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Integral Index of Water Quality: A New Methodological Proposal for Surface Waters

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Abstract: A methodology is proposed aimed at defining an integral index of water quality in surface waters that incorporates the information for five variables currently used to independently measure the condition of water in the Cupatítzio River, Michoacán. The variables considered were the current water quality index used by CONAGUA, the concentration of metals, biodiversity as assessed through the BMWP index, microbiological values for *Escherichia coli*, and the level of toxicity. The index was applied at 17 sites along the Cupatitzio riverbed in the dry season of 2017. Each variable was assigned a rank, which was standardized to a scale of 1–10 and subsequently multiplied by a weight (W) that numerically represented the degree of importance and influence that each factor had in terms of pollution. These factors depended on the anthropic condition of the area, with a value of 5 indicating the method with the most significant impact and 1 the least. The integral index of water quality (IIWQ) was calculated as the arithmetic sum of each factor considered, generating a single value. It had intervals of 15 points minimum to 150 maximum. Five water quality levels were proposed: excellent, good, fair, bad, and very bad. The results showed that, of the 17 sites studied, the majority (ten) were in the fair quality category, ranging from 69 to 95 points; six were in the good category (96 to 122 points); and only one was in the bad category (42–68 points). With the application of this methodology incorporating the information for the five variables already described, it was possible to assess the water quality conditions in the Cupatitzio River as adequate and the water as suitable for its uses in the different socioeconomic activities for which it is destined.

Keywords: pollution; risk; physicochemical variables; microbiology; macroinvertebrates

Citation: Silva-García, J.T.; Cruz-Cárdenas, G.; Moncayo-Estrada, R.; Ochoa-Estrada, S.; Villalpando-Barragán, F.; Ceja-Torres, L.F.; Flores-Magallón, R.; Arroyo-Damián, M.; Estrada-Godoy, F.; Álvarez-Bernal, D. Integral Index of Water Quality: A New Methodological Proposal for Surface Waters. *Water* **2023**, *15*, 1414. https://doi.org/10.3390/w15071414

Academic Editors: Bahram Gharabaghi, Hossein Bonakdari and Ed McBean

Received: 21 February 2023
Revised: 27 March 2023
Accepted: 1 April 2023
Published: 5 April 2023

1. Introduction

Currently, water quality is a global issue since most rivers have collapsed due to the high level of contamination of their waters, making it almost impossible for human beings to obtain a supply of clean water and causing the depletion of nature's valuable aquatic biodiversity [1]. Water quality indices (WQIs) are measures that allow the efficient evaluation of the health status of water resources, and the first one was implemented by the National Science Foundation (NSF) in the United States. The states of North America [2] consider it an effective tool [3,4].

In terms of the evaluation of the quality of contaminated water, as has been shown for several decades, different methodologies have been developed and implemented worldwide to monitor water quality based on a series of independent parameters according to the official standards of each country [5]; therefore, many national and international agencies establish different criteria and parameters for assessment.

For example, the IWQs proposed in [6] and by the US National Sanitation Foundation (NSFWQI) [7,8], the Canadian Council of Ministers of the Environment (CCMEWQI) [9], British Columbia (BCWQI), and Oregon (OWQI) [10] are based on the comparison of the water quality parameters that have been proposed in the regulatory standards presented by the respective countries to speed up decision making on this resource [11].

Other indices have been developed for the evaluation of the water resources destined for human consumption, which include physicochemical and microbiological parameters related to the level of sanitary risk that could be present in the water, such as the public supply IAP in Brazil, the Universal Water Quality Index [12], and the Drinking Water Quality Index (DWQI).

In Mexico, at the beginning of the 1970s, faced with the need to find a uniform and consistent method to publicize water quality in an accessible way for the population, a water quality estimation system was developed that required the physical measurement of the parameters of water contamination and the use of a standardized measurement scale to express the relationship between the existence of various contaminants in water and the degree of impact on the different uses. This system, called the water quality index (WQI), allows comparisons of pollution levels in different areas [13].

The measurement of water quality using biotic parameters has seen an upturn in its levels of relevance. The use of macroinvertebrates as water quality indicators based on their abundance and diversity has been extensively studied [14–17]. One of these indices is the Biological Monitoring Working Party (BMWP), proposed in England in [18].

Roldán [19] reviewed the studies carried out during the last four decades in Colombia and Latin America and described the current knowledge on the different groups of aquatic macroinvertebrates in terms of taxonomic resolution, ecological aspects, and their use as water quality bioindicators. Carrero and Fierro [20] stated that, when monitoring a river, it is essential to determine the changes that have occurred in the water and the structure of the biotic communities it houses; the presence or absence of the different taxonomic groups of invertebrates determines the appropriate treatment to use to prevent the ecosystem from continuing to degrade.

Ladrera [21] showed that there are different biological indicators for aquatic ecosystems, such as fish, macrophytes, algae, and macroinvertebrates. However, the latter are the most widely used due to their high diversity and relatively long lifespan, making it possible to define a site's history of interest. Some antecedents to the application of biotic indices in Mexico include the work by Ramírez-Herrejon [22], who analyzed the feasibility of using two biological integrity indices (IBIs) based on fish communities in lotic and lentic environments in the subbasin of the Angulo River (Lerma-Chapala Basin), estimating the environmental quality through the evaluation of the quality of the water and the habitat at each site and finding poor, fair, and good biotic integrity. The study did not show areas with good environmental quality.

Álvarez [23] presented an integrated analysis of two studies in which biotic integrity indices (IIBs) were proposed for two rivers with contrasting conditions in the Tuxtlas region, Veracruz. They identified a total of 60 species of crustaceans, mollusks, and fish and classified them by their type of feeding, habits, and origin in order to later build an IIB for each river. The resulting calculations indicated that both rivers had good conditions.

In research on the presence of heavy metals, measurements of these elements are aimed at determining their concentration levels in water based on the official ICP standard (ISO 11885), the same being the case for the measurement of toxicity [24]. It is essential to know these parameters since they can have harmful effects at concentrations higher than those recommended, in addition to causing damage to the health of human beings, living organisms, and even crops.

Although the development of water quality indices has played a vital role in the ecological and environmental context, all of them have limitations, making it necessary to search for new methodological approaches that guarantee the comprehensive evaluation of this valuable resource [11]. The measurement of these contamination levels essentially involves independent parameters. Therefore, there are quality indices following official standards based on chemical aspects, microbiological organisms, biotic characteristics, concentrations of heavy metals, and toxicity. However, they only sometimes coincide in terms of quality and often contradict each other. The conjunction of each aspect within each variable would help in providing greater representativeness at the moment of the chemical quality analysis of the water body, as well as being more effective and precise in the environmental diagnosis.

In this context, the objective of this study was to develop a methodological proposal to define a comprehensive water quality index that incorporates the information for five variables currently used to independently measure surface water quality in the Cupatítzio River, Michoacán.

2. Materials and Methods

Considered one of the most important rivers in the state of Michoacán, the Cupatitzio has its origin to the northwest of the city of Uruapan, Michoacán, on El Pario Hill at an altitude of 2750 m, together with the Tepalcatepec and Tacámbaro rivers. They represent one of the most important factors for the formation of the Balsas hydrological region, considered one of the most polluted in Mexico.

The Cupatitzio River is part of the Balsas River hydrological region (RH18) within the Tepalcatepec-Infiernillo (I) hydrological subregion [25]. It is located in the central western part of Michoacán (Figure 1) between coordinates 18°49′58″ and 19°36′11″ N and 101°59′30″ and 102°13′16″ W. It has an approximate area of 782.9 km^2 and altitudes above the sea that fluctuate between 400 m in its lowest portion in the municipality of Múgica and 3300 m in its northern part in the municipality of Paracho.

