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A comparative study of several types of indices for river quality assessment

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ABSTRACT

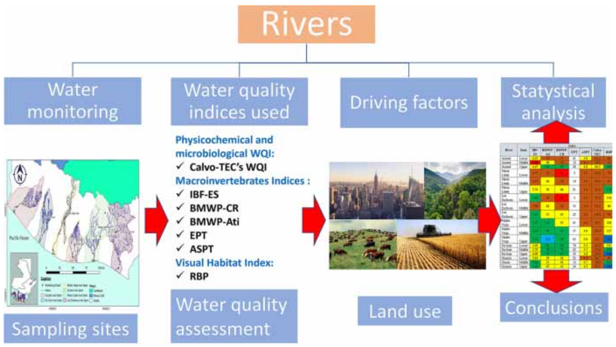
Water is vital for humans, plants, and animals; unfortunately, some anthropogenic activities adversely alter water quality (WQ). Many indicators can be used for WQ assessment; fortunately, extensive data can be simplified by using WQ indices (WQIs). The main difference among WQIs lies in the way of assessing pollution and the number and types of WQ indicators used; therefore, the selection of a reliable WQI should be the first step. This research aimed to compare several types of indices and evaluate their effectiveness. Eighteen sampling sites were monitored, and the selected indices showed different results. Biological indices exhibited a significant statistical correlation and yet different quality results. In addition, biological WQIs showed different outcomes from the physicochemical index. The high concentrations of phosphates, fecal coliforms, and biological oxygen demand, found in most rivers, were responsible for adversely influencing the quality results of the physicochemical index; however, their high concentrations found in some sampling sites had no adverse effect on the macroinvertebrate's existence; therefore, biological WQ assessment showed better quality results than the physicochemical index. The Rapid Bioassessment Protocol index, based on visual habitat observations, proved to be an easy way to classify WQ and an adequate replacement for biological indices.

Key words: biological, indices, macroinvertebrates, physicochemical, water quality

HIGHLIGHTS

- Different indices lead to dissimilar water quality evaluations.
- Biological indices are well correlated and yet show different results.
- The lack of correlation among some indices relied on their different indicators used.
- The Rapid Bioassessment Protocol index is a visual habitat analysis and very reliable.
- High physicochemical indicators content may not affect benthonic life.

GRAPHICAL ABSTRACT



INTRODUCTION

In 2015 the United Nations adopted 17 global Sustainable Development Goals (SDGs) based on several topics: poverty, health, education, social inequality, environment, and economic growth. Two of them are focused on bringing clean water and sanitation (SDG_6) and protecting life below water (SDG_{14}) (UN 2019). Water is vital for life: clean freshwater is necessary for drinking and sanitation, for our crops, livestock, and industry, as well as for creating and sustaining the ecosystems on which all life depends. Unfortunately, many anthropogenic activities cause adverse effects on the environment, such as wastewater from industrial and domestic disposals, as well as on agricultural and urban activities that affect life's sustainability (Calvo-Brenes 2015; Carter *et al.* 2017). The change in land use, such as the expansion of pastures, agriculture, or human settlement areas, destroys primary habitat and causes severe forest fragmentation and, therefore, degradation and destruction of aquatic biodiversity (Duschek *et al.* 2019; Carrasco *et al.* 2020). Therefore, the water quality (WQ) of rivers must be monitored frequently, and contaminated rivers will also affect the oceans and their environment, affecting communities that depend on fishing. Moreover, 80% of worldwide health diseases are related to water (OMS 2018).

WQ assessment requires the use of extensive data based on different WQ indicators. Fortunately, when water quality indices (WQIs) are used instead, the data can be simplified to a lesser number of indicators required for its calculation, and this index is expressed as a single number (Calvo-Brenes 2018; Gupta *et al.* 2021; Uddin *et al.* 2021). Several indices are available; however, their main difference lies in the way of assessing the pollution in terms of quality levels, numbers, colors, calculation formulas, and the number of indicators used. Moreover each of the many possible outcomes will show different quality results; therefore, the selection of a reliable WQI is a major task (García-Ávila *et al.* 2022). Physicochemical WQIs provide a reliable WQ assessment for a specific space and sampling time, such as the Calvo-TEC's WQI, developed for Costa Rica (Calvo-Brenes 2019) but still useful for other countries. Additionally, biological indices can provide an integrated and comprehensive assessment of WQ over time and reliable information on the presence of anthropogenic stressors with a direct influence on aquatic fauna assemblages (Desrosiers *et al.* 2020; Tampo *et al.* 2021). Moreover, they are relatively easy to collect and little infrastructure is needed to identify them (Fenoglio & Doretto 2021).

Both types of indices require different indicators for their calculation; therefore, there is no surprise that WQ results may be different (Calvo-Brenes 2018). Physicochemical indices were developed to measure WQ caused by environmental physicochemical changes (Balaban & Constantinescu 2021). Several aggregation formulas and subindexes calculation formulas for each quality indicator have been proposed, as well as number, color, and contamination classification scales (Olomukoro *et al.* 2022); therefore, variations on physicochemical indexes are expected, normal, and should not cause any surprise. Biological indices are used to assess river conditions and to detect changes in biological conditions, over time. Variables that impact biota are water temperature, dissolved oxygen (DO), nutrients, salination, pesticides, and suspended matter (Abdelkarim 2020). It is being recognized that a unique and universal WQI is difficult to accomplish; therefore, the use of both biological and physicochemical evaluations is necessary (Calvo-Brenes 2018). Moreover, Cude's comments (Cude 2002) on this issue were 'In spite of the scores of water quality indices developed in the United States, there is no recognized "US National Water Quality Index". This may be a reflection of the variety of purposes and monitoring programs for which water quality indices have been developed'. Moreover, it is being said that a specific WQI should be selected according to specific monitoring and assessment needs (Abdelkarim 2020). Another useful and popular cost-effective practical technique is the Rapid Bioassessment Protocol (RBP), which is a synthesis of existing methods already used by some State Water Resources Agencies in the United States of America. This index was developed through a comparison between habitats and physicochemical and biological WQIs. Once the relationship is understood, WQ impacts can be objectively inferred from only habitat evaluations through this validated methodology, and it proved to be a reliable tool and easy to apply (Barbour *et al.* 1999). In general, habitat and biological diversity are closely linked; moreover, the presence of altered habitat structure is considered one of the major stressors of aquatic systems. Therefore, RBP is based on the evaluation of different variables: epifaunal substrate/available coverage, embeddedness, stream characteristics, sediment deposition, channel flow attributes, and vegetative protection conditions (Barbour *et al.* 1999).

