains.

In the Chetumal/Corozal System the mean annual temperature was similar in 2017 and 2018 (28.57 ºC ± 1.78 and 28.55 ºC ± 1.92, respectively). In relation to seasonal behavior, dry (April) and wet (August) seasons registered the highest mean temperature in both years. Thus, in 2017 temperatures of 29.98 ºC ± 0.79 and 30.31 ºC ± 0.60 were registered, and for 2018 of 29.27 ºC ± 0.87 and 29.57 ºC ± 1.41, respectively (Table 2).

Table 2.- Comparison of the minimum, maximum and mean value (± standard deviation) of temperature (°C), in Chetumal / Corozal Bay, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	29.98±0.79	30.31±0.60	26.45±0.90	29.27±0.87	29.57±1.41	26.34±1.67
	Min.	27.40	29.30	25.90	28.0	27.90	23.80
	Max.	30.29	31.89	27.86	30.71	32.11	29.20

In August of the two years, values higher than 31ºC were recorded in sites 9 to 13, which are located in front of the Chetumal city and the Hondo river (Fig. 1). While in November (Nortes season) the lowest mean temperatures were recorded in 2017 (26.45 ºC ± 0.90) and 2018 (26.34 ºC ± 1.67) (Table 2), where the sites 18 to 32 located in the southern zone of the system, presented values lower than 26ºC (Fig.1).

Dissolved Oxygen.-

Dissolved oxygen (DO) is essential for the respiration of aerobic aquatic organisms, so it is considered that 5 mg/l is the minimum value necessary to maintain the life of a healthy aquatic system (SEDUE, 1989). However, the decomposition of organic matter by aerobic microorganisms implies the consumption of DO, so that an excess of organic load could cause the decrease of this parameter. Organic matter can originate from natural sources such as wetlands, or from anthropogenic sources such as untreated wastewater discharges. Therefore, this parameter has been used as an important indicator of the aquatic environment.

In the Chetumal/Corozal System, the mean annual DO concentration was the same in 2017 and 2018 (7.46 mg/l ± 1.45 and 7.25 mg/l ± 1.13). In general, the system registered mean values higher than 7 mg/l in the three seasons (Table 3).

Table 3.- Comparison of the minimum, maximum and mean value (± standard deviation) of dissolved oxygen (mg/l), in Chetumal / Corozal System, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	7.36±0.92	6.93±1.30	8.09±1.79	7.19±1.14	7.24±1.18	7.35±1.07
	Min.	5.88	2.99	2.64	3.39	3.67	3.06
	Max.	9.23	9.82	11.04	9.22	9.62	8.67

Interestingly, during the period 2017-2018, site 19 registered DO levels below the Maximum Permissible Limit of 5 mg/l, established in the CECAs for the protection of brackish and marine aquatic life (SEDUE, 1989) (Table 3). This site is located in front of the mouth of New River, in shallow waters of Corozal Bay, where a high organic load could be demanding DO for its decomposition.

Salinity.-

The variation of salinity in a water body, indicates the influence of freshwater and marine inputs, which can modify the spatial and temporal distribution of water quality indicators and aquatic species.

In the Chetumal/Corozal System the annual mean salinity value was 13.7 ‰ ± 6.4 in 2017 and in 2018 of 14.4 ‰ ± 6.6. These values are typical of estuarine systems influenced by fresh and marine water, as in this case.

Table 4.- Comparison of the minimum, maximum and mean value (± standard deviation) of salinity (‰), in Chetumal / Corozal Bay, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	15.9±7.1	15.0±6.4	10.1±4.0	14.0±8.4	16.4±6.9	14.5±6.5
	Min.	4.6	2.5	0.5	1.5	3.3	0.5
	Max.	38.3	30.7	18.2	37.2	34.2	29.0

The lowest seasonal average salinity was recorded in the northeastern year of 2017 (10.1 ‰ ± 4.0) and the highest in the rainy season of 2018 (16.4 ‰ ± 6.9) (Table 4). In 2018 the highest salinity was recorded, particularly in the rainy season, due to lower rainfall in this year; so the influence of seawater was greater. The spatial behavior of the salinity, indicated that values lower than 5 ‰ were presented in sites 13 (Hondo river), 9 to 12 (Calderitas Town and Chetumal City) and 19 (New River), where there is surface and underground discharge of fresh water (Fig. 1).

Conductivity.-

This parameter is analyzed only for Chetumal Bay, because it was not measured in Corozal Bay.

Conductivity may have a similar behavior than salinity, because this indicator is sensitive to variations in dissolved solids, mainly mineral salts (Chapman, 1996). Thus, the annual mean of salinity and conductivity in Chetumal Bay, was the same in 2017 (12.1 ‰ ± 4.1 and 20.2 mS/cm ± 6.5, respectively) and in 2018 (12.2 ‰ ± 4.8 and 20.2 mS/cm ± 7.5, respectively).

Table 5.- Comparison of the minimum, maximum and mean value (± standard deviation) of conductivity (mS/cm), in Chetumal/Corozal System, in the monitoring period 2017-2018.

		2017			**2018**		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Media ± DS	21.5±6.9	20.6±7.3	18.5±5.0	16.7±7.7	21.8±6.6	23.4±6.9
	Min.	8.3	4.6	1.1	2.9	6.1	4.3
	Máx.	36.6	28.1	22.7	24.9	29.9	31.0

The temporal variability of the two parameters was also similar. Thus, during 2017 salinity registered a descending behavior from dry to nortes seasons, (13.5 ‰ ± 4.5, 12.7 ‰ ± 4.6 and 11.1 ‰ ± 3.1, respectively), and the same occurred with conductivity (Table 5). In contrast, by 2018 the seasonal behavior of salinity was ascending from dry to nortes seasons (10.2 ‰ ± 4.8, 13.4 ‰ ± 4.2 and 14.7 ‰ ± 7.9, respectively), as well as in conductivity (Table 5). This behavior could be associated with lower rainfall during 2018, which favored a greater marine influence.

In relation to spatial behavior, the lowest values of conductivity and salinity during the monitoring period, were recorded in front of Hondo River (site 13), Chetumal City and Calderitas Town (sites 8 to 12) (Fig. 1). All with influence of surface and underground fresh water discharge.

pH.-

The pH is an important variable in the evaluation of water quality, because it influences many chemical and biological processes. In most water bodies, the pH is in the range of 6.0 to 8.5, although higher values can occur in eutrophic waters (Chapman, 1996).

Table 6.- Comparison of the minimum, maximum and mean value (± standard deviation) of pH (units), in Chetumal / Corozal System, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	7.92±0.49	7.98±0.34	8.33±0.33	7.97±0.37	8.07±0.26	8.47±0.32
	Min.	6.88	6.74	7.27	6.41	7.53	7.76
	Max.	8.86	8.42	8.71	8.44	8.40	8.97

In the Chetumal / Corozal System the mean annual value of pH was similar in 2017 and 2018, with values of 8.07 ± 0.43, and 8.14 ± 0.38, respectively. The pH had an ascending seasonal behavior from dry to nortes seasons (Table 6), without statistically significant differences. These values are in the normal range of natural water bodies. Values higher than 8.5 were recorded in sites near of Chetumal City, which coincide with ammonium and phosphate levels above the Maximum Permissible Limit of the CECAs, for the protection of aquatic life of brackish waters (SEDUE, 1989).

<u>*Turbidity and Transparency*</u>*.-*

According to Chapman (1996), the turbidity and transparency of water are controlled by the type and concentration of the suspended matter, which is composed of particles of silt, clay, organic and inorganic matter, plankton and other microorganisms. Turbidity is a measure of the dispersion and absorption of light by particles in a water body, while transparency measures the visibility limit in the water column. According to these concepts, both variables are complementary, since a greater turbidity in the water column corresponds to a lower transparency, and vice versa.

As turbidity was assessed in Chetumal Bay and transparency in Corozal Bay, the mean values of these indicators are reported separately (Table 7). It is important to indicate that turbidity data are not available for Chetumal Bay in November 2018, due to sensor failures in the multiparameter probe.

Table 7.- Comparison of the minimum, maximum and mean value (± standard deviation) of the turbidity (NTU), in Chetumal Bay, and transparency (%) in Corozal Bay, in the monitoring period 2017-2018.