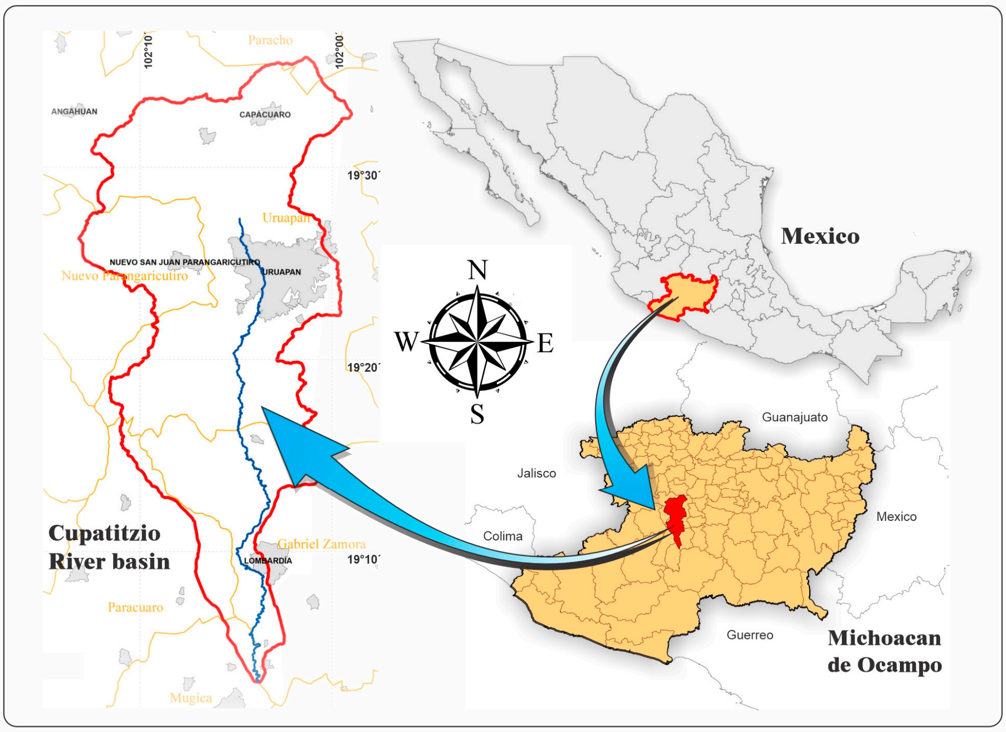

Figure 1. Location of the study area. Cupatitzio River basin.

The method proposed here, called the integral index of water quality (IIWQ), incorporates information from five variables that are used to measure the quality of surface water independently: the current quality index of water used by CONAGUA, the concentration of metals, biodiversity as assessed through the BMWP index, microbiological values for Escherichia coli, and the level of toxicity. We applied the IIWQ at 17 sites along the Cupatitzio riverbed during the dry season.

2.1. Description of the Factors That Make up the Integral Index of Water Quality (IIWQ)

The first variable to consider was the IWQ-CONAGUA value, which takes into account the measurement of nine parameters: fecal coliform organisms [26], BOD5 [27], pH, temperature, total dissolved solids, turbidity and dissolved oxygen (measured in situ using a Hydrolab DS5 multisensor), nitrates [28], and phosphorus [29]. The scale to be considered was the one handled by the method.

In the case of metals, the concentration levels of 11 elements (Cd, Be, Al, Cr, Cu, Fe, Hg, Ni, Pb, and Zn) were measured, as well as the As, B, and Se. The method used for the analysis was inductively coupled plasma mass spectrometry (ICP-MS; Model Thermo ICAP 6500Duo), which can detect concentrations of up to parts per billion, with the international standards SLRS-4 and NIST 1640. A measurement scale was built using the number of elements within the limits set by the ICP official standard (ISO 11885) as a criterion: if the total of the 13 average elements was within the limits set by the official standard, the water was classified as very good.

To investigate the biotic aspects of the river and their association with its contamination, the Biological Monitoring Working Party (BMWP) index, instituted in England in 1970, was used as a simple method to assign a score to all macroinvertebrates groups. Organisms were identified at the family level to obtain presence–absence data. The assigned score ranged from 1 to 10 as an indication of tolerance to contamination (Table 1). The most sensitive families scored 10 and the least sensitive family scored 1 [30].

Table 1. Sensitivity values used for macroinvertebrate families to determine the BMWP index [30].

Families	Score
Siphlonuridae, Heptageniidae, Leptophebiidae Potamanthidae, Ephemeridae, Taeniopterygidae, Leuctridae, Capniidae, Perlodidae, Perlidae, Chloroperlidae, Aphelocheiridae, Phryganeidae, Molannidae, Beraeidae, Odontoceridae, Leptoceridae, Goeridae, Lepidostomatidae, Brachycentridae, Sericostomatidae, Athericidae, Blephariceridae, Anomalopsydae, Atriplectididae, Calamoceratidae, Ptilodactylidae, Chordodidae, Gomphidae, Hidridae, Lampyridae, Lymnessiidae, Oligoneuriidae, Polythoridae, Psephenidae	10
Ampullariidae, Dystiscidae, Ephemeridae, Polycentropodidae, Xiphocentrinidae, Gyrinidae, Hydrobiosidae, Leptophlebiidae, Philopatomidae, Euthplociidae	9
Gerridae, Hebridae, Helicopsydae, Hidrobiidae, Lleptoceridae, Lestidae, Palaemonidae, Pleidae, Pseudothelphusidae, Saldidae, Simuliidae, Vellidae Astacidae, Calopterygidae, Gomphidae, Cordulegasteridae, Aeshnidae, Corduliidae, Libellulidae, Psychomyiidae, Philopotamidae, Glossosomatidae	8
Baetidae, Caenidae, Calopterygidae, Coenagrionidae, Corixidae, Dixidae, Dryopidae, Glossosomatidae, Hyalellidae, Hydroptilidae, Hydropsychidae, Leptothyphidae, Naucoridae, Notonectidae, Planariidae, Psychodidae, Scirtidae, Ephemerellidae, Nemouridae, Rhyacophilidae, Polycentropodidae, Limnephilidae	7
Aeshnidae, Ancylidae, Corydalidae, Elmidae, Libellulidae, Limnichidae, Lutrochidae, Megapodagrionidae, Sialidae, Staphylinidae, Neritidae, Viviparidae, Hydroptilidae, Unionidae, Corophiidae, Gammaridae, Platycnemididae, Coenagriidae	6
Belostomatidae, Gelastocoridae, Mesovelidae, Nepidae, Planorbiidae, Pyralidae, Tabanidae, Thiaridae, Oligoneuriidae, Dryopidae, Elmidae, Helophoridae, Hydrochidae, Hydraenidae, Clambidae, Hydropsychidae, Tipulidae, Simuliidae, Planariidae, Dendrocoelidae, Dugesiidae	5
Chysomelidae, Stratiomydae, Empididae, Sphaeridae, Lymnaeidae, Hydrometridae, Noteridae, Dolichoponidae, Baetidae, Caenidae, Haliplidae, Curculionidae, Tabanidae, Dixidae, Ceratopogonidae, Anthomyidae, Limoniidae, Psychodidae, Sialidae, Piscicolidae, Hidracarina	4
Ceratoponidae, Glossiphonidae, Cyclobdellidae, Hydrophilidae, Physidae, Tipulidae. Mesoveliidae, Hydrometridae, Gerridae, Nepidae, Naucoridae, Pleidae, Notonectidae, Corixidae, Helodidae, Dysticidae, Gyrinidae, Valvatidae, Hydrobiidae, Lymnaeidae, Planorbidae, Bithyniidae, Sphaeridae, Hirudidae, Erpobdellidae, Asellidae, Ostracoda	3
Chironomidae, Culicidae, Muscidae, Thaumaleidae, Ephydridae Sciomyzidae, Syrphidae	2
Oligochaeta	1

The ranges used to determine the water quality classes were those established for the proposed BMWP index [31]. For the collection of benthic macroinvertebrates, an Ekman dredger (Wildco Cole-Parmer México®) with a surface area of 225 cm^2 and a Surber net with a rectangular frame of 25.4 $\times$ 45.7 cm (mouth area 1160.7 cm^2) and mesh opening of 365 μm were used to capture organisms in all the habitats present. The collection was carried out for a period of 10 min, which is the maximum time recommended by the ISO standard [32]. To identify organisms and classify them up to the family taxonomic level, we employed a specialized bibliography.