Since the appropriate selection of a WQI for river assessment is crucial, the aim of this research was to compare several types of WQIs to establish their reliability level. Statistical relationships were also studied among the WQIs since some of them are based on physicochemical WQ indicators; others in the abundance, and richness of benthic macroinvertebrates families; and another, in the visual habitat evaluation. The WQIs used for the assessment were Calvo-TEC's WQI (Gil-Rodas *et al.* 2021), the Biotic Index at the Family Level modified for El Salvador (IBF-ES), Biological Monitoring Working Party modified for Atitlán, Guatemala (BMWP-Ati), Biological Monitoring Working Party modified for Costa Rica (BMWP-CR), Percentage of Ephemeroptera, Plecoptera and Trichoptera (EPT), Average Score per Taxon (ASPT), and visual habitat evaluation using the RBP methodology.

MATERIALS AND METHODS

Site description

Guatemala is divided into three major sites: the Caribbean, the Pacific, and the Gulf of Mexico; 58% of the population lives on the Pacific slope, where 18 different rivers are located and lead to the Pacific Ocean. The upper, middle, and lower zones for each river showed different environmental conditions that affect the WQ. Population densities are usually lower than 3,000 inhabitants/km^2, however, some areas could have higher densities like the middle zone in the Acomé (3,000–6,500 inhabitants/km^2) or the upper zone of Maria Linda River with densities greater than 12,000. This variable is important to consider in sampling site selection since there is a relationship between population and WQ: more population density means lower river WQ (Estrada 2015). The inhabitants of the Pacific side are mainly dedicated to agricultural activities, which means high demand for water (Chan & Peña 2015; MARN 2016). Monocultures like corn, cardamom, wheat, sugarcane, coffee, rubber, African palm, banana, and fruits are the most important crops found on this site, activities that keep growing and demanding 59.5% of the water resources just for crop irrigation. In Guatemala, 65% of the population requires firewood to cook, an activity that contributes to a 2–5% reduction in forest coverage, which in some way reduces natural runoff barriers and the recharge of aquifers as well. Some of these monocultures are responsible for higher erosion in soil, and in association with runoff, both variables contribute to the transportation of different contaminants to the rivers (Calvo-Brenes 2015).

Sampling sites and rate

Six rivers were selected for sampling during March, June, October, and December 2018: Acomé, María Linda, Los Esclavos, Madre Vieja, Sis Ican, and Ocosito rivers. Each river was divided into three zones: lower, middle, and upper; since geomorphological conditions, forest coverage, population density, and land use are usually different and those variables have a strong impact on WQ. Therefore, 18 samples were collected for each field trip for a total of 72 samples in 2018. Sampling sites can be seen in Figure 1.

Physicochemical and microbiological samples were collected and preserved according to the Standard Methods for the Examination of Water and Wastewater (APHA 2017).

Physicochemical and microbiological WQI

Calvo-TEC's WQI

Since the environmental conditions in Central America are similar for each country, the Calvo-TEC's WQI developed by Calvo-Brenes is expected to be a reliable tool for the region as well. Since Guatemala does not have specific quality regulations to apply in the country for river quality evaluation purposes; therefore, Costa Rican regulations were applied to the WQ conditions of Guatemala. The selected WQ indicators for the calculation of the Calvo-TEC's index were ammonia, fecal coliforms, biochemical oxygen demand (BOD), phosphates, nitrates, DO, pH, and turbidity (Gil-Rodas *et al.* 2021).