		2017			**2018**		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal Bay	Mean ± SD	31.3±40.0	13.8±24.0	3.1±3.0	13.6±16.0	21.7±40.0	sd
	Min.	0.0	0.0	0.0	0.1	0.0	sd
	Max.	104.0	78.6	12.4	53.7	129.0	sd
Corozal Bay	Mean ± SD	66±34	68±35	79±28	79±25	74±27	69±30
	Min.	5	16	9	29	29	27
	Max.	100	100	100	100	100	100

Table 7 shows that in the dry season (April) of 2017, Chetumal Bay and Corozal Bay registered the highest turbidity (31.3 NTU ± 40.0) and therefore the lowest transparency (66% ± 34), respectively. While the lowest turbidity (3.1 NTU ± 3.0) and therefore the highest transparency (79% ± 28) was observed in the nortes season. This could be due to a higher rainfall in the dry season (132 mm) than in the northerly (74 mm) season of 2017, which represented a source of suspended solids runoff to the estuarine system.

In contrast, by 2018, the dry season recorded the lowest turbidity value (13.6 NTU ± 16.0) and the highest transparency (79% ± 25); while in the nortes season (69% ± 30) the lowest transparency was registered. As in 2018 the rainfall was similar in April (92 mm) and November (78 mm), it is possible that the turbidity and transparency in Chetumal/Corozal System, was regulated by the chlorophyll *a* concentration, which was higher in April (2.94 µg/l ± 1.22) than in November (2.15 µg/l ± 1.66) (Table 13).

In relation to spatial behavior, the highest turbidity in Chetumal Bay was always observed in the sites near to Chetumal City (9 to 12) and the Hondo river (13) (Figure 1). While the lowest transparency in Corozal Bay, it was observed in sites 17 to 21, located in front of New River and Corozal City.

Nutrient Indicators and Chlorophyll a:

In this section, the spatial and temporal behavior of the organic load indicators in the Chetumal/Corozal System is analyzed, in the monitoring period of 2017-2018. Likewise, to determine the water quality, the concentration of nutrients is compared with the Maximum Permissible Limits (MPL) established in the Ecological Water Quality Criteria (CECAs for its acronym in Spanish) for the protection of brackish and marine aquatic life (SEDUE, 1989).

Phosphorus and nitrogen are essential nutrients for all living beings. The inorganic forms of these elements are used by photosynthetic organisms for the production of biomass, which is the basis of food chains. In water bodies, excess nutrients from natural and anthropogenic sources could stimulate the production of biomass from microscopic plants such as phytoplankton. When this biomass decomposes, it will demand the use of dissolved oxygen by the degrading microorganisms, decreasing its concentration and availability for aerobic organisms. This process is called eutrophication. Due to the important role played by nutrients in the functioning of aquatic ecosystems, they have been used as indicators of water quality.

With the objective of determining the quality of water in the Chetumal / Corozal System in the period 2017-2018, the spatial and temporal behavior of nitrites, nitrates, ammonium and phosphates is analyzed; and its concentration is compared with the CECAs. The behavior of the silicates is also analyzed as a pollutant tracer of the groundwater to the aquatic system, due to the different human activities in the basin. In addition, chlorophyll *a* is evaluated as a response of the water body to the excessive presence of nutrients.

Nitrites.-

In the Chetumal / Corozal System, the nitrites mean annual concentration was the same in 2017 and 2018 (0.003 mg / l ± 0.004). The wet (August) and nortes seasons (November) for both years, presented mean values above the Maximum Permissible Limit (MPL) of 0.002 mg/l, established in the CECAs for the protection of the brackish and marine aquatic life (Table 8).

Table 8.- Comparison of the minimum, maximum and mean value (± standard deviation) of nitrites (mg / l), in Chetumal-Corozal System, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	0.002±0.005	**0.004**±0.004	**0.003**±0.002	0.002±0.002	**0.003**±0.004	**0.003**±0.005
	Min.	0.0001	0.001	0.001	0.0002	0.0001	0.0001
	Max.	**0.027**	**0.016**	**0.010**	**0.011**	**0.015**	**0.022**
	Percentage	16% (5)	50% (16)	32% (10)	25% (8)	35% (11)	32% (10)

In relation to the spatial variability in the Chetumal / Corozal System, for the dry season (April) the percentage of sites with values exceeding the CECAs, increase from 2017 (16%) to 2018 (25%), mainly in front of cities of Chetumal and Corozal, and Orchid Bay, which are shallow areas influenced by rainwater discharges and groundwater mixed with wastewater (Fig. 2).

For the wet season (August) the percentage of sites with levels exceeding the CECAs increases with respect to the dry season, but decreases from 2017 (50%) to 2018 (35%). Sites with poor water quality were located from the Calderitas Village to the Hondo river, and from Corozal City to the Sarteneja Town (Fig. 3).

The water quality improved In nortes season, where 32% of the sites had values that exceeded the CECAs, in both years of monitoring. The poor water quality remained in sites near of Chetumal City and extended to the north of the bay, mainly due to the sediments resuspension with a high content of organic matter, influenced by the winds (Fig. 4).

Nitrates.-

The mean annual concentration of nitrates in the Chetumal/Corozal System decreased from 2017 (0.037 mg/l ± 0.057) to 2018 (0.028 mg/l ± 0.044). Although this decrease was observed for the dry (April) and wet (August) seasons, in nortes (November) the concentration increased from 2017 (0.012 mg/l ± 0.015) to 2018 (0.032 mg/l ± 0.045) (Table 9).

Table 9.- Comparison of the minimum, maximum and mean value (± standard deviation) of nitrates (mg/l), in Chetumal-Corozal System, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	**0.074**±0.077	0.024±0.040	0.012±0.015	0.030±0.053	0.022±0.034	0.032±0.045
	Min.	0.002	0.002	0.001	0.001	0.002	0.000
	Max.	**0.242**	**0.169**	**0.060**	**0.184**	**0.155**	**0.188**
	Percentage	63% (19)	13% (4)	3% (1)	19% (6)	9% (3)	22% (8)

In relation to the spatial variability in the Chetumal/Corozal System, for the dry season (April) of 2017, 63% of the sites (8 to 13, 17 to 25 and 29 to 32) presented concentrations exceeding the MPL of the CECAs (0.04 mg/l). All sites located on the west coast, where human settlements and wetlands with high organic content are found, so the sources are of anthropogenic and natural origin. By 2018, the sites with values above the CECAs comprised only 19% (sites 8 to 13), which are located in front of Calderitas Village, Chetumal City and Hondo River mouth (Fig. 2).

For the wet season (August), 19% of the sites (8 to 14) in 2017 presented values exceeding the CECAs, and decreased to 9% (sites 11 to 13) in 2018; in both years the sites were located in front of Calderitas Town, Chetumal City and Hondo river (Fig. 3). While for the nortes season (November), the sites with values exceeding the CECAs increased from 2017 (3%) to 2018 (22%), mainly in places near of Chetumal City (8 to 12), Hondo River (13) and Corozal City (17 and 21) (Fig. 4).

Ammonium.-

The mean annual concentration of ammonium decreased from 2017 (0.040 mg / l ± 0.028) to 2018 (0.031 mg / l ± 0.020) in the system, due to the dry (April) and wet (August) seasons. In contrast, an increase was recorded for the nortes season (Table 10).

In April and August 2017, 100% and 97% of the 32 monitored sites presented ammonium values above MPL (0.01 mg/l) for the protection of brackish and marine aquatic life of the CECAs. By 2018, the sites that exceeded the CECAs decreased to 66% in April and 88% in August (Fig. 2 and 3). While for November (nortes season), 66% of the sites in 2017 presented higher values than the CECAs, and increased to 100% by 2018 (Fig.4).

Table 10.- Comparison of the minimum, maximum and mean value (± standard deviation) of ammonium (mg/l), in Chetumal-Corozal System, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	**0.043**±0.021	**0.057**±0.034	**0.021**±0.012	**0.034**±0.029	**0.028**±0.016	**0.032**±0.013
	Min.	**0.022**	**0.012**	0.001	0.001	0.004	0.015
	Max.	**0.124**	**0.159**	**0.058**	**0.112**	**0.074**	**0.060**
	Percentage	100% (32)	97% (31)	66% (21)	66% (21)	88% (28)	100% (32)

The sources of ammonia in the western coast of Chetumal Bay and the northern coast of Corozal Bay, are related to leaking sewage from leached septic tanks and stormwater runoff, as well as agricultural areas of the Hondo River and New River, respectively. Ammonium on the southern coast of Corozal Bay comes from the surface runoff of wetlands with high organic load. While the mineralization of organic matter in the sediments of sites in the north and center of Chetumal Bay, is the cause of the high content of this nutrient.