To determine the concentration of *Escherichia coli* (EC), the most probable number of multiple tubes method from the NMX-AA-042-SCFI-2015 standard [26] was employed.

The toxicity indices were based on the standard NMX-AA-112-1995-SCFI (Analysis of water and sediments—Evaluation of acute toxicity with *Vibrio fischeri*) [24]. The test is based on measuring the luminescence emitted by the bacterium *Vibrio fischeri*, which is reduced when the bacterium is exposed, for periods from 5 to 30 min, to samples containing toxic compounds generally derived from point sources, such as industrial or municipal wastewater discharges. Luminescence tends to decrease in accordance with the toxic load of a test sample. This decrease occurs due to the involvement of the metabolic processes associated with bacterial respiration.

An important aspect of structuring the index was that the different components that made it up did not express the same thing and were not highly correlated, so there was no redundancy or trend in the results. In this context, the relationships between the qualitative and quantitative values of the methods that made up the index were reviewed. The first concerned the category assigned to the sites using the methods with the five classes from very bad to excellent. For this, a correlation between categorical variables was applied with Pearson's chi-square test and it was standardized with the calculation of Cramer's V. In the analysis of the quantitative data, the numerical values for each method per site were considered, both the original data and the normalized data, using the Spearman correlation.

2.2. Integral Index of Water Quality (IIWQ)

To obtain the index values, the following procedure was used. Each of the water quality scales for each method, defined according to the assessment of its components, was assigned a range that was standardized to an interval of 1–10. With this, we ensured that they had the same dimensions. Subsequently, the range value was multiplied by a weight (P) that numerically represented the degree of importance and influence that each method had in quantifying contamination, which depended on the anthropic impact condition of the area. A value of 5 was assigned to the index with the most significant impact and 1 to the index with the least significant impact (Table 2).

Table 2. Methods considered for calculating the IIWQ with their respective weights, scales, and ranges.

Water Quality Index (IWQ-CONAGUA)		Concentration Values for 13 Heavy Metals		BMWP Index		Microbiology: Levels of *Escherichia coli* Organisms		*Vibrio fischeri* Toxicity Levels		
P = 5		**P = 4**		**P = 3 (Roldan, 2003)**		**P = 2**		**P = 1**		
Scale	**Range**	**Scale**	**Range**	**Scale**	**Range**	**Scale**	**Range**	**Scale**	**Range**	
91–100	8.1–10	13	8.1–10	>100	8.1–10	0–10	8.1–10	0–10	8.1–10	Excellent
71–90	6.1–8	10–12	6.1–8	61–100	6.1–8	10–100	6.1–8	10–100	6.1–8	Good
51–70	4.1–6	8–10	4.1–6	36–60	4.1–6	100–1000	4.1–6	100–1000	4.1–6	Fair
26–50	2.1–4	6–8	2.1–4	16–35	2.1–4	1000–10,000	2.1–4	1000–10,000	2.1–4	Bad
<26	0–2	0–6	0–2	<16	0–2	>10,000	0–2	>10,000	0–2	Very Bad

The maximum weight was assigned to the IWQ variable as it is currently the most widely used indicator for diagnosing surface water quality in Mexico and can incorporate up to nine measurement aspects, providing a very approximate value for the conditions.

Heavy metals were assigned to level 4, given their importance and the impact that high concentrations can have on the ecosystem and public health. The biotic variable was assigned to level 3 since it currently represents a good indicator of water quality conditions. In some countries, biotic variables are already part of the official standards; however, in Mexico, there is no official standard that refers to this aspect.

Microbiology (level 2) and toxicity (weight level 1) analyses are aspects that CONAGUA currently considers more often in the measurements of water quality in rivers. These variables generally leave records in the water and are always associated with the levels and types of wastewater discharges.

The integral index of water quality (IIWQ) was calculated as the arithmetic sum of each of the factors considered, generating a single value with, according to the provisions of this method, intervals of at least 15 points and a maximum of 150 points:

$$\text{IIWQ} = (\text{IWQr} \cdot \text{IWQp}) + (\text{MPr} \cdot \text{MPp}) + (\text{Br} \cdot \text{Bp}) + (\text{ECr} \cdot \text{ECp}) + (\text{Tr} \cdot \text{Tp})$$

where IIWQ = integral index of water quality, IWQ = water quality index, MP = heavy metal index, EC = *Escherichia coli* index, B = BMWP biodiversity index, T = toxicity index, r = scale or assessment factor, p = range or weighting factor.

For the IIWQ, five levels of water quality were proposed, with level 1 (N1) representing excellent water quality and the minimum values (N5) representing lower water quality (Table 3).

Table 3. Categories and ranges for the integral index of water quality.

Symbology	Category	Range
N1	Excellent	123–150
N2	Good	96–122
N3	Fair	69–95
N4	Bad	42–68
N5	Very bad	15–41

Level 1 was associated with excellent water quality where anthropogenic disturbances had not yet directly impacted the original state of the surface water and the water could be used in any socioeconomic activity.

Level 2 represented a condition classified as good, where the original water quality had begun to record slight disturbances but the water did not yet require costly treatment for use in socioeconomic activities.

Level 3 represented a condition classified as bad and the disturbances registered in the quality of the water were already slightly significant, conditioning its use for some activities of an economic nature. Levels 4 and 5, classified as poor to very poor, represented sites where the water entailed very high risks for use in any activity and required important sanitation measures.

3. Results and Discussion

Figure 2 shows the location of the 17 water sampling sites along the riverbed of the Cupatitzio River, starting at its origin, the spring at Devil's Knee (RC1), and progressing to the endpoint at the confluence with the Jicalán River in the area known as El Marques (RC17).