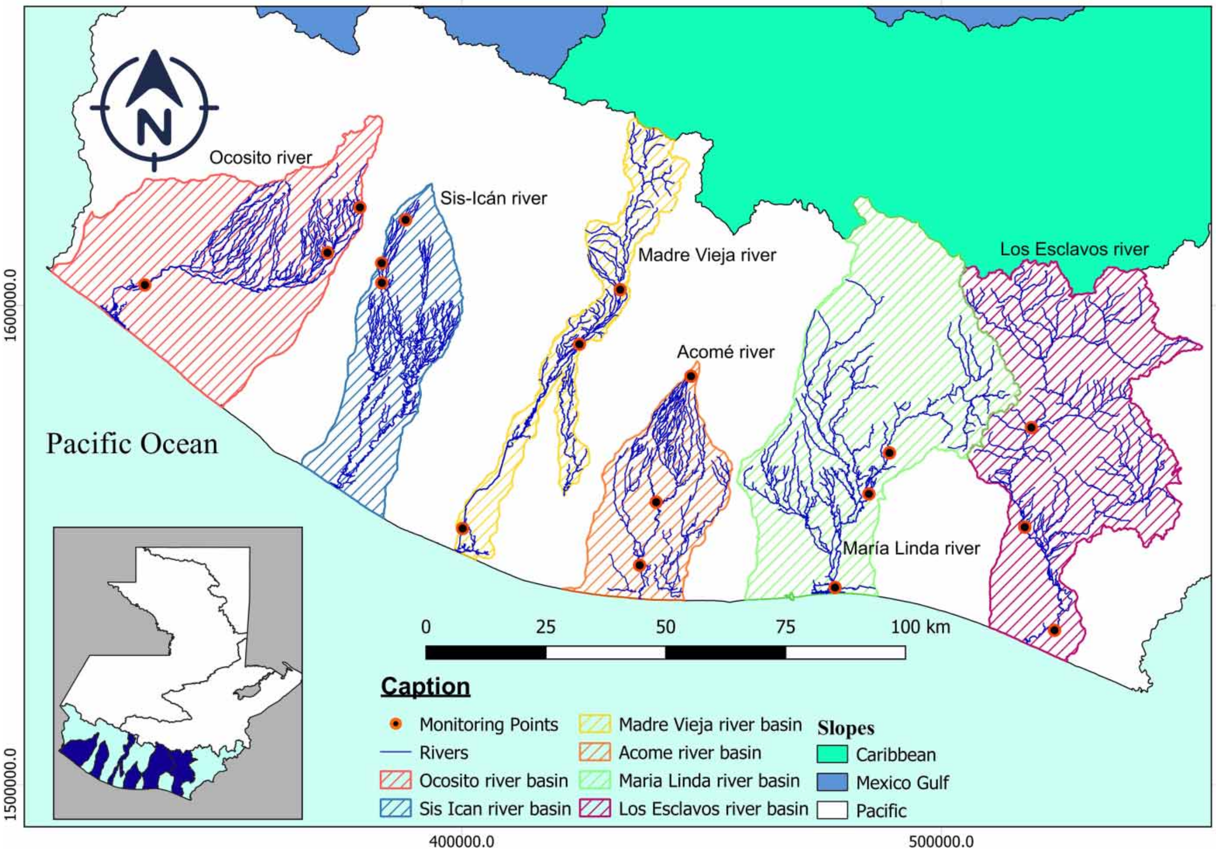


Figure 1 | Rivers' site location is on the Pacific side of Guatemala. *Source*: Gil-Rodas *et al*. (2021).

Calculation of a WQI requires the transformation of each WQ indicator in subindexes (SIs) before the WQI is calculated through an aggregation formula. Details of these transformations and calculations can be found in Gil-Rodas *et al.* (2021). Interpretation of the WQI numbers, color, and WQ classification is based on Table 1 (Calvo-Brenes 2019).

Macroinvertebrate WQIs

Biological sampling

Macroinvertebrate samples were collected using a 'D' network, for 5 min in three different places and not far from each other, according to the methodology of Sermeño *et al.* (2010). The samples were placed in hermetic bags and preserved in 70% ethanol before transportation to the Water Quality Laboratory of the Center for Marine Studies and Aquaculture-CEMA of the University of San Carlos de Guatemala-USAC (Cornejo *et al.* 2017).

Table 1 | Classification of WQ by ranges and qualities for Calvo-TEC's WQI

Range (%)	Class	Contamination level	Color
90,0 - 100	1	None	
75,0 - < 90,0	2	Incipient	
45,0 - < 75,0	3	Moderate	
20,0 - < 45,0	4	Severe	
0 - < 20,0	5	Very severe	

Source: Calvo-Brenes (2019).

Macroinvertebrates identification

Biological samples in the laboratory were cleaned and subsequently identified using a stereoscope Premiere brand and specialized taxonomic keys: Merritt *et al.* (2017) and Sermeño *et al.* (2010).

IBF-ES

The IBF is another biological index, adapted for El Salvador (IBF-ES), and it is based on the method modified by Sermeño *et al.* (2010) for this modified index. The scores consider the taxonomic groups found at each sampling site, weighted by their relative abundance. Thus, the index has two main components: the score assigned to each group of aquatic invertebrates and the relative abundance of each group found (Sermeño *et al.* 2010). The calculated score indicates their tolerance to disturbance conditions (degree of sensitivity to water pollution). Values close to 0 indicate low tolerance and those close to 10 are related to high tolerance to water contamination. However, relative abundance is an indicator of the level of disturbance (Sermeño *et al.* 2010). The WQ classification is according to Table 2.

BMWP-CR

This method is based on the presence of certain macroinvertebrates, and it was modified for use in Costa Rica. The index is calculated by adding the scores assigned to the different taxa found in the macroinvertebrates. This score is assigned based on the degree of sensitivity to contamination. The score per family ranges from 1 (for tolerant species) to 10 (for sensitive species) for organic contaminants; and the total value of the index is obtained by adding the scores of each family present, regardless of its abundance or diversity. The classification uses a scale from 0 to 200 (MINAE 2007). The WQ classification is according to Table 3.

BMWP-Ati

BMWP-Ati is a modification of BMWP-CR based on macroinvertebrates present in a river that flows into Lake Atitlán (Reyes 2012). Some families in this index were assigned a higher score in this habitat and taxa found in this river were also included, which were not listed in the BMWP-CR. The tolerance value was assigned based on field observations, data analysis, and researchers' experience (Reyes 2012). The methodology followed for the calculation of this index was the one proposed by Reyes (2012), and the WQ classification is according to Table 4.

EPT

The EPT index considers the abundance of three orders of insects: Ephemeroptera (greater tolerance to contamination), Trichoptera (medium tolerance), and Plecoptera (does not tolerate contamination and exists only in clean waters) (Buenaño *et al.* 2018). It is calculated by adding all the individuals belonging to each order, divided by the total number of individuals collected (Peña *et al.* 2019). Details of this methodology are found in Buenaño *et al.* (2018) and Peña *et al.* (2019). The WQ classification is according to Table 5.

This index has no color classification scale like many others; therefore, a suggested one is added to Table 5, based on its contamination level.

Table 2 | Classification of WQ by ranges and qualities for IBF-ES

Range	Class	Contamination level	Color
0.00-3.75	1	Excellent	(dark blue)
3.76 -4.25	2	Very good	(light blue)
4.26-5.00	3	Good	(pale blue)
5.01-5.75	4	Regular	(green)
5.76-6.50	5	Poor regular	(yellow)
6.51-7.25	6	Poor	(brown/orange)
7.26-10.00	7	Very poor	(red)

Source: Sermeño *et al.* (2010).