Phosphates.-

In the Chetumal/Corozal System, the mean annual concentration of phosphates increased from 2017 (0.003 mg/l ± 0.003) to 2018 (0.004 mg/l ± 0.002), due to the increase recorded during the nortes season (November); since in dry (April) and wet seasons (August), the mean monthly concentration decreased or remained unchanged (Table 11).

Table 11.- Comparison of the minimum, maximum and mean value (± standard deviation) of phosphates (mg/l), in Chetumal-Corozal System, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	**0.005**±0.003	**0.004**±0.003	0.001±0.000	**0.004**±0.002	**0.004**±0.003	**0.003**±0.002
	Min.	0.001	0.001	0.001	0.001	0.002	0.001
	Max.	**0.012**	**0.010**	0.002	**0.008**	**0.017**	**0.008**
	Percentage	75% (24)	53% (17)	0%	63% (20)	66% (21)	53% (17)

In April, in 75% of the sites in 2017, the phosphate level (0.002 mg/l) established for the protection of brackish and marine aquatic life was exceeded, which decrease to 63% by 2018. For the wet season (August), sites with values higher than the LMP increased from 53% in 2017 to 66% in 2018. While in nortes season (November) only in 2018 the CECAs were exceeded, in 53% of the sites.

In general, the sites that exceeded the CECAs were located mainly in front of Chetumal and Corozal Cities, the Hondo and New rivers, as well as the southern coast of Corozal Bay (Fig. 2, 3 and 4). The sources of phosphates are associated with human settlements, superficial runoff of organic load of rivers and wetlands, as well as decomposition of organic matter in the estuarine bed.

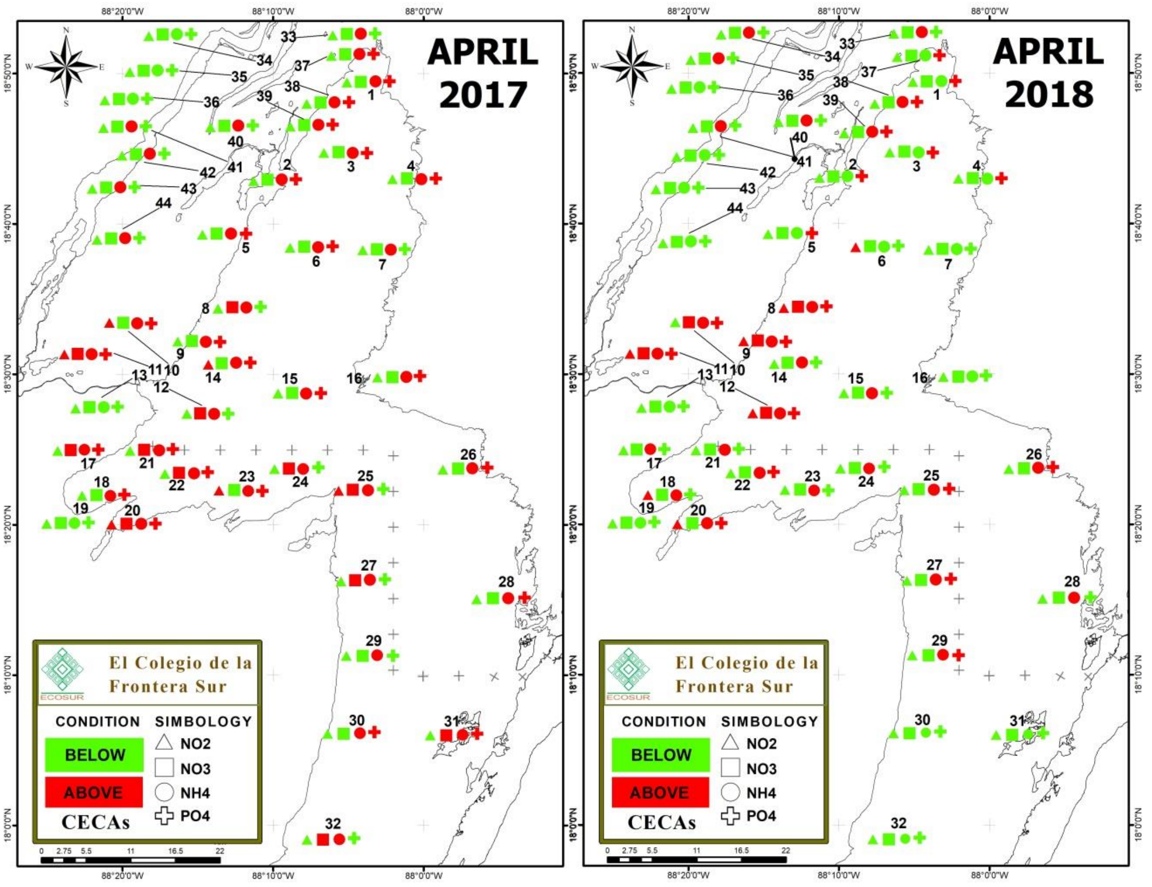

Fig. 2.- CECAs spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in dry season (April, 2017 and 2018).

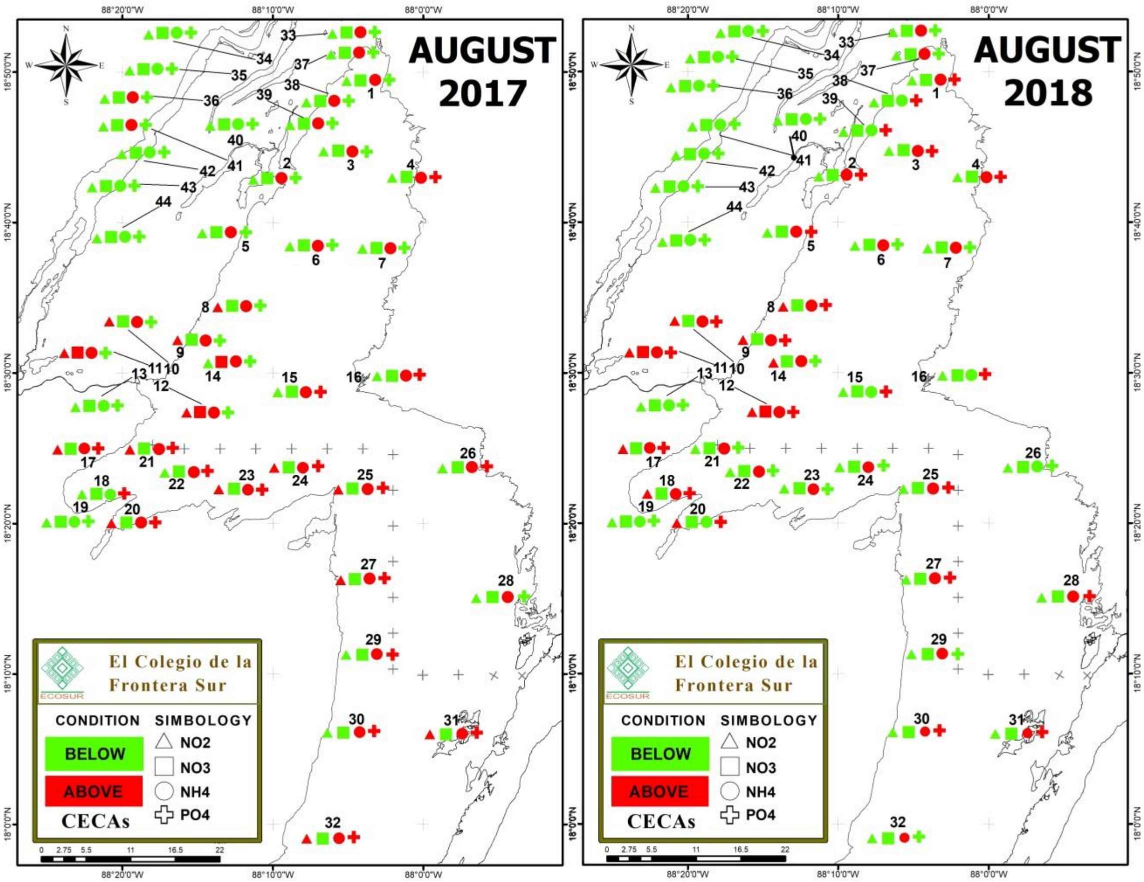

Fig. 3.- CECAs spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in wet season (August, 2017 and 2018).