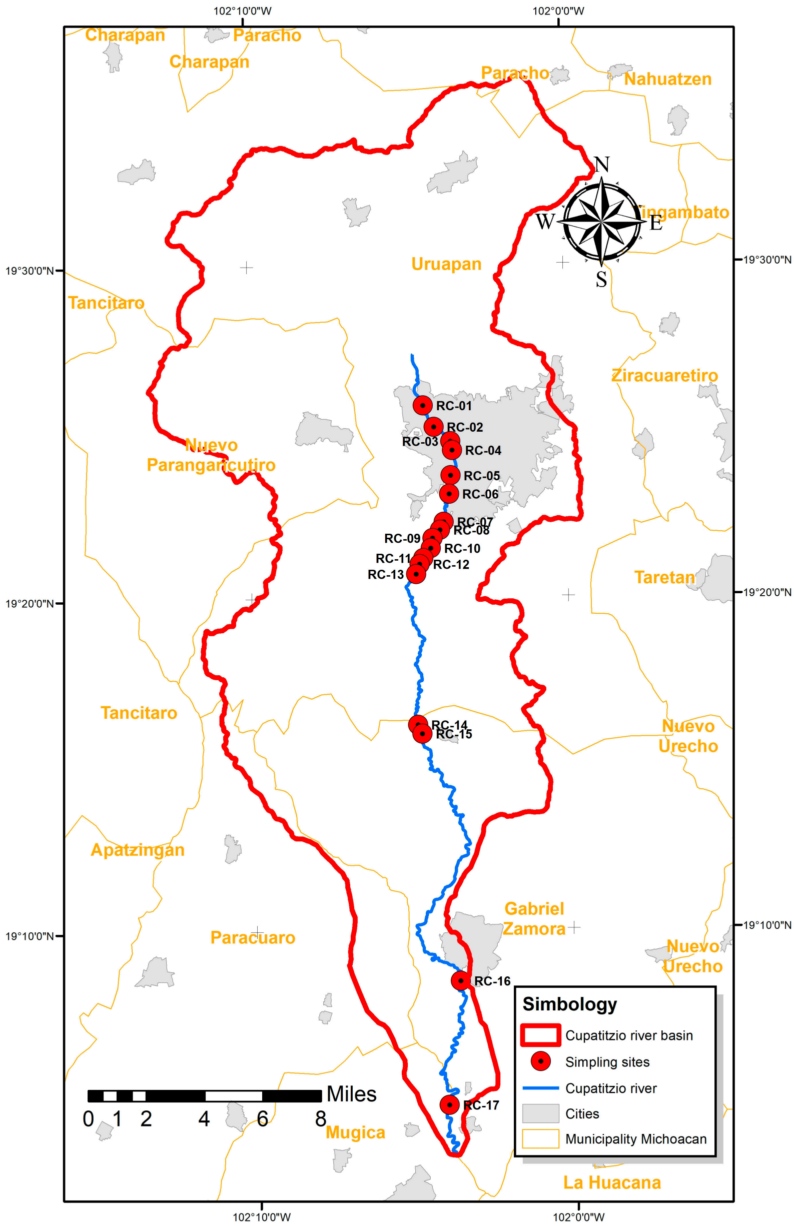

Figure 2. Location of the 17 sampling sites in the Cupatitzio River.

The values obtained for each site and each variable are presented, in accordance with the official standards that each parameter represented, in Table A1 (See Appendix A). Figure 3 graphically shows the behavior of the IWQ indicator; the range of values between 22.41 (which would be classified as very poor quality water) and 64.67 (fair quality) stands out. In general, 11 of the sampled sites showed values in the fair quality range (51–70), five at the poor quality level (26–50), and only one at the very poor level (<25), which was located in the middle part of the Cupatitzio River basin. None of the sites exceeded the limits for the water ranges for good to excellent quality. Table A2 shows the results obtained from the physicochemical analysis in the Cupatitzio River.

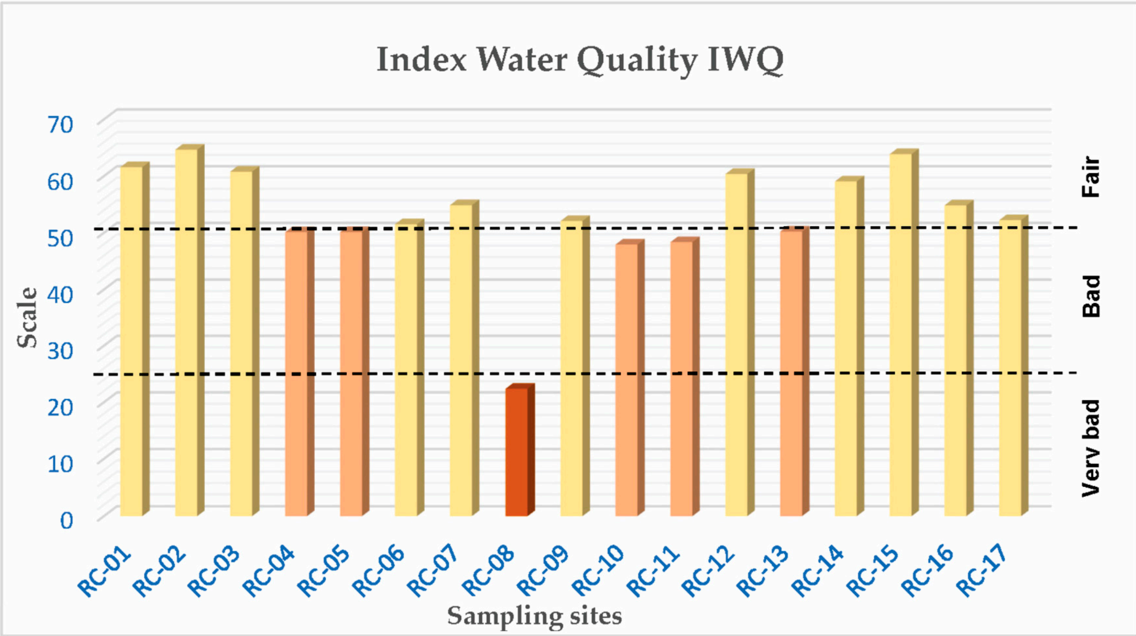

Figure 3. Ranges obtained for the IWQ.

These values are similar to those reported for other surface water currents, such as in the Duero River basin [33]. This study described the chemical quality of the water resources, both underground and surface water, finding negative impacts due to the presence of a strong organic water load. In the Atemajac basin, the water for urban and agricultural use was mostly poor quality (IWQ = 30–49) and, to a lesser extent, highly contaminated (IWQ < 30); [34].

For the BMWP parameter (Table A3), Figure 4 graphically shows how the water quality differed compared to the IWQ. Seven sites were classified as having good quality water in the range from 61 to 96 points; five sites were located in the fair range, with values from 37 to 52 points; four sites were defined as very good (101 to 142 points); finally, only one site was in the very poor quality range, with a value of 30 points.

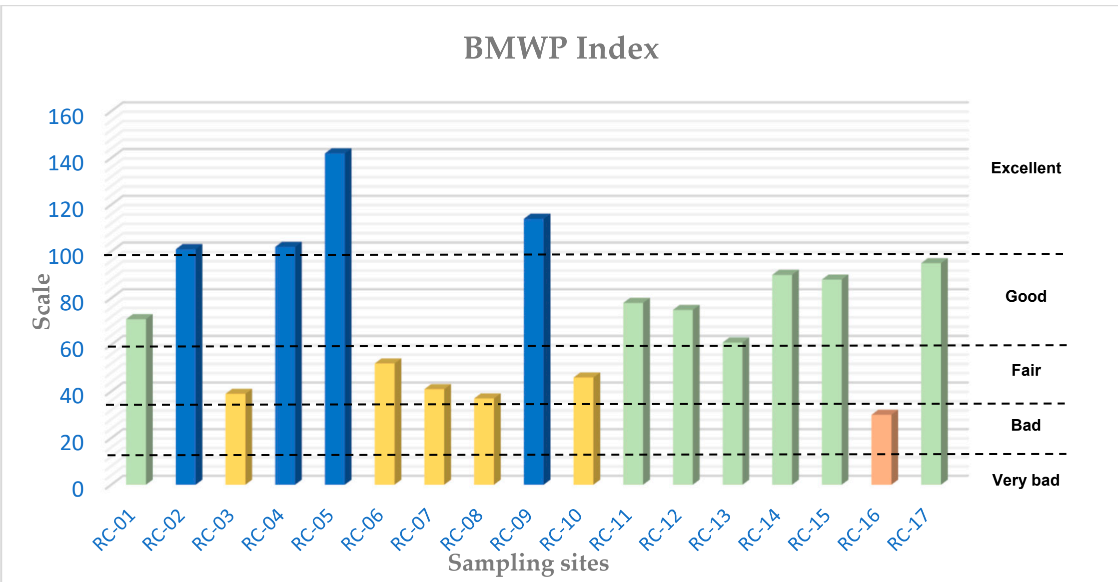

Figure 4. Ranges obtained with the BMWP index.