Table 3 | Classification of WQ by ranges and qualities for BMWP-CR

Range	Contamination level-	Color
>120	Excellent	
101-120	Good	
61-100	Regular	
36-60	Poor	
16-35	Very poor	
<15	Extremely poor	

Source: MINAE (2007).

Table 4 | Classification of WQ by ranges and qualities for BMWP-Ati

Range	Class	Contamination level-	Color
>120	I	Excellent	
101-120	II	Good	
61-100	III	Regular	
36-60	IV	Bad	
16-35	V	Very bad	
<15	VI	Extremely bad	

Source: Reyes (2012).

Table 5 | Classification of WQ by ranges and qualities for EPT

Range (%)	Class	Contamination level-	Color
75-100	1	Very good	
50-75	2	Good	
25-50	3	Regular	
0-25	4	Bad	

Source: Carrera Reyes & Fierro Peralbo (2001).

ASPT

The ASPT is the average index per taxon, and it is determined by calculating the total score of the BMWP divided by the number of reported taxa. The score values for individual families reflect tolerance to contamination based on knowledge of distribution and abundance, according to the methodology proposed by Álvarez (2005), and the WQ classification is according to Table 6.

Visual habitat index

Rapid Bioassessment Protocol

The RBP is a visual habitat analysis based on the relationship established between this index with physicochemical and biological WQIs, measured in the past. Once the relationship is understood, WQ impacts can be objectively inferred from visual habitat evaluations. Thus, different variables are measured: epifaunal substrate/available coverage, embeddedness, stream characteristics, sediment deposition, channel flow attributes, and vegetative protection conditions. The methodology followed is found in Barbour *et al.* (1999). The original method considers four different categories, but since most of the other indices have five categories, the classification was increased to five different categories, as shown in Table 7, so that the reader can compare each index based on color classification.

Table 6 | Classification of WQ by ranges and qualities for ASPT

Range	Class	Contamination level-	Color
>8-10	I	Good	
>6.5-8	II	Acceptable	
>4.5-6.5	III	Doubtful	
>3-4.5	IV	Critical	
≥ 1-3	V	Very Critical	

Source: Álvarez (2005).

Table 7 | Classification of WQ by ranges and qualities for RBP

Range	Contamination level-	Color
200-166	Optimal	
165-126	Suboptimal	
125-86	Regular	
85-46	Marginal	
45-0	Poor	

Source: Modified from Barbour *et al.* (1999).

Statistical analysis

The Statistical Program for Social Science Software (SPSS software, version 25) was used for the statistical analysis. Pearson's correlation analysis was carried out to evaluate the relationship between pairs of indices.

RESULTS AND DISCUSSION

All the selected sites were sampled during March, June, October, and December 2018. Therefore, 18 samples were collected during each field trip for a total of 72 samples for this year. The calculation of five different biological indices (IBF-ES, BMWP-Ati, BMWP-CR, EPT, and ASPT) was used, as well as the physicochemical and microbiological index (Calvo-TEC's WQI) and a visual habitat index (RBP).

Table 8 shows WQ conditions using the Calvo-TEC's WQI for each sampling site during March, June, October, and December. March and December had 'moderate' contamination levels as well as 'severe' contamination levels. These two months correspond to the dry season when no runoff usually occurs by precipitation and, therefore, the river's WQ improves. On the contrary, June and October are rainy months, when the occurrence of runoff is usual. In October, most of the sampling sites were 'severe' contamination and in June, half of the sites were classified as 'very severe' contamination.

When all the WQ indicators used by a particular WQI are put together through an aggregation formula, the resulting WQI gives overall information. A WQ level is, therefore, the contribution of each indicator individually to the overall result. Moreover, each indicator contributes differently, and it is in that sense that checking each calculated indicator SI will be useful since it reveals important information about the sources of river contaminants.

Table 9 shows WQ levels on each site in time (March, June, October, and December) but considering only each indicator. The indicators nitrates and ammonia had consistently low concentration levels throughout the year, with pH values ranging between 7.5 and 8.7; moreover, their quality level corresponds to 'no contamination'. High levels of ammonia and nitrates are associated with the use of fertilizers as well as multipurpose livestock and domestic wastewaters, which contributes to contamination and eutrophication (Calvo-Brenes 2018), but Table 9 shows that this is not the case. DO in rivers is the result of the interaction of the water with the air, the photosynthesis of aquatic plants, plant respiration, the turbulence of rivers, and it is also influenced by the river temperature (Calvo-Brenes 2018). While low concentration levels of DO can be detrimental to biota in rivers by reducing their populations, it is worth noting that the data presented in

Table 8 | Calvo-TEC's WQI results for each sampling month

River	Zone	WQI Calvo-TEC			
		March	June	October	December
Acome	Lower	65.9	22.5	26.1	26.4
Acome	Middle	25.7	20.5	26.7	26.4
Acome	Upper	46.1	63.3	73.9	81.6
María Linda	Lower	45.9	18.8	26.1	38.9
María Linda	Middle	54.9	18.9	24.8	58.9
María Linda	Upper	61.9	28.5	24.9	50.3
Los Esclavos	Lower	26.6	16.1	23.1	61.4
Los Esclavos	Middle	26.7	19.2	18.4	25.3
Los Esclavos	Upper	46.1	16.2	25.2	27.9
Madre Vieja	Lower	44.6	19.7	26.4	26.4
Madre Vieja	Middle	23.9	19.5	26.6	25.8
Madre Vieja	Upper	24.1	19.7	26.1	26.6
Sis Ican	Lower	25.9	27.3	26.2	26.2
Sis Ican	Middle	25.8	62.5	27.2	27.0
Sis Ican	Upper	25.7	27.3	19.6	27.0
Ocosito	Lower	61.2	27.2	45.5	45.0
Ocosito	Middle	62.1	31.2	30.9	31.0
Ocosito	Upper	26.4	27.2	19.4	19.6