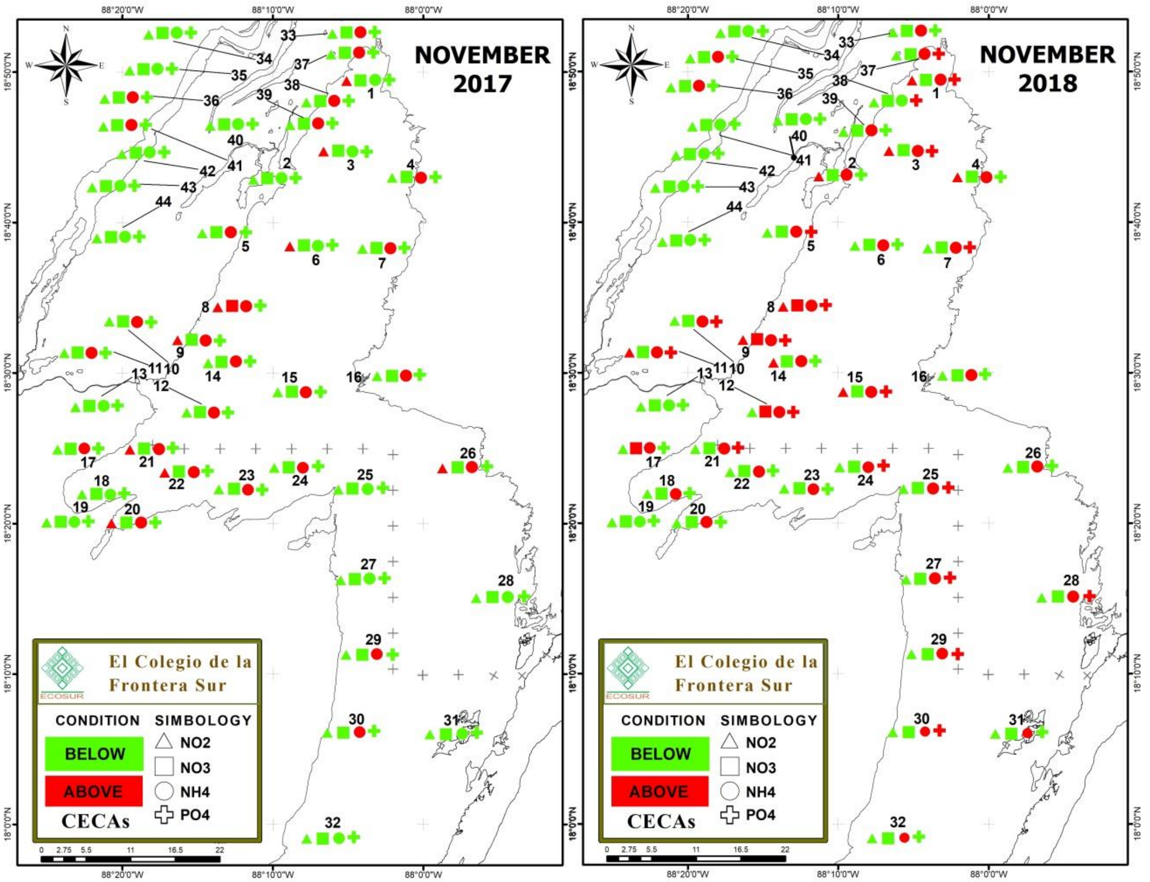

Fig. 4.- CECAs spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in nortes season (November, 2017 and 2018).

Silicate.-

The silicates are used as a tracer of the discharge of groundwater to surface water bodies. According to Stewart et al (2007), the concentration of this element increases in the water that infiltrates the soil, by the silicate minerals dissolution in their transport to the aquifer. The Chetumal/Corozal System receives the discharge of groundwater that can be accompanied by leachates with high organic content, due to deficient septic tanks and sanitary landfills used in human settlement areas. Therefore, the evaluation of silicates can be used to identify potential sources of contamination to surface water bodies.

The average annual concentration of silicates in the Chetumal / Corozal System increased from 2017 (2.75 mg / l ± 2.02) to 2018 (5.44 mg / l ± 2.88). The increase is probably explained by lower rainfall in April and August 2018, compared to 2017 (National Water Commission); which favored the predominance of silicate-rich groundwater discharge for these seasons (Table 12).

Table 12.- Comparison of the minimum, maximum and mean value (± standard deviation) of silicate (mg/l), in Chetumal-Corozal System, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	Mean ± SD	5.80±2.18	2.62±0.95	2.83±0.57	6.28±2.33	7.34±2.40	2.69±1.37
	Min.	0.98	0.48	1.44	0.74	1.07	0.52
	Max.	9.74	5.11	4.59	10.92	12.74	5.54

On the spatial behavior of this indicator, the highest concentrations of silicates were recorded at sites where the main groundwater inflows would be found. Mainly in front of Chetumal and Corozal cities, Rio Hondo, New River, and Orchid Bay (sites 9 to 13 and 17 to 22) (Fig. 1). The presence of nitrites, nitrates and ammonium predominated at the groundwater discharge points.

Chlorophyll a.-

Chlorophyll *a* is a green pigment present in most photosynthetic organisms, which provides an indirect measure of algae biomass, so it has been used as an indicator of the trophic state of water bodies (Chapman, 1996).

Tabla 13.- Comparison of the minimum, maximum and mean value (± standard deviation) of chlorophyll *a* (μg/l), in Chetumal-Corozal System, in the monitoring period 2017-2018.

		2017			2018		
System	**Statistics**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Bahía Chetumal/Corozal	Mean ± SD	3.21±1.43	1.68±0.83	3.46±0.92	2.94±1.22	3.86±1.04	2.15±1.66
	Min.	0.79	0.51	1.99	1.30	2.18	0.00
	Max.	5.99	3.50	5.79	5.44	6.17	5.80

In the Chetumal/Corozal System the mean annual concentration of chlorophyll *a* increased from 2017 (2.78 μg/l ± 1.34) to 2018 (2.99 μg/l ± 1.49), mainly due to the wet season (August) (Table 13).

In both years the highest chlorophyll *a* concentrations (4 to 6 μg / l) were registered in sites located in front of Corozal City, Orchid Bay, Sarteneja Town and the communication channel with the Caribbean Sea (17, 21 to 24 and 29 to 31); where phosphates and nitrites regulated the response of this indicator (Fig. 1).

3.2.- Spatial and temporal behavior of the TRIX Trophic Index

The organic enrichment of water bodies by pollution sources associated with human activities, is the cause of the eutrophication process. This consists of increasing biomass of primary producers such as microalgae that use nitrogen and phosphorus for photosynthesis. When this organic matter decomposes, demands dissolved oxygen by degrading microorganisms, resulting in a decrease in this essential element for aerobic organisms, which can cause the death of sensitive aquatic species.

In the evaluation of the organic enrichment of bodies of water, various trophic indices have been used, such as that of Karidis et al (1983) that determines the trophic status for each nutrient, and which was used in the final reports of this monitoring project. Another trophic index is the TRIX of Vollenweider et al (1998), which estimates the quality of the water body from four variables: chlorophyll *a*, dissolved oxygen, dissolved inorganic nitrogen (nitrites + nitrates + ammonium) and dissolved inorganic phosphorus (phosphates). From the equation, four trophic levels are obtained: 1) Oligotrophic: High quality of unproductive waters, 2) Mesotrophic: Good quality of moderately productive waters, 3) Eutrophic: Poor quality of waters between moderate and highly productive, and 4) Hypertrophic: Poor quality of highly productive waters.

Table 14 reports the percentage of sites that presented the different trophic levels, by season during the monitoring period.

Table 14.- Comparison of the TRIX Trophic Index, in Chetumal-Corozal System, in the monitoring period 2017-2018. High = Oligotrophic, Good = Mesotrophic and Poor = Eutrophic.

		2017			2018		
System	**TRIX**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Chetumal/Corozal Bay	High	16% (5)	37% (12)	66% (21)	47% (15)	22% (7)	64% (16)
	Good	62% (20)	53% (17)	34% (11)	50% (16)	75% (24)	32% (8)
	Poor	22% (7)	10% (3)	-	3% (1)	3% (1)	4% (1)

In the Chetumal / Corozal System, water quality improved from 2017 to 2018, since the percentage of sites with high or oligotrophic level increased (34% to 41%, respectively), and sites with good or mesotrophic quality decreased (60% to 51%). On a temporary scale, the nortes season (November) presented the best water quality in both years, because more than 60% of the sites presented oligotrophic conditions (high quality); while the worst water quality was recorded in the dry season of 2017 and the wet season of 2018, since about 80% of the sites presented mesotrophic and eutrophic conditions (Table 14).

At the spatial level, sites 9, 11, 13, 17 to 20, 24 and 31 that presented a eutrophic condition in April 2017, changed to a meso and oligotrophic state for 2018 (Fig. 5). These sites are located in front of the cities of Chetumal and Corozal, Río Hondo and New River; where nutrients are discharged into leachate from septic tanks and fertilizers from agricultural soils.