Recent studies that have used this index showed similar conditions. The authors of [35] pointed out that using benthic macroinvertebrates as biological indicators has a long tradition in developed countries, and they are incorporated in all evaluations of the ecological quality of river systems. This was also documented in [36], where the authors mentioned that 80% of aquatic ecosystems, including rivers, suffer from some degree of contamination in Mexico. For example, based on the results obtained using biotic indicators (macroinvertebrates), the Apulco tributary basin contributes poor quality water to the main channel of the Tuxcacuesco River.

The microbiological panorama for the Cupatítzio River is shown in the graph in Figure 5 (Table A6), and the differences when cataloging a site in terms of its quality with the parameters mentioned above are again observable: six sites were defined as very bad quality (1.70×10^4 to 2.30×10^8), seven sites were classified as bad quality in the range from 1.30×10^3 to 9.00×10^3, one site was defined as having good quality water (270), and, finally, three sites were classified as excellent quality, with values of 2.00. Table A4 shows the results obtained from microbiological analysis in the Cupatitzio River.

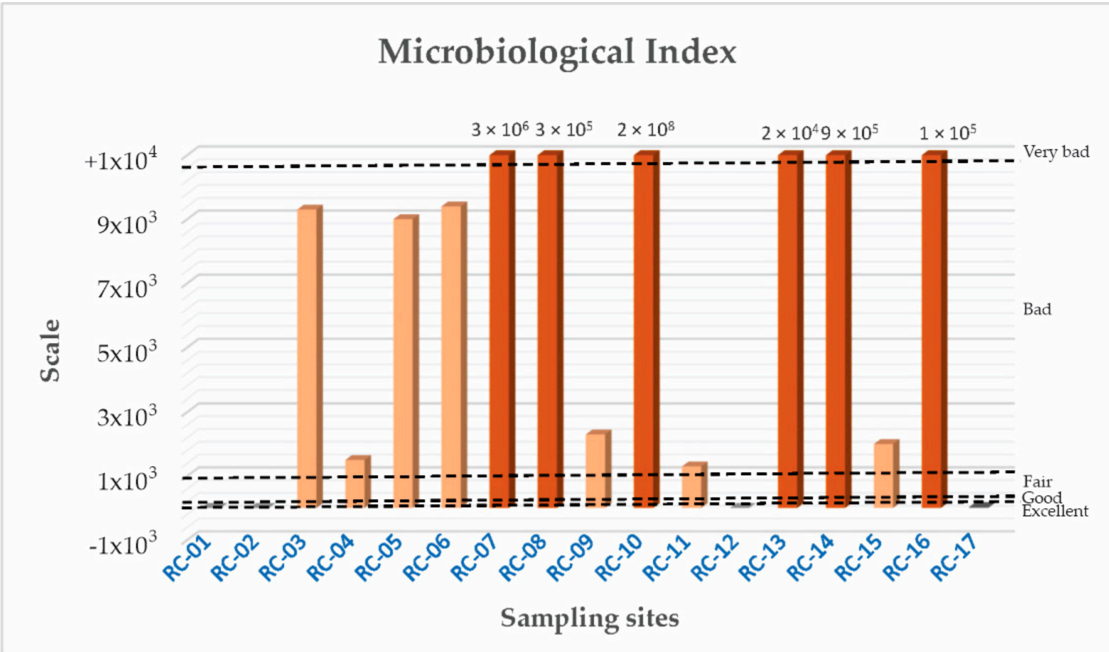

Figure 5. Ranges obtained from the microbiological index (*Escherichia coli*).

The conditions in the Cupatitzio River are not at all different from the situation for large parts of the surface waters in Mexico; the Lerma, Pánuco, Bravo, San Juan, and Balsas basins alone receive 50% of the nation's wastewater discharge [37]. Rivers such as the Lerma, the Duero, the Seco, and Lake Chapala show high contamination rates due to fecal organisms, as also found here [38–40].

When we did not refer to the concentration levels for heavy metals (Figure 6), discrepancies appeared again. For this parameter, in 13 of the sites, between 11 and 12 elements were within the range of permissible limits, and they were defined as good quality. Only four registered values for all the elements within the official limits, making them waters of excellent quality. Table A5 shows the results obtained for heavy metals in the Cupatitzio River.

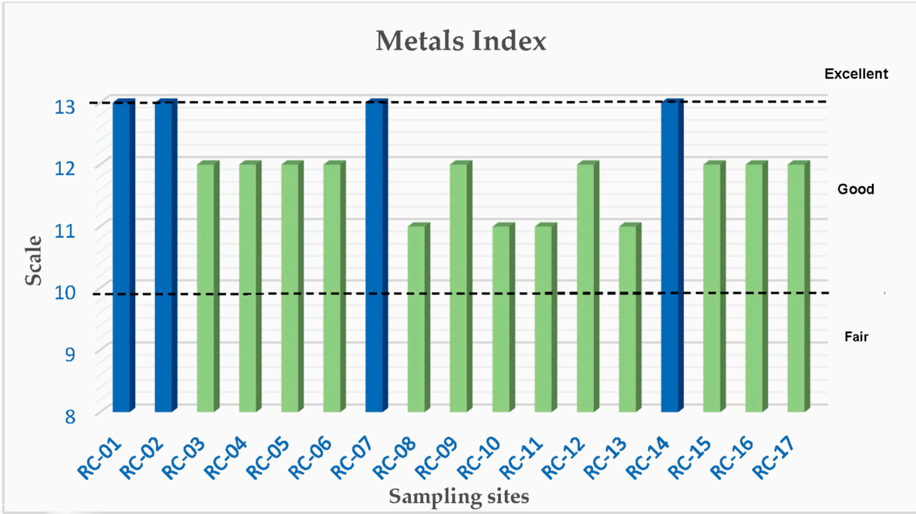

Figure 6. Ranges obtained with the heavy metals index.

In Mexico, where surface waters are in a state of advanced environmental deterioration, the presence of heavy metals potentially derived from anthropic sources is very common. An example is described in [41], where concentrations of Cd, Ni, Cr, Mn, Zn, and Pb above the official limits—associated with illegal discharges of sewage from nearby homes, hospital waste, and infiltration from other polluted lagoons—were reported in sediments from Laguna de las Ilusiones, Tabasco.

Another example is described in [42], where the presence and distribution of heavy metals in the sugarcane area of the Río Hondo basin, south of Quintana Roo, Mexico, were determined by measuring the total concentrations of Hg, Cd, Cu, and Fe, which were, in each case, above the official limits, with the authors stating that they could have come from anthropogenic sources.

Finally, in terms of the toxicity index, Figure 7 graphically shows that nine sites in the Cupatitzio River registered poor water quality levels, while three had very bad quality, three had fair quality, and only two had excellent water quality, repeating the differences obtained when classifying each site in terms of its quality. Table A7 shows the results obtained from toxicity analysis in the Cupatitzio River.