Table 9 | SI calculated for each WQ indicator based on time

River	Zone	Subindex Calculations on March								Subindex Calculations on June							
		pH	DO	NO_3^-	PO_4^{3-}	Turb	CF	DBO	NH_3	pH	DO	NO_3^-	PO_4^{3-}	Turb	CF	DBO	NH_3
Acome	Lower	100.0	100.0	94.09	42.2	96.7	75.5	41.2	100.0	100.0	70.6	87.1	18.5	58.3	10	21.9	100.0
Acome	Middle	100.0	63.8	99.36	39.4	95.9	10	41.2	59.6	100.0	72.8	73.7	18.7	75.8	10	13.5	98.6
Acome	Upper	100.0	98.3	96.99	20.0	97.5	77.5	41.2	100.0	100.0	91.8	81.5	29.6	99.0	80.4	86.9	100.0
María Linda	Lower	100.0	100.0	88.54	20.5	92.6	59.4	41.2	100.0	100.0	85.6	85.2	22.4	69.9	10	10	97.8
María Linda	Middle	100.0	100.0	96.99	26.6	95.2	77.5	41.2	100.0	100.0	98.5	77.5	19.1	62.0	10.5	10	95.4
María Linda	Upper	100.0	100.0	98.36	34.0	97.5	79.1	41.2	100.0	100.0	102.5	73.7	24.2	92.3	11.6	86.9	100.0
Los Esclavos	Lower	100.0	100.0	96.41	10.0	90.6	77.5	41.2	100.0	100.0	114.0	77.5	10.0	55.5	10	10	94.6
Los Esclavos	Middle	100.0	100.0	95.09	10.0	95.9	79.1	41.2	100.0	100.0	108.4	66.8	10.0	32.1	10	86.9	97.8
Los Esclavos	Upper	100.0	100.0	96.21	20.1	85.1	79.1	41.2	100.0	100.0	100.2	73.7	10.0	74.3	10	10	98.9
Madre Vieja	Lower	100.0	100.0	99.36	19.1	96.3	70.3	41.2	100.0	100.0	109.4	88.5	96.9	94.5	10	10	94.1
Madre Vieja	Middle	100.0	100.0	96.21	18.7	94.5	10	41.2	98.9	100.0	111.4	89.9	99.2	45.3	10	10	100.0
Madre Vieja	Upper	100.0	100.0	94.09	19.3	95.2	10	41.2	100.0	100.0	114.3	91.5	99.1	80.5	10.1	10	100.0
Sis Ican	Lower	100.0	51.4	95.93	43.9	93.9	10	41.2	100.0	100.0	113.4	85.2	99.8	98.0	10	86.9	100.0
Sis Ican	Middle	100.0	81.8	98.36	34.3	96.7	10	41.2	100.0	100.0	111.8	83.6	99.8	97.5	27.9	86.9	100.0
Sis Ican	Upper	100.0	82.5	93.56	33.7	98.5	38.9	10	100.0	100.0	112.6	91.5	99.2	99.0	10	86.9	100.0
Ocosito	Lower	100.0	99.8	88.54	40.6	86.0	51.4	41.2	100.0	100.0	111.2	95.1	99.1	69.9	10	86.9	100.0
Ocosito	Middle	100.0	100.0	97.66	38.3	94.5	59.4	41.2	96.2	100.0	115.4	91.5	99.2	79.9	11.6	86.9	100.0
Ocosito	Upper	100.0	100.0	96.21	43.4	96.3	10.1	41.2	100.0	100.0	112.6	89.9	99.2	74.3	10	86.9	100.0

River	Zone	Subindex Calculations on October								Subindex Calculations on December							
		pH	DO	NO_3^-	PO_4^{3-}	Turb	CF	DBO	NH_3	pH	DO	NO_3^-	PO_4^{3-}	Turb	CF	DBO	NH_3
Acome	Lower	100.0	84.7	99.4	30.4	85.6	10	92.6	100.0	69.5	101.5	84.8	36.9	94.2	10.0	92.6	100.0
Acome	Middle	100.0	79.2	64.7	48.4	90.9	10	92.6	100.0	100.0	84.2	99.4	34.9	96.3	10.0	92.6	100.0
Acome	Upper	100.0	79.0	96.2	50.4	97.1	51.4	92.6	100.0	100.0	103.5	90.6	49.4	97.5	80.4	92.6	100.0
María Linda	Lower	100.0	85.7	96.2	30.6	80.9	10	92.6	99.5	81.3	90.4	67.8	25.7	92.0	18.4	92.6	100.0
María Linda	Middle	100.0	96.0	91.5	21.1	73.2	10	92.6	100.0	77.2	109.9	89.9	55.7	97.5	27.9	92.6	100.0
María Linda	Upper	100.0	92.5	85.2	22.4	57.6	10	92.6	97.8	69.5	111.0	94.4	20.9	97.1	82.7	92.6	100.0
Los Esclavos	Lower	100.0	91.2	98.4	19.3	54.2	10	25.7	97.0	100.0	103.1	94.9	35.3	86.8	38.9	92.6	100.0
Los Esclavos	Middle	100.0	95.7	87.1	18.9	50.1	10	10	97.0	100.0	105.9	95.3	27.0	88.8	10.0	41.2	100.0
Los Esclavos	Upper	100.0	96.4	97.7	23.1	69.6	10	92.6	96.5	100.0	90.0	94.9	40.2	93.9	10.5	92.6	100.0
Madre Vieja	Lower	100.0	91.2	94.1	35.3	78.3	10	92.6	100.0	100.0	103.1	94.9	35.3	86.8	10.0	92.6	100.0
Madre Vieja	Middle	100.0	91.1	97.0	39.1	87.5	10	92.6	100.0	100.0	105.9	95.3	27.0	88.8	10.0	92.6	100.0
Madre Vieja	Upper	100.0	86.6	85.2	32.0	88.5	10	92.6	92.8	100.0	90.8	94.9	40.2	93.9	10.0	92.6	92.8
Sis Ican	Lower	100.0	99.4	99.4	56.8	97.1	10	35.2	100.0	94.9	76.0	98.4	66.1	97.5	10.0	35.2	100.0
Sis Ican	Middle	100.0	97.0	92.7	62.8	98.5	10.1	92.6	100.0	100.0	69.5	98.0	55.1	97.5	10.1	92.6	100.0
Sis Ican	Upper	100.0	100.3	81.5	69.5	96.7	10	10	97.8	100.0	68.0	98.8	66.1	97.1	10.0	92.6	100.0
Ocosito	Lower	100.0	93.3	99.4	61.0	92.3	18.4	92.6	100.0	100.0	59.5	98.2	73.0	95.9	18.4	92.6	100.0
Ocosito	Middle	100.0	93.0	89.9	58.0	91.8	11.6	92.6	100.0	100.0	64.5	98.2	83.0	94.9	11.6	92.6	100.0
Ocosito	Upper	100.0	85.0	81.5	39.8	76.0	10	10	97.8	100.0	73.0	98.6	75.2	92.6	10.0	10.0	97.8