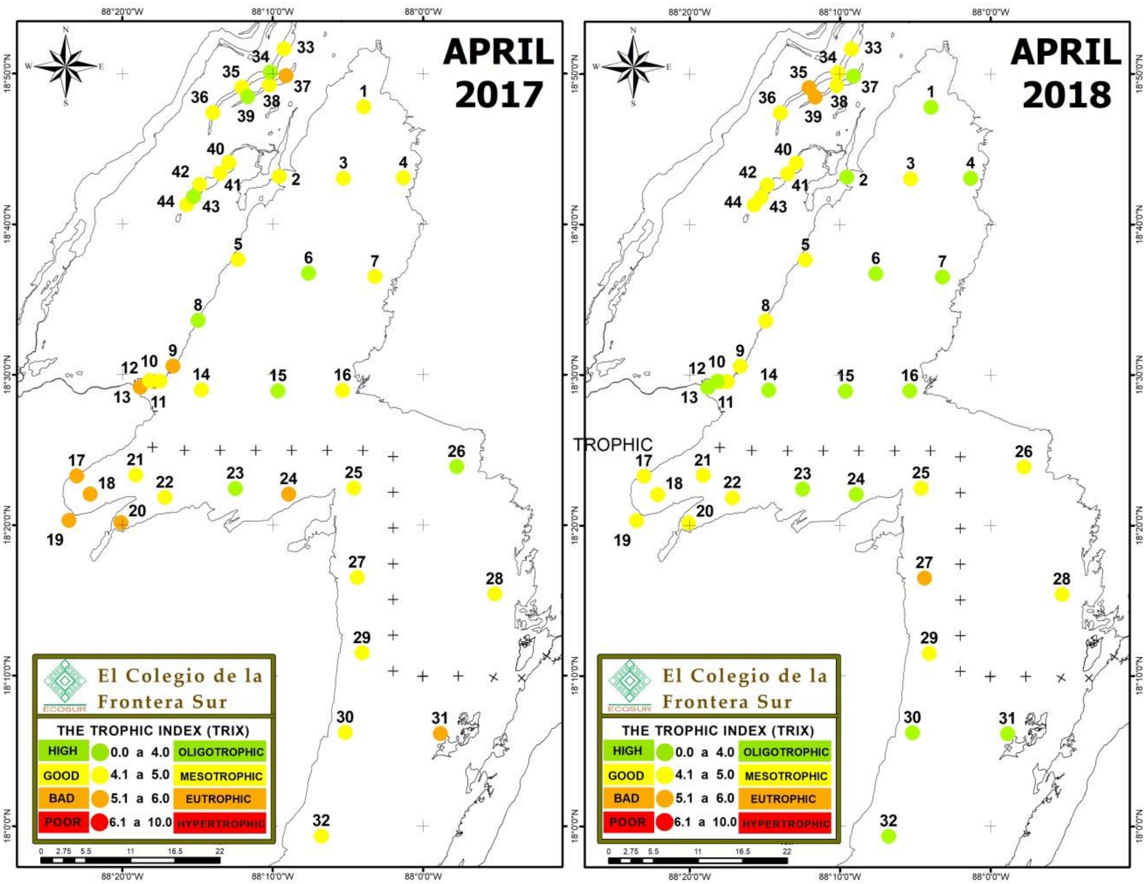

Fig. 5.- TRIX trophic index spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in dry season (April, 2017 and 2018).

In the wet season (August) of 2017, sites 4, 29 and 31 presented poor water quality (eutrophic conditions). At site 31, the eutrophic state was maintained in 2018 (Fig. 6). Due to the geographical position of the sites, the poor quality of the water was associated with the decomposition of organic matter deposited in the sediments, and the surface runoff from nearby wetlands.

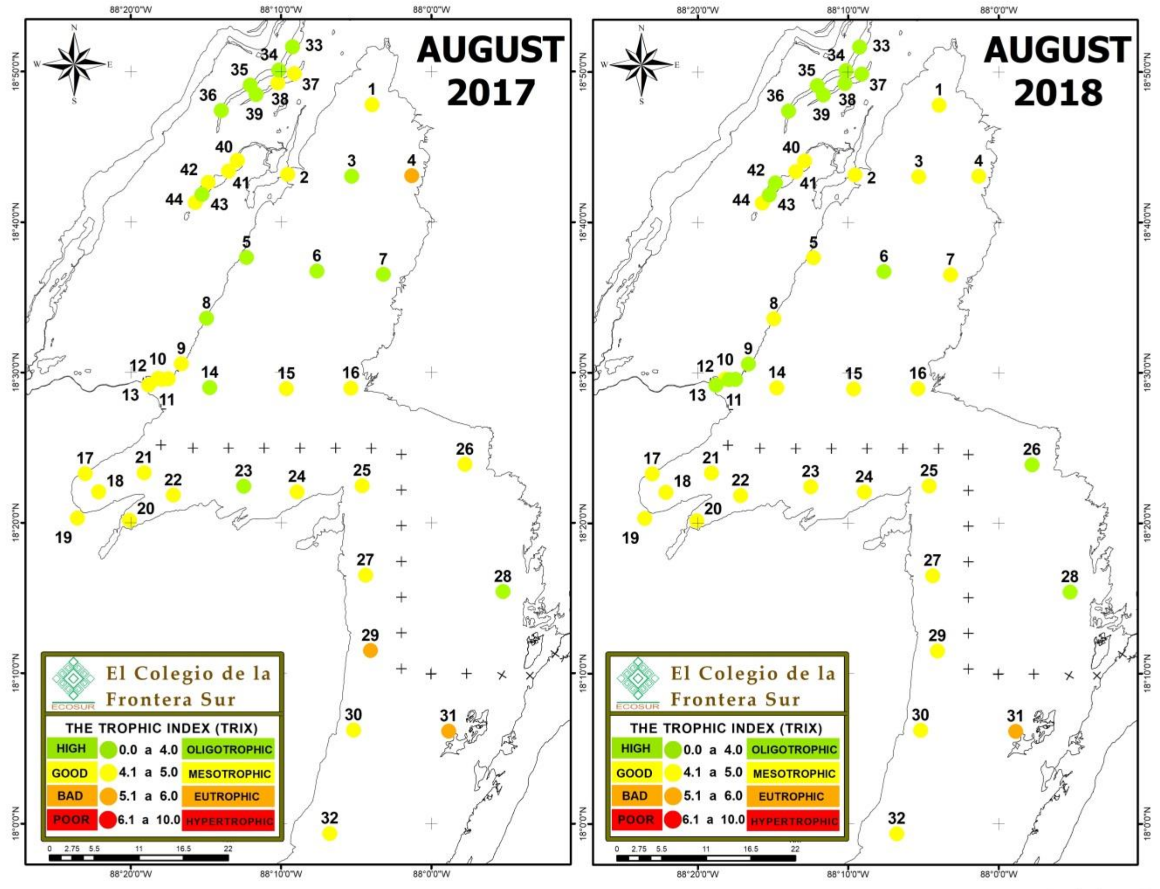

Fig. 6.- TRIX trophic index spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in wet season (August, 2017 and 2018).

Although the nortes season (November) presented the best water quality in most of the system, in specific sites there was a decrease in the trophic condition from 2017 to 2018. It was the case for site 12 that changed from mesotrophic to eutrophic, and for sites 21, 25 and 28 that changed from oligotrophic to mesotrophic (Fig. 7). At site 12, the source of contamination is a pluvial channel in the Parque del Renacimiento of the Chetumal city. For the other sites, its location in shallow areas favored the resuspension of sediments to the water column, which increased the organic load.