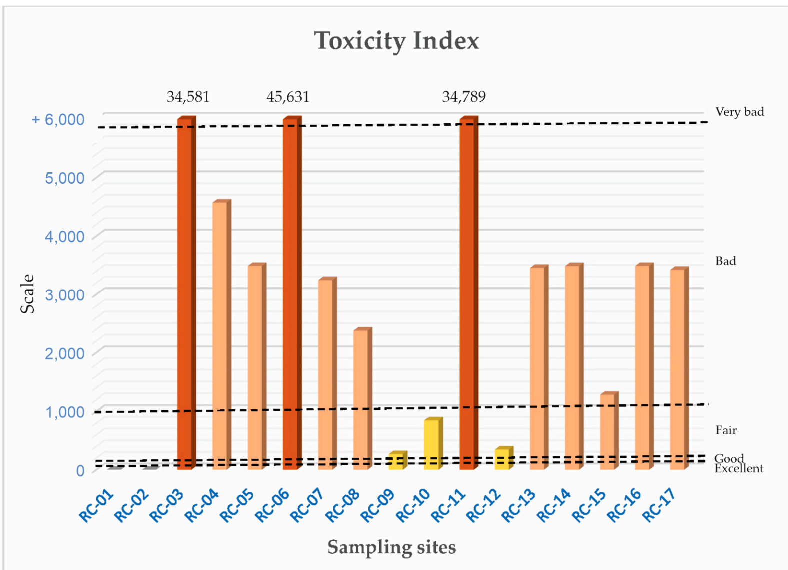

Figure 7. Ranges obtained with the toxicity index.

Toxicity is a parameter that is increasingly used worldwide to analyze water quality conditions. The authors of [43] reported high toxicity levels using *Vibrio fischeri* in the Atoyac River, making it very high risk for public health. The authors of [44] determined the toxicity of the sediments in the upper course of the Lerma River, State of Mexico, finding that the mean effective concentration (EC50) in *Vibrio fischeri* could be classified as extremely toxic, which is indicative of the impact of the domestic and industrial discharges received by this important body of water.

The correlation analysis results for the categories' qualitative variables established significant differences between the five methods used ($\chi^2 = 83.69$; $p = 3.57 \times 10^{-11}$); they were independent. This is important because it implies that there was no redundancy in the results. However, there had to also be a certain relationship that would make it possible to obtain a complementary view of the methods. When the coefficient was standardized, the independence was moderate (Cramer's V = 0.496), which was appropriate because there was a certain relationship between the results of the methods.

Considering the quantitative data that were directly obtained with the individual methods, there was a significant relationship between the IWQ and metals (Spearman = 0.75; $p = 0.0005$) and, with lower magnitude, between the BMWP index and *E. coli* (Spearman = 0.53; $p = 0.029$). This gives a general initial approximation considering that the methods employed different units, magnitudes, and data characteristics (Figure 8).

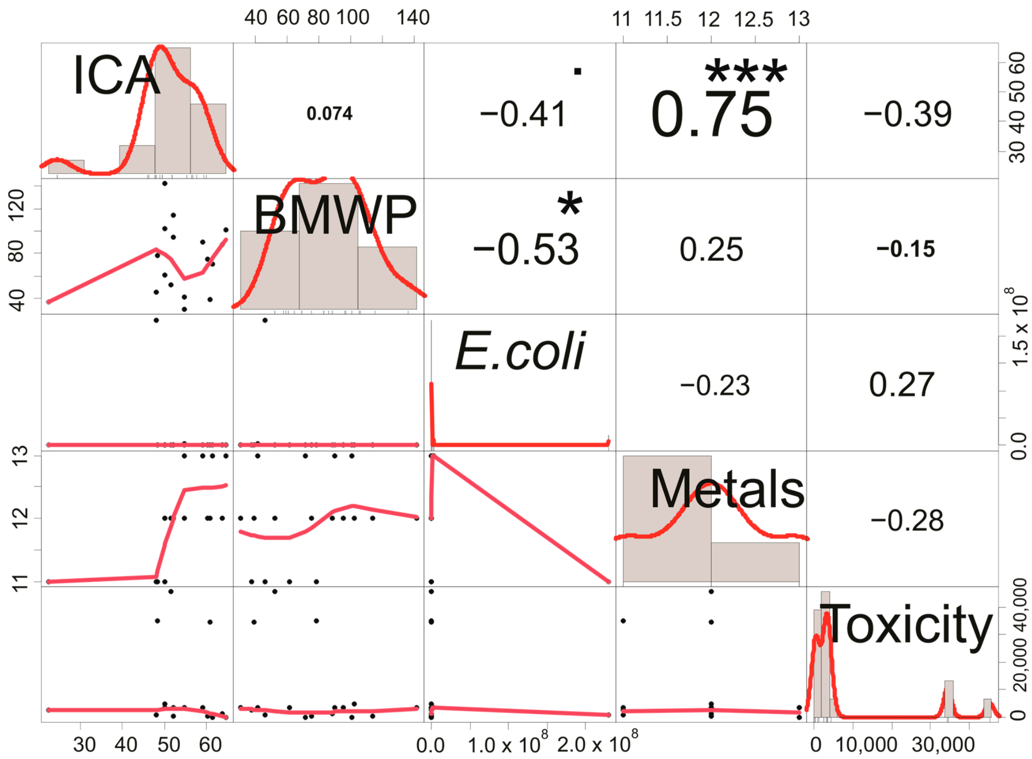

Figure 8. Correlation matrix: scatter plot for pairs of methods used for water quality measurements. Spearman correlation coefficients are also indicated for each pair of methods. * = 0.05, and *** = 0.001 correspond to the level of significance.

As expected, the correlations increased with the standardization of the values, and some became more significant (Figure 9). In particular, the *E. coli* index was most closely related to the compound index, and metals were the least closely related. In general, *E. coli* and toxicity were related, and this can be explained by the fact that bacteria were analyzed in both cases. The IWQ and metals created another interaction. The BMWP index remained separate, but its correlation with the integral index was high, which was suitable as it was an element that complemented the latter's results (Figure 10).

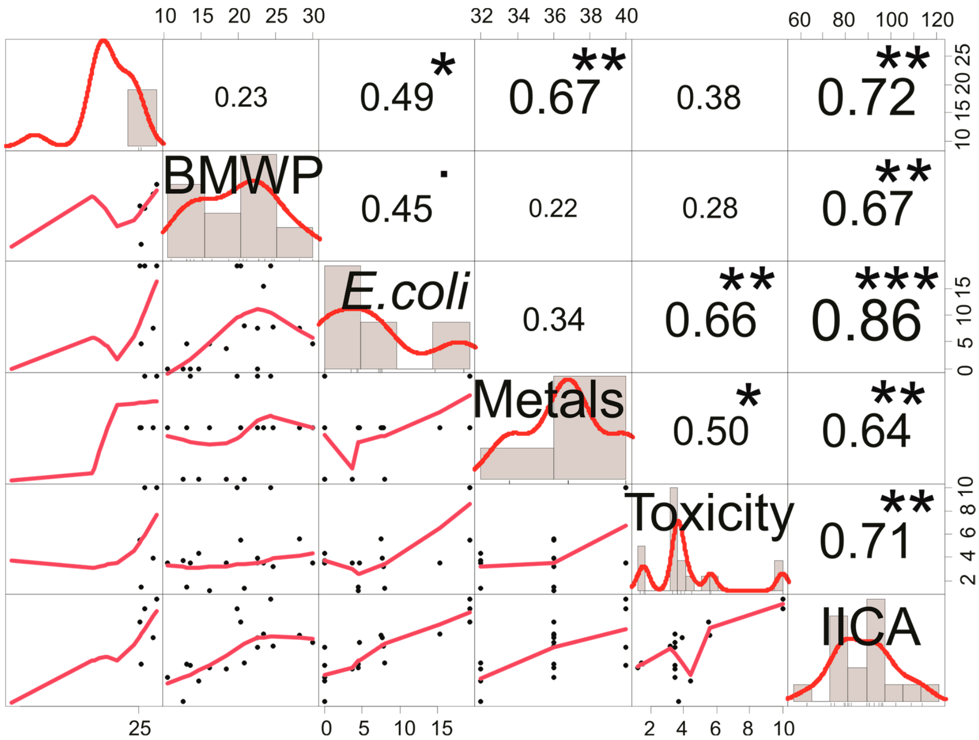

Figure 9. Correlation matrix: scatter plot for pairs of standardized methods used for water quality measurements. Spearman correlation coefficients are also indicated for each pair of methods. * = 0.05, ** = 0.01, and *** = 0.001 correspond to the level of significance.