Table 9 and the WQ levels indicate predominantly 'no contamination' for DO. Furthermore, it is important to consider other variables that influence the health of biota in rivers, such as water temperature, nutrient levels, and pollutant concentrations. These additional factors play a significant role in determining the overall ecosystem condition. The recorded DO levels ranging from 4.16 to 11.67 mg of oxygen per liter (mg/L) suggest a favorable oxygen concentration range, which, coupled with favorable conditions in other variables, contributes to a relatively healthy environment for biota in the rivers.

Turbidity affects river WQ and during dry season (December and March) the classification corresponded to 'no contamination'. Rainy season (June and October) is associated with runoff caused by rainfall; therefore, WQ oscillated from 'incipient' to 'moderate' contamination.

BOD is mainly associated with organic matter coming from domestic wastewaters, among other sources (Calvo-Brenes 2018); in October and December, levels were low, related to 'no contamination', but the rest of the months it switched from 'incipient' to 'severe' contamination. On the other hand, phosphates and fecal coliforms remained on high levels, mostly classified as 'severe' and 'very severe' contamination.

When careful examination of data in Tables 8 and 9 is done, we arrive at the conclusion that the indicators responsible for the 'severe' contamination levels shown in Calvo-TEC's WQI are caused mainly by BOD, phosphate, and CF. High phosphate level is associated with some fertilizers as well as domestic wastewaters (Calvo-Brenes 2018). Even though low nitrates levels were found throughout the year, the high phosphate levels measured in rivers may be responsible for eutrophication processes, whose consequences were visible in some river sites far away from our sampling areas. Fecal coliforms may have its origin in domestic wastewaters and wild or farm animal excrement.

Table 10 shows each WQI grouped as an average result per year for each sampling site. Since each river usually has different environmental conditions, it is expected to show different WQ levels. Those conditions were shown by each WQI, except for the Calvo-TEC, whose contamination levels are basically the same for each sampling site in Table 10; however, looking into Table 8, it is also shown that the variability is almost negligible.

In general, if we look at a particular sampling site, the color classification varies for each WQI (Table 10). This behavior among WQI is in accordance with Olomukoro *et al.* (2022), Calvo-Brenes (2018), and Cude's opinions (2002).

Pearson's correlation bivariate analysis will bring information about possible similarities that may exist among the studied WQIs (Table 11) in this research.

Pearson's bivariate correlation statistical analysis (Table 11) showed that there is no correlation between the Calvo-TEC's WQI and the rest of the indices at a 95% probability level ($p < 0.05$). However, there is some correlation between this index and the IBF-ES index, but the probability correlation level was 88.6%. These results agree with Abdelkarim (2020) who considers that chemical monitoring to assess certain environmental impacts and pressures caused by the aquatic biota. Moreover, he considers that the effects of physicochemical indicators on the biota are difficult to predict. Physicochemical indices reflect the actual contamination level at the moment of collecting the sample that can change suddenly; inversely, biota conditions may be the result of the effect of past stressors, now absent, but the negative effects still remaining (Calvo-Brenes 2015; Abdelkarim 2020).

The RBP, a visual habitat index, presented correlations with all biological indices, with significance levels in the range of 0.001–0.005 between this index and IBF-ES, BMWP-Ati, BMWP-CR, and EPT. Concerning RBP and ASPT, the significance level was 0.019.

The correlation among BMWP-Ati, BMWP-CR, EPT, and ASPT was high with a significance level less than 0.001. Even though there was a high correlation between them, there were differences in the WQ classification, by colors and numbers as well on each sampling site. IBF-ES and BMWP-Ati, BMWP-CR, EPT, and ASPT indices showed correlations with significance levels ranging from 0.054 to 0.070. Abdelkarim (2020) considers that the BMWP index, developed in the United Kingdom, has been the most applied as well as the most modified, causing similarities and differences among them.

Based on data gathered in Table 10, it is observed that Calvo-TEC's WQI classified every sampling site as 'severe' contamination, except the upper sampling site of Acomé. The ASPT index ranked María Linda and Los Esclavos rivers, as well as the Acomé Middle site and Ocosito Lower site as 'critical contamination'. The rest of the sampling sites are classified as 'doubtful' contamination with this index. The IBF-ES, BMWP-Ati, and BMWP-CR showed some similarities in their classifications, ranging mainly from 'regular', 'poor', and 'very poor' classification (using the BMWP classification code). Finally, the EPT and RBP varied in their classification depending on each sampling site.