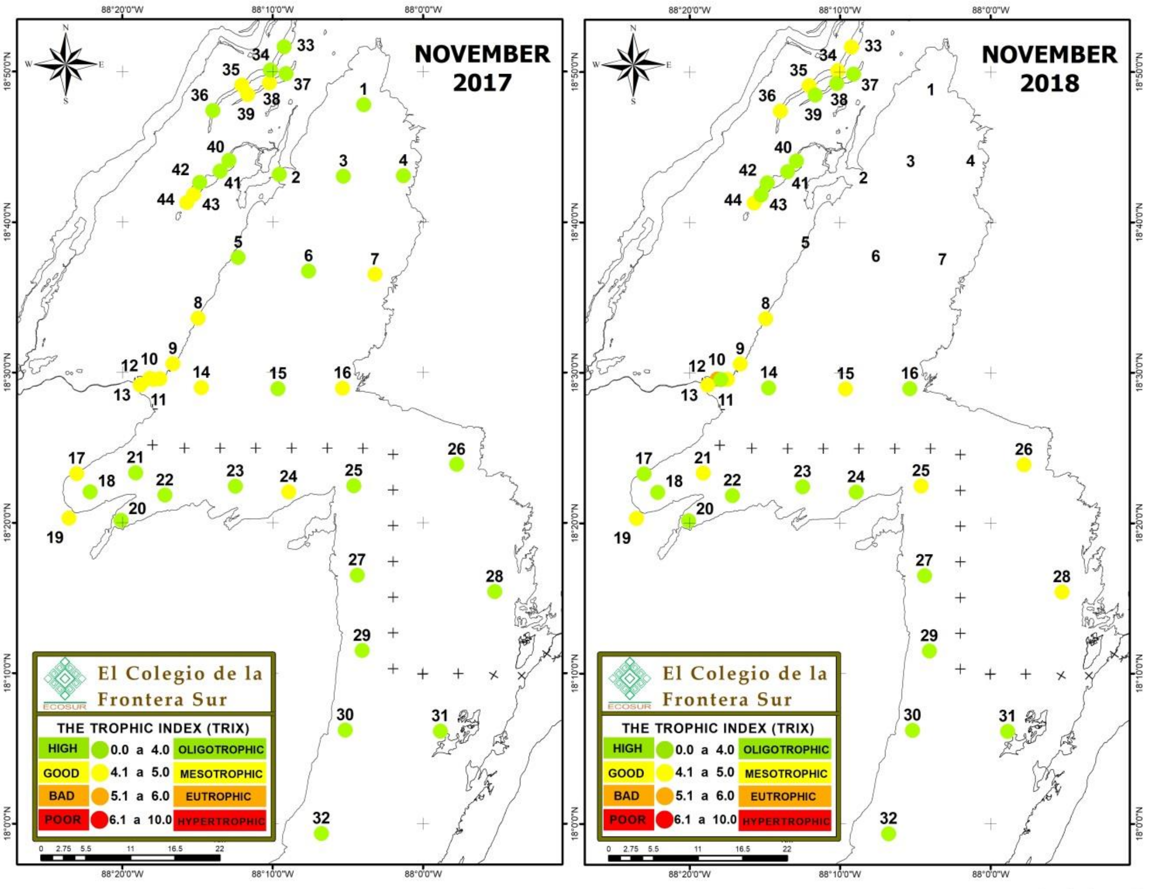

Fig. 7.- TRIX trophic index spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in nortes season (November, 2017 and 2018).

3.3.- Spatial and temporal behavior of the Condition Index (USEPA)

The condition index of the Chetumal / Corozal System was obtained based on the method proposed by the Environmental Protection Agency (EPA, 2004). Thus, for each nutrient the good, regular or poor state was obtained from its reference values. Subsequently, with the condition value of each variable, the overall condition was rated based on the following criteria: a) good: less than 10% of sites in poor condition and less than 50% of sites in fair and poor condition combined, 2) fair: less than 20% of sites in poor condition or more than 50% in fair and poor condition, and 3) poor: more than 20% of sites in poor condition.

Table 15.- Comparison of the USEPA Condition Index, in Chetumal-Corozal System, in 2017-2018 monitoring period.

		2017			2018		
System	**TRIX**	**Dry**	**Wet**	**Nortes**	**Dry**	**Wet**	**Nortes**
Bahía Chetumal/Corozal	Buena	-	3% (1)	56% (18)	32% (10)	34% (11)	22% (7)
	Regular	75% (24)	88% (28)	44% (14)	56% (18)	54% (17)	72% (23)
	Pobre	25% (8)	9% (3)	-	12% (4)	12% (4)	6% (2)

At an annual level, the system maintained a regular condition in the two years of monitoring, because more than 50% of the monitored sites presented a regular and poor condition. On a temporary scale, during 2017, extreme conditions were recorded, because in the dry season (April) the condition was poor, while for the northern season (November) it was good. In the rest of the seasons a fair condition prevailed (Table 15).

In April 2017, sites 11, 13, 14, 17, 20, 22 and 25 presented a poor condition. Most of them are in front of Río Hondo, the cities of Chetumal and Corozal, and Orchid Bay. All with the influence of agricultural runoff, leachate of sewage from septic tanks and the decomposition of organic matter in shallow areas. For April 2018, sites 11 and 13 were kept in poor condition and sites 8 (Calderitas Village) and 9 (Dos Mulas Beach) changed to a poor condition (Fig. 8).

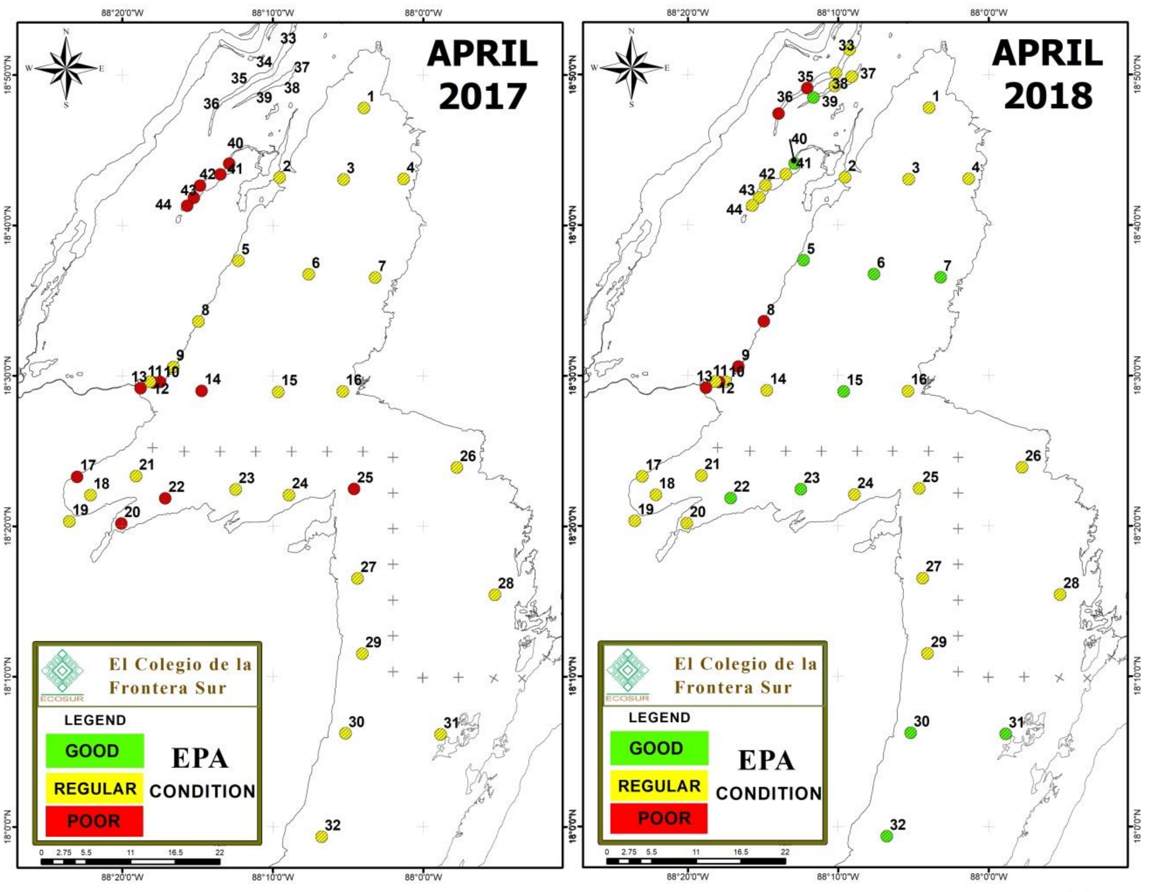

Fig. 8.- EPA Condition Index spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in dry season (April, 2017 and 2018).

In the wet season (August) of both years, sites 8 (Calderitas Village) and 11 (Fiscal Dock) maintained a poor condition. While site 13 (Rio Hondo) changed from a regular condition in 2017 to poor for 2018 (Fig. 9). Finally, for the nortes season (November) of 2018, sites 11 and 13 maintained the poor condition (Fig. 10).