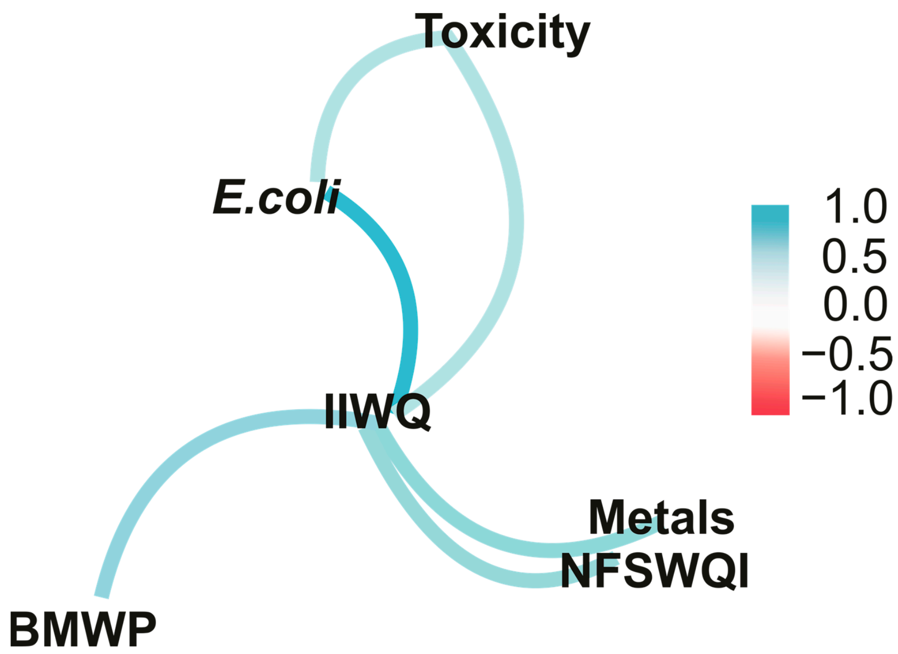

Figure 10. Graphic results for the Spearman correlation between the different standardized methods of measuring water quality and the integral index.

The results obtained by applying the proposed method in the calculation of the integral index of water quality for the 17 points analyzed in the Cupatitzio River are shown in Table A7. The graph in Figure 11 shows that, of the 17 sites studied, a total of 10 were in the fair quality category (N3), ranging from 69 to 95 points; six were in the good quality category (N2); and only one was in the poor quality category (N4).

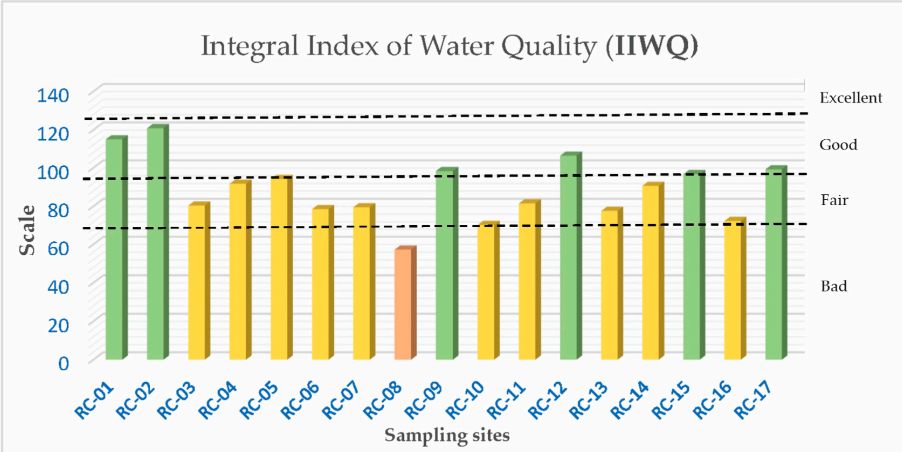

Figure 11. Ranges obtained with the integral index of water quality (IIWQ).

For the analyzed period, the Cupatitzio River demonstrated an integral condition of water quality that indicated that it is still acceptable to use it in the different socioeconomic activities for which it is destined, which, currently, are preferably agricultural livestock uses and the generation of electrical energy. For domestic uses, other aspects required by official standards must be considered.

Figure 12 graphically shows the location of each site analyzed with the IIWQ. Excellent water quality conditions were present at the first two sampling stations, representing the beginning of the river. However, in the river's course through the urban sprawl, it can be clearly noted that the quality was modified by the prevailing anthropic pressure from wastewater discharge, changing the river status to medium quality up to the RC-08 site, which had bad quality.

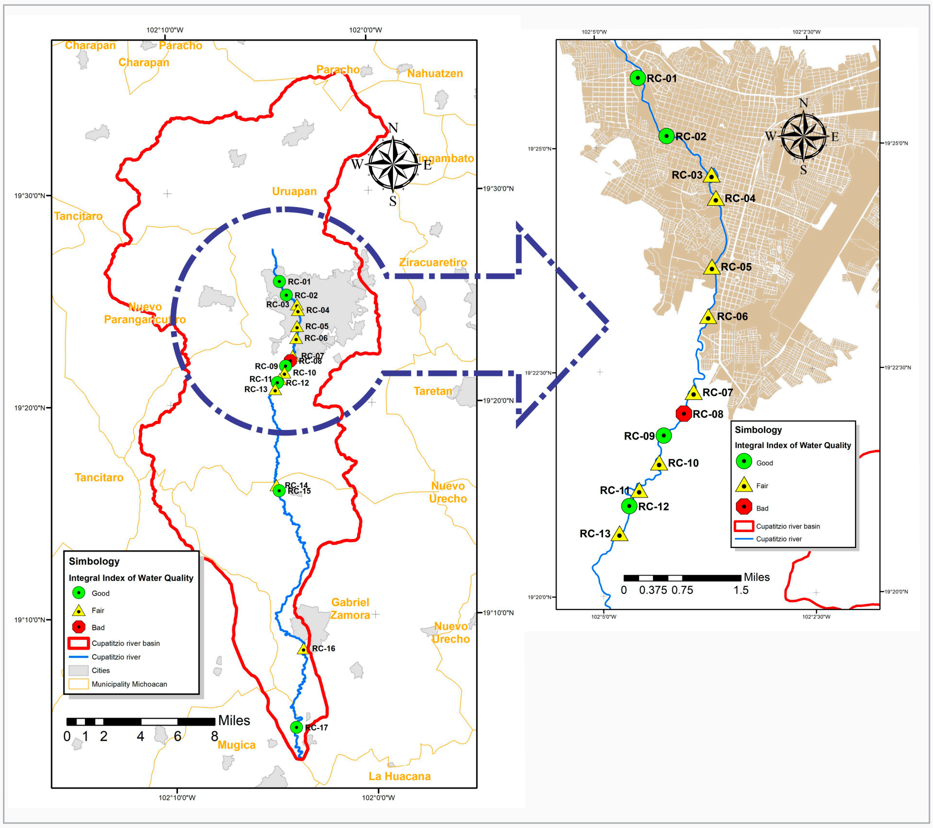

Figure 12. Map of water quality in the Cupatitzio River analyzed with the IIWQ.

In the middle basin, the water quality improved from fair (69–95 points) to good (96–122 points) in the channel known as El Marques (RC-17).

Figure 13 shows a comparison of the average water quality levels for each variable analyzed. None of the measured variables coincided in quality; the averages for the IWQ index placed the river in the fair range, while the BMWP index defined it as good. With the microbiological and toxicity methods, the river conditions ranged from bad to very bad; in contrast, the heavy metals index indicated the water quality as excellent.