Table 10 | Average WQ classification of six rivers using seven different WQIs

River	Zone	Index						
		IBF-ES	BMWP-Ati	BMWP-CR	EPT	ASPT	Calvo-TEC	RBP
Acomé	Lower	6.23	35	27	41	5.0	35.2	46
Acomé	Middle	7.62	48	33	12	4.1	24.8	63
Acomé	Upper	6.47	82	74	28	4.8	66.2	149
María Linda	Lower	6.97	22	8	2	4.1	32.4	70
María Linda	Middle	6.83	44	30	10	3.8	39.4	82
María Linda	Upper	5.79	56	48	21	4.4	41.4	152
Los Esclavos	Lower	5.08	30	15	2	3.8	31.8	114
Los Esclavos	Middle	7.08	42	34	33	4.4	22.4	86
Los Esclavos	Upper	5.43	51	41	22	4.2	28.8	84
Madre Vieja	Lower	5.27	66	51	41	4.3	29.3	103
Madre Vieja	Middle	5.69	95	87	57	4.9	24.0	117
Madre Vieja	Upper	5.31	104	98	63	5.0	24.1	168
Sis Ican	Lower	5.92	93	86	78	5.3	26.4	121
Sis Ican	Middle	5.78	78	73	62	5.1	35.6	150
Sis Ican	Upper	6.08	75	67	53	4.8	24.9	166
Ocosito	Lower	5.83	59	42	22	4.2	44.7	80
Oosito	Middle	5.43	51	41	16	4.7	38.8	131
Ocosito	Upper	5.26	47	41	36	4.5	23.1	169

Note: The color classification code is different for each WQI; therefore, codification is not included in this table.

The WQ indicators used for Calvo-TEC's WQI were ammonia, fecal coliforms, BOD_5, phosphates, nitrates, DO, pH, and turbidity. Getting in more details considering Table 9, the calculation values of the pH and DO SI both kept values around 90–100% related to the levels of 'no contamination' during the four sampling periods (Table 9). Another important WQ indicator analyzed was nitrate concentration, whose presence in soil is related to the use of fertilizers and livestock dung. June typically represents the beginning of the rainy season, and the appearance of rainfall provokes runoff that carries soil contaminants to the rivers (Ahmed *et al.* 2020). The nitrate concentration (see Table 9) showed values related to 'no contamination' in March, October, and December 2018, except for June 2018 when the SI calculations dropped to classification levels of 'incipient contaminations' (María Linda and Madre Vieja rivers) and 'moderate contamination' (Los Esclavos River). The same behavior is exhibited by turbidity that showed good WQ during the year, except during June when SI values varied from 98 to 32%, this lower value being associated with 'severe contamination' levels. BOD is an indicator attributed to organic matter discharges, usually from domestic and industrial sources that are constant throughout the year. Therefore, differences in the river flow, between the dry and the rainy seasons, affect the environmental impact on the river. October and November, months associated with the rainy season and the usual high river flow rate, showed low BOD contents and, therefore, 'no contamination' levels for this indicator. June is considered a transition month between the dry and the rainy season, then, the river flow

Table 11 | Pearson's correlation bivariate analysis among indices

	IBF-ES	BMWP-Ati	BMWP-CR	EPT	ASPT	Calvo-TEC	RBP
IBF-ES	1	-.300	-.307	-.288	-.216	.081	-.519*
BMWP-Ati		1	.992**	.809**	.707**	-.007	.584*
BMWP-CR			1	.844**	.766**	-.026	.626**
EPT				1	.869**	-.312	.442
ASPT					1	-.041	.441
Calvo-TEC						1	.043
RBP							1

Note: Colors related to significance level.

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

increases. This month, 'very severe contamination' levels were associated with the Acome, María Linda, and Madre Vieja rivers, the first two related to high-density populations; meanwhile, the other rivers had little BOD contamination levels. March was a month associated with the dry season and, therefore, low river flow rates showed levels of 'severe contamination'. The sources of phosphates are usually associated with agricultural fertilizers and household cleaning products from domestic and industrial discharges. The use of these products is expected to be the same throughout the year and, therefore, discharges should remain the same; meanwhile, the lower flow rate of the rivers during the dry season causes an expected increase in river contamination levels. In June, Madre Vieja, Sis Ican, and Ocosito showed 'no contamination levels' but the other sampling sites were in a 'very severe' contamination level this month. For the rest of the months, all sampling sites showed a contamination range of 'moderate' to 'very severe' levels. The last indicator analyzed for this index was fecal coliforms, which may be associated with human or animal sources. In general, concentration levels were high throughout the year and classified as 'very severe' contamination levels. Therefore, the 'severe' contamination level showed in the Calvo-TEC's WQI was mainly due to phosphates, fecal coliforms, and BOD high concentrations levels.

Research reported in the literature indicates that fish and macroinvertebrates are not harmed by exposure to fecal coliforms or other microorganisms. Macroinvertebrates have different tolerance to the presence of phosphate in rivers; however, lethal toxicity is reported at more than 5 mg/L (Julius-Daud 2020) and the concentrations found in rivers in this study were below 2.5 mg/L. Another indicator responsible for the Calvo-TEC's WQI being ranked as 'severe' contamination is the BOD. Research carried out by Donoso *et al.* (2018) did not find any correlation between taxa concentration and high concentrations of BOD. It is expected that high concentrations of this indicator may affect macroinvertebrates' lives but probably because high BOD concentrations eventually reduce the DO, which has a direct impact on fish and macroinvertebrates' survival. However, in this investigation, the DO was usually high and over 5 mg/L, which is the minimum concentration required to keep aquatic animals alive. Therefore, phosphates, fecal coliforms, and BOD high concentrations levels found in the rivers provoked and Calvo-TEC's WQI was ranked as 'severe' contamination (as shown in Table 8) at sampling sites, while the use of the biological WQI indicated WQ classification levels from 'regular' to 'good' since there were no apparent adverse effects on macroinvertebrates life.

Figure 2 shows the overall results found on each sampling site in terms of WQ levels. As discussed before, the RBP habitat index, based on the way it was developed, was taken as a reliable index to be used as an index control, to compare the others.