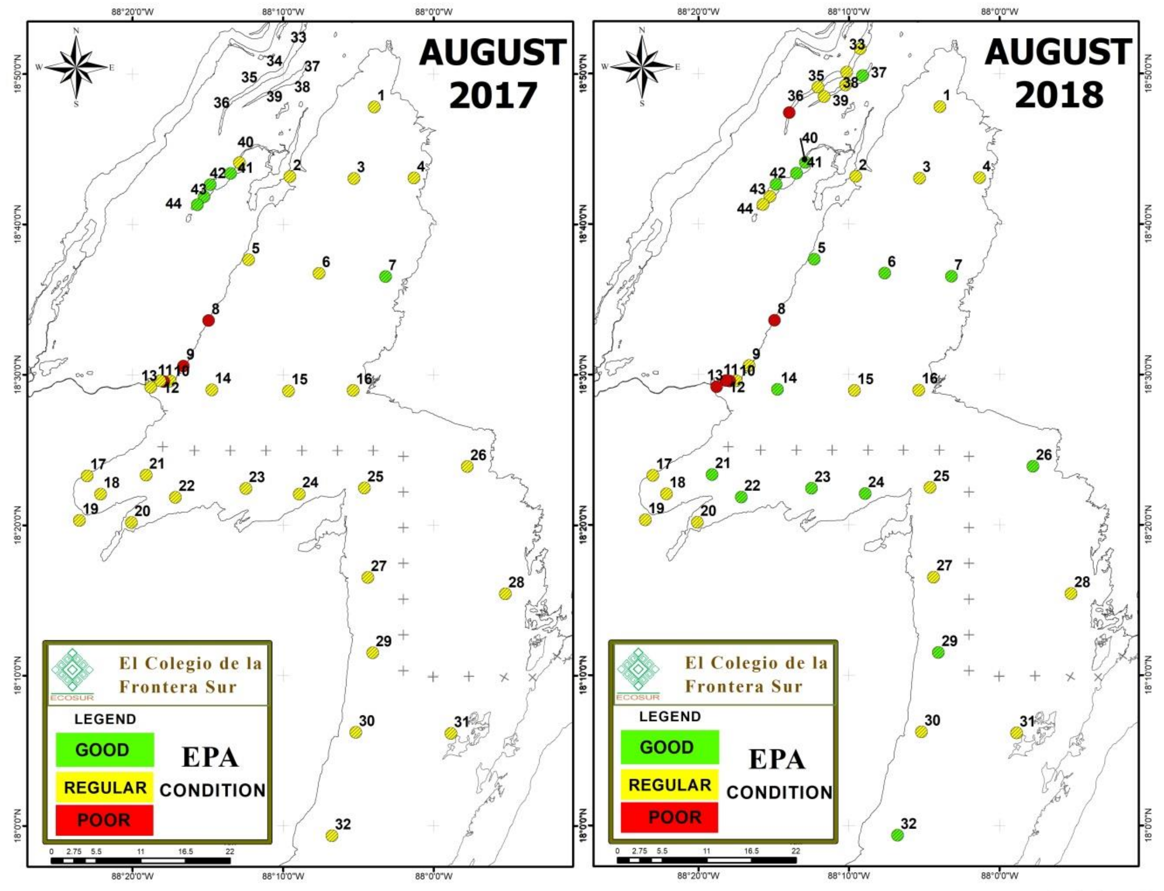

Fig. 9.- EPA Condition Index spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in wet season (August, 2017 and 2018).

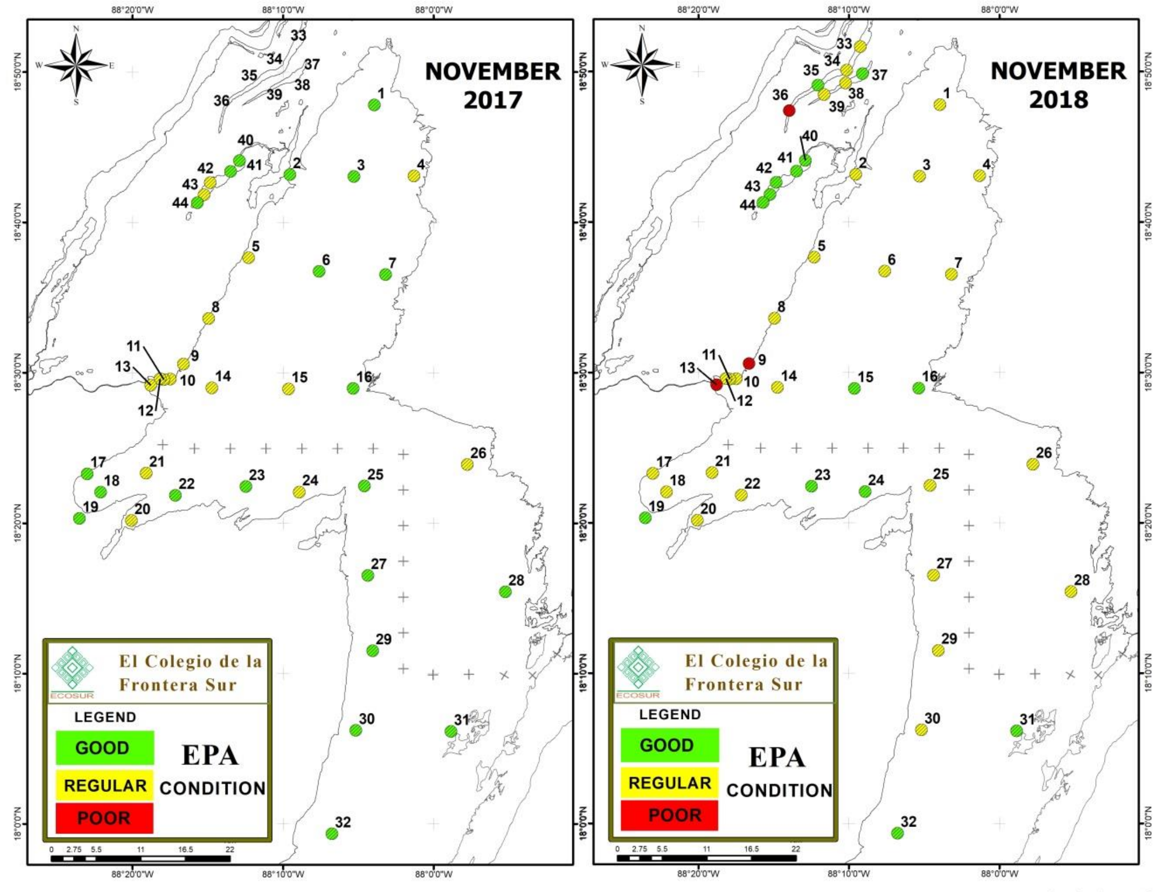

Fig. 10.- EPA Condition Index spatial behavior, in the 32 monitoring sites of Chetumal/Corozal System, in nortes season (November, 2017 and 2018).

3.4.- Main sources of contamination to the Chetumal / Corozal Bay.

The input of pollutants into surface water bodies can come from point and non-point sources. The point sources are related to pollutant discharges that are easily identified because they are located at an exact point and can be measured, as an example are the pipes of a treatment plant or storm discharge channels. While non-point sources are the result of various activities on large areas of the territory, which can deposit pollutants in the water via runoff, leaks to the aquifer and dry deposition of particles from the atmosphere. These characteristics make non-point sources difficult to measure and regulate. Due to the volume and extent of the discharge of pollutants, as well as the difficulty of their control, currently non-point sources are considered as the main source of pollution of rivers, lakes, wetlands, estuaries and oceans (NAS, 2003; Brown and Froemke, 2012).

The sources of nitrogen and phosphorus contamination that cause organic enrichment processes in the Reserva Estatal Santuario del Manatí Bahía Chetumal (RESMBCH) and the Corozal Bay Wildlife Sanctuary (CBWS), are mainly non-point and are described below.

Two point sources were identified in the system:

A) Stormwater discharges potentially mixed with sewage, located at different points along the coastline of the Chetumal and Corozal cities;

B) Discharges of the Hondo and New rivers, with a high content of nitrogen and phosphorus due to the use of fertilizers in the agricultural areas of the Mexico and Belize banks, as well as by septic tank filtrations of human settlements along their course.

Non-point sources of contamination are found throughout the system and are of three types:

A) Surface runoff along the coastline, which is predominant during the rainy and northern seasons, that come from the extensive wetlands in southern Belize, agricultural areas with high use of fertilizers and farms with animal husbandry where food and manure residues are generated, located mainly on the banks of the Hondo and New River. As well as urban and semi-urban areas where rainwater carries waste and pollutants from streets and buildings, as in the Chetumal and Corozal cities, and the Calderitas and Sarteneja villages.

B) Groundwater leaks along the coastline and on the bay bed, with high nutrient content probably due to leachate from septic tanks and open dumps. The data that support the importance of this source of pollution are related to a low sanitation coverage for the city of Chetumal of 45% (CAPA, 2019), which means that the remaining 55% of wastewater is deposited in septic tanks. While in the city of Corozal all its wastewater is found in latrines and septic tanks (Silva, 2015). Regarding the disposal of solid waste, both countries have sanitary landfills that, due to their poor management that includes the lack of membranes that retain leachates, it is more appropriate to refer to them as controlled landfills (Mojica, 2015). The highly permeable karst soil of the region facilitates the infiltration into the aquifer of leachates from septic tanks and open dumps of the main cities and smaller towns, located throughout the entire system.

C) Atmospheric deposition of nitrogen and phosphorus that may come from gases released from fertilized agricultural soils, and the burning of coal and gasoline (ESA, 1998). Although it is an unmeasured flow in the area, the presence of polycyclic aromatic hydrocarbons has been reported in sediments of the Hondo River and Chetumal Bay, which come from the burning of sugar cane on the banks of Mexico and Belize that are transported by the currents of air (Alvarez-Legorreta, 2014; Alvarez-Legorreta and Sáenz-Morales, 2005).

4.- CONCLUSIONS

1.- Water quality improved from 2017 to 2018, mainly due to a decrease in the nitrates and ammonium concentration. However, the increase in the phosphates and chlorophyll a concentration, kept the water body in a regular condition and a mesotrophic state; where the levels of ammonium and phosphates were higher than the maximum permissible limit established in the Ecological Criteria of Water Quality for the protection of aquatic life of brackish environments.

2.- In the dry season (April) the lowest water quality was presented, due to the higher concentrations of all nutrients. While the nortes season (November) maintained the best water quality, with the lowest levels of all nutrients.

3.- Poor water quality was recorded mainly at sites near the cities of Chetumal and Corozal, the towns of Calderitas and Sarteneja, as well as at the mouth of the Hondo and New rivers.

4.- The most important pollution sources due to its extension, scope within the system and its difficulty in being controlled, are of non-point type: surface runoff, groundwater leaks combined with leachates of various types, as well as atmospheric deposition of pollutants generated in agricultural and urban areas. However, point sources such as stormwater discharges combined with sewage from the cities of Chetumal and Corozal, as well as the discharges of the Hondo and New rivers, also have influence although with a more limited scope to the emission area.

5.- RECOMMENDATIONS

The following recommendations are of binational application, with the main objective of improving and / or maintaining the water quality of the Chetumal / Corozal Bay System:

1.- As the main sources of pollution to the system are non-points, the actions of recovery of coastal and riparian vegetation (for the Hondo and New rivers), would favor the reduction of nutrient discharge to water bodies; since pollutants and soil particles transported in surface runoff from agricultural areas, would be retained by vegetation.

2.- Promote in the Chetumal city the connection to the sewage collection system in areas where the infrastructure is already available. In Belize, provide the water quality data of this study to the corresponding authorities, to support the search for financing of sewage collection and treatment systems for the Corozal city. In small towns such as Calderitas, Laguna Guerrero, Raudales and Sartenenja, among others, favor programs for the installation of wastewater collection systems with appropriate technologies that are environmentally friendly and have a lower operating cost. All these actions would help reduce the use of latrines and septic tanks, and consequently the leachates that pollute the groundwater whose final destination is the Bay of Chetumal / Corozal.

3.- It is essential to include the monitoring of persistent organic pollutants and trace metals in the sediments, which allow the potential exposure risk of aquatic species of ecological and commercial value to be assessed. Since ECOSUR studies have detected the presence of organochlorine pesticides, polycyclic aromatic hydrocarbons, mercury and cadmium, in sediments and aquatic species of the Chetumal Bay and the Hondo River. The sources and mechanisms of transport of these pollutants are the same as those mentioned in this diagnosis.

4.- Maintain a long-term monitoring plan for water quality indicators, which allows evaluating the effectiveness of the actions implemented for the elimination of point and non-point sources of pollution.

6.- ACKNOWLEDGMENTS

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7.- REFERENCES

Alvarez-Legorreta, T. 2019. Continuación del Monitoreo de la calidad del agua en la Reserva Estatal Santuario del Manatí, Bahía de Chetumal. Informe final. IBANQROO, MAR FUND, Banco Alemán de Desarrollo (KFW) y ECOSUR. 142 p.

Álvarez-Legorreta T. 2014. Presencia de hidrocarburos aromáticos policíclicos (HAP) en sedimentos del río Hondo, Quintana Roo, México. Alfonso V. Botello, Jaime Rendón von Osten, Jorge A. Benítez y Gerardo Gold-Bouchot editores. Golfo de México. Contaminación e impacto ambiental: diagnóstico y tendencias. VOL I. México. Universidad Autónoma de Campeche, Instituto de Ecología, Pesquerías y Oceanografía del Golfo de México : Universidad Nacional Autónoma de México, Instituto de Ciencias del Mar y Limnología : Centro de Investigación y de Estudios Avanzados-ipn Unidad Mérida. ISBN: 978-607-7887-71-3. pp. 425-436.

Alvarez Legorreta T. y Sáenz Morales R. 2005. Hidrocarburos aromáticos policíclicos en sedimentos de la Bahía de Chetumal. En: Botello A.V., Rendón-von Osten J., Gold-Bouchot G. y Agraz-Hernández C. (Eds.). Golfo de México. Contaminación e impacto ambiental: Diagnóstico y Tendencias. 2a. Edición. Universidad Autónoma de Campeche, UNAM, INE. 696 p. pp. 299-310.

Brown T.C. and P.Froemke. 2012. Nationwide Assessment of Nonpoint Source Threats to Water Quality. BioScience,Vol. 62 (2): 136-146.

CAPA. 2019. Avances en la Comisión de Cuenca del Rio Hondo: Agua Potable, Drenaje Sanitario y Saneamiento. PPT.

Carrillo, L., E. Palacios-Hernández, M. Yescas and AM. Ramírez-Manguilar. 2009. Spatial and Seasonal Patterns of Salinity in a Large and Shallow Tropical Estuary of the Western Caribbean. Estuaries and Coasts, 32:906–916.

Chapman, D. 1996. Water Quality Assessments- A guide to use of biota, sediments and water in environmental monitoring-Second Edition. WHO by F & FN Spon. 651 p.

EPA. 1992. An Updated Summary of Status and Trends in Indicators of Nutrient Enrichment in the Gulf of México. U.S. Environmental Protection Agency Office of Water, gulf of México Program, United States of America, 272 pp

EPA. 2004. National Condition report II. Office of Water. U.S.Environmental Protection Agency. EPA-620-R03/0002, December.

ESA. 1998. Nonpoint Pollution of Surface Waters withPhosphorus and Nitrogen. Issues in Ecology. No. 3. Ecological Society of America. 14 p.

Karydis, M., L. Ignatiades and N. Moschopoulou. 1983. An index associated with nutrient eutrophication in the marine environment. Estuarine, Coastal and Shelf Science. 16: 339-344.

Mojica., A. M. 2015. Evaluación Rápida de la Efectividad de Manejo en las cinco Áreas Protegidas del Proyecto - FASE II. Proyecto Proyecto Conservación

de Recursos Marinos en Centroamérica. Fondo para el Sistema Arrecifal Mesoamericano. 243 pp.
NAS. 2003. Clean coastal waters: understanding and reducing the effects of nutrient pollution. National Academy of Sciences. 310 p.
SACD. 2009. Corozal Bay Wildlife Sanctuary Management Plan 2010 – 2014. Sarteneja Alliance for Conservation and Development. 106 p.
SEDUE. 1989. Criterios Ecológicos de Calidad del Agua CE-CCA-001-89. Secretaría de Desarrollo Urbano y Ecología. Diario Oficial 13 de diciembre de 1989, 17 p.
Silva, Homero. 2015. Baseline Assessment Study on Wastewater Management
Belize. Caribbean Regional Fund for Wastewater Management. GEF. 172 p
Stewart, MK., J. Melhorn and S. Elliott. 2007. Hydrometric and natural tracer (oxygen-18, silica, tritium and sulphur hexafluoride) evidence for a dominant groundwater contribution to Pukemanga Stream, New Zealand. Hydrol. Process. 21, 3340–3356
Vollenweider RA, Giovanardi F, Montanari G, Rinaldi A. 1998. Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: proposal for a trophic scale, turbidity and generalized water quality index. Environmetrics, 9:329–57.