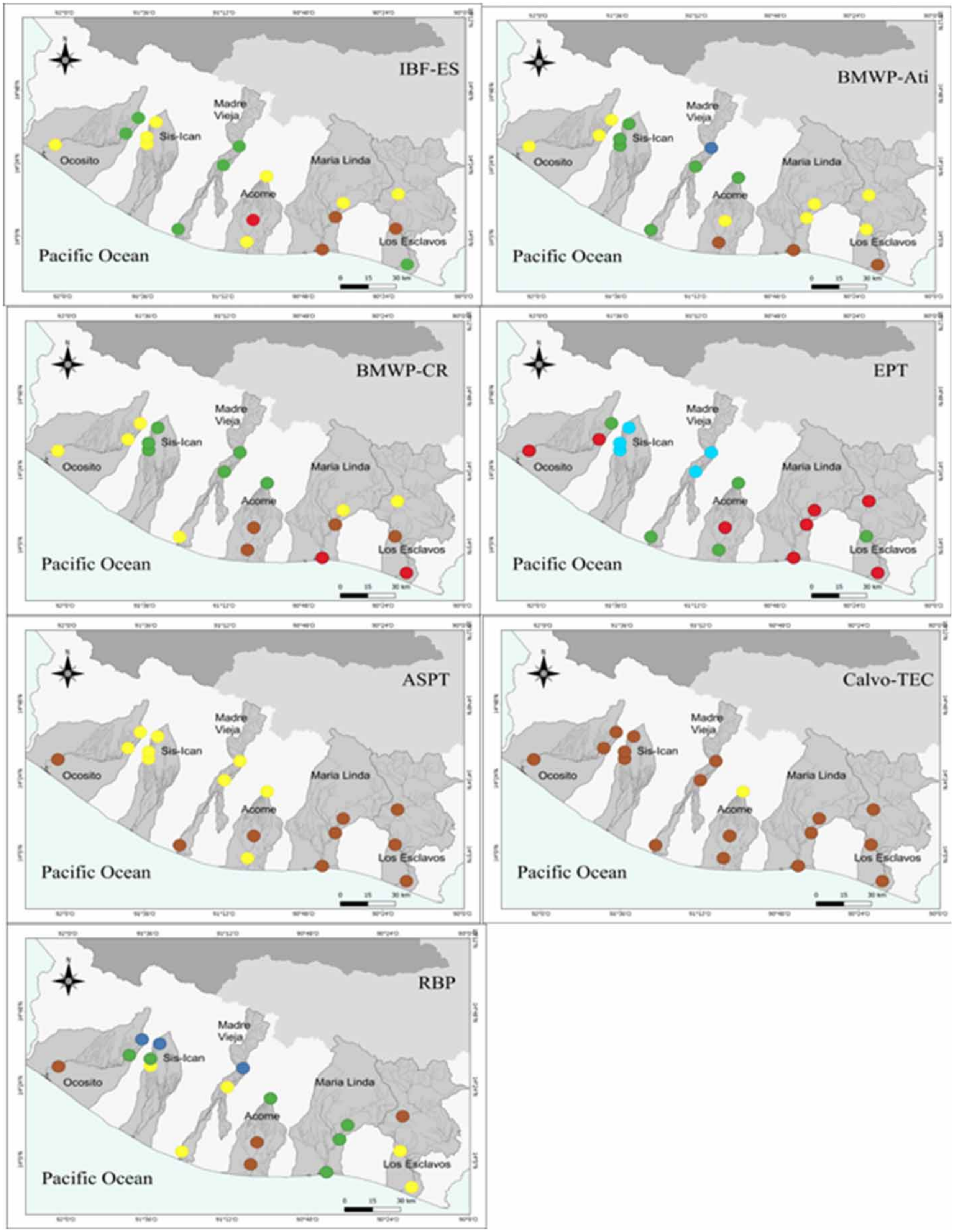


Figure 2 | WQIs-based maps showing overall WQ classification on each sampling site.

CONCLUSIONS

In general, the biological WQIs behaved very similarly in their WQ analysis of the different sampling sites. The correlation between them was high, but this situation does not mean the same WQ ranking for each sampling site, in terms of color and classification levels for each biological index.

The Calvo-TEC's WQI ranked the waters in Table 10 as 'severe' contamination, except for the Acomé upper river. The three WQ indicators responsible for this classification were the high concentrations in phosphates, fecal coliforms, and BOD, as seen in Table 9; indicators that, according to information found in the literature, do not affect the existence of macroinvertebrates, at least at the concentrations found in this study.

The RBP classified the WQ in an easy way since it is based on visual habitat observations. The correlation probability level of this index and any of the other biological indexes is superior to 99.5%. That means that very well-trained technicians in this methodology can substitute any of the biological tools by the RBP index, but always considering its limitations.

The lack of correlation between physicochemical indices and biological ones relies on the fact that indicators used for each index are different and, therefore, measure different environmental conditions in a different time scope. Therefore, if the assessment of WQ in rivers must be based on physiological indicators, the Calvo-TEC WQI becomes a good choice. If the assessment of WQ is required to be based on biological indices, there are several options with different results from each other. However, the use of the habitat index (RBP) looks like a good substitute for biological indices.

Physicochemical indicators, selection criteria and the country's WQ regulations describe the desired condition of a water body and how that condition will be protected or achieved. Water bodies can be used for different purposes, like fishing, and the protection of human health and aquatic life in these waters. If there is a significant difference among biological and physicochemical indices, it might be a sign of inappropriate assignment of the regulations' standard limits for the WQ indicators.

It is worth mentioning the opinion expressed by Abdelkarim (2020), which is in agreement with this research and its conclusions, that complementation of different biological organisms in terms of sensitivity and tolerance to contamination levels is recommended to monitor river contamination. Moreover, the combination of physicochemical, biological, and habitat WQIs is most useful to evaluate different kinds of environmental stressor when evaluating mitigation actions and management programs.

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All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by N.G.-R., G.R., G.D., D.G., A.C.-P., P.A., and M.M. The first draft of the manuscript was written by N.G.-R., M.G.-M., and G.C.-B. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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