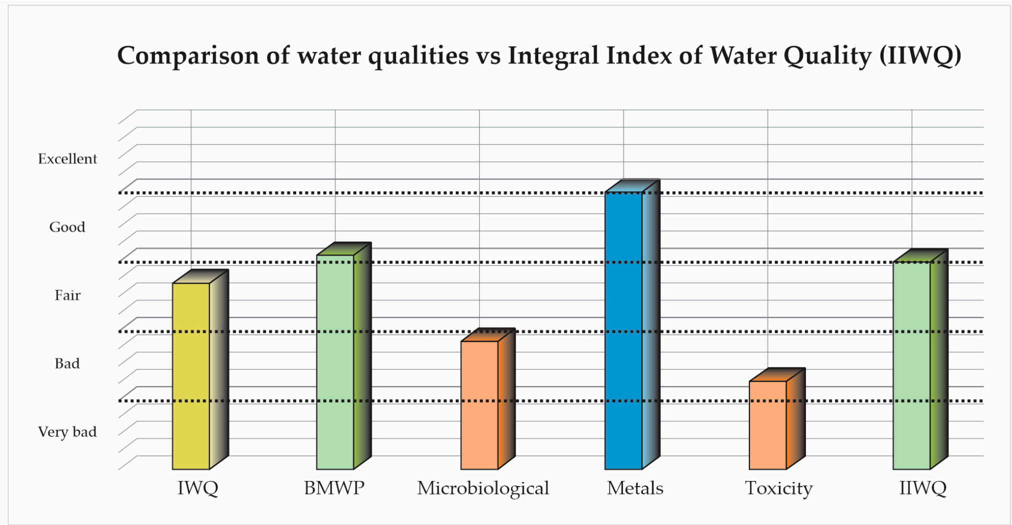

Figure 13. Comparative graph of average water qualities obtained for each variable and the integral index of water quality (IIWQ).

In this context, the application of this methodological proposal resulted in a comprehensive water quality index that incorporated the information for the five variables already described; it is thus possible to more adequately delineate the situation of the water quality in the Cupatitzio River as good. Therefore, it is very important to measure each of the parameters individually considered here, as they reflect the specific water use requirements.

The proposed index provides a good approximation for the definition of the water quality situation of a river. It is as comprehensive as possible, as well as being innovative, and employs a multiparametric scheme that helps to eliminate specific inconsistencies, as demonstrated in this work. It should be noted that, in the literature, there is nothing similar to what has been described here. Reports have only mentioned the use of independent parameters; i.e., only measuring the quality of water based on the IWQ, the microbiological environment, heavy metals, or biotic or toxicity indices.

4. Conclusions

This original approach employing a methodology aimed at defining an integral index of water quality in surface waters obtained satisfactory results for the Cupatítzio river, Michoacán, since it was possible to properly delimit the quality condition of its waters, which were found to be of good quality and suitable for use in the different socioeconomic activities for which they are intended.

The method offers the advantage of being representative of the five different conditions evaluated in the field for river pollution, employing a discretized regional panorama and integrating into it those factors mentioned in the official regulations, making it possible to extrapolate the findings to other rivers.

The results obtained provide a first approximation for the determination of the state of a river in terms of its environmental contamination in a fast, efficient, and very comprehensive way. This minimizes possible discrepancies between individually evaluated variables, jointly delimiting each measured element.

Multiparameter methods generally present methodological disadvantages, mainly in relation to the assignment of weight and range values for each parameter. Such assignments arise from experience and knowledge related to the different parametric phases used to measure water quality, as well as existing interrelationships. It is important to mention that this integrative proposal does not replace the individual water quality assessments of each parameter, since each of them can delimit a specific condition and purpose for a place.

Author Contributions: Conceptualization, J.T.S.-G. and R.M.-E.; methodology, G.C.-C., D.Á.-B., S.O.-E., R.F.-M., F.E.-G., F.V.-B., L.F.C.-T. and M.A.-D.; formal analysis, G.C.-C., R.M.-E. and D.Á.-B.; investigation, G.C.-C., D.Á.-B., S.O.-E., R.F.-M., F.E.-G., F.V.-B., L.F.C.-T. and M.A.-D.; writing—original draft preparation, J.T.S.-G.; writing—review and editing, R.M.-E., G.C.-C., D.Á.-B., S.O.-E., R.F.-M., F.E.-G., F.V.-B., L.F.C.-T. and M.A.-D.; funding acquisition, J.T.S.-G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CONACYT, grant number 266025.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author, [D.A.-B.].

Acknowledgments: The authors thank the National Council of Science and Technology, as well as the National Polytechnic Institute, for the financial support given to this project. All authors were supported by the Comisión de Operación y Fomento de Actividades Académicas (COFAA) and Estímulo al Desempeño Académico (EDI).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Results obtained for each measured variable.

Sampling Sites	IWQ	BMWP Index Roldan, 2003	Microbiology: Levels of *Escherichia coli* Organisms NMP/100 mL	Metals ICP (ISO 11885)	Toxicity (UT)
RC-01	61.59 Fair	71 Good	2.00 Excellent	13 Excellent	<10 Excellent
RC-02	64.67 Fair	101 Excellent	2.00 Excellent	13 Excellent	<10 Excellent
RC-03	60.80 Fair	39 Fair	9.30×10^3 Bad	12 Good	34,581 Very bad
RC-04	50.13 Bad	102 Excellent	1.50×10^3 Bad	12 Good	4574 Bad
RC-05	50.15 Bad	142 Excellent	9.00×10^3 Bad	12 Good	3489 Bad
RC-06	51.53 Fair	52 Fair	9.40×10^3 Bad	12 Good	45,631 Very bad
RC-07	54.89 Fair	41 Fair	3.00×10^6 Very bad	13 Excellent	3246 Bad
RC-08	22.41 Very bad	37 Fair	3.30×10^5 Very bad	11 Good	2378 Bad
RC-09	52.1 Fair	114 Excellent	2.30×10^3 Bad	12 Good	269 Fair
RC-10	47.95 Bad	46 Fair	2.30×10^8 Very bad	11 Good	847 Fair
RC-11	48.37 Bad	78 Good	1.30×10^3 Bad	11 Good	34,789 Very bad
RC-12	60.38 Fair	75 Good	2.00 Excellent	12 Good	348 Fair

Table A1. *Cont.*

Sampling Sites	IWQ	BMWP Index Roldan, 2003	Microbiology: Levels of *Escherichia coli* Organisms NMP/100 mL	Metals ICP (ISO 11885)	Toxicity (UT)
RC-13	50.24 Bad	61 Good	1.70×10^4 Very bad	11 Good	3456 Bad
RC-14	59.08 Fair	90 Good	9.30×10^5 Very bad	13 Excellent	3487 Bad
RC-15	63.89 Fair	88 Good	2.00×10^3 Bad	12 Good	1278 Bad
RC-16	54.85 Fair	30 Bad	1.10×10^5 Very bad	12 Good	3489 Bad
RC-17	52.25 Fair	95 Good	2.70×10^1 Good	12 Good	3423 Bad

Table A2. Physicochemical analysis results for the Cupatitzio River.

Sampling Sites	pH	Biochemical Oxygen Demand DBO5 (mg/L)	Nitrates (mg of NO_3^-/L)	Orthophosphate (mg of PO_4^{3-}/L)	Water Temperature (°C)	Turbidity (UNT)	Total Dissolved Solids (mg/L)	Dissolved Oxygen (mg/L)
RC-01	6.95	3.42	3.02	0.72	16.10	0.00	155.64	10.40
RC-02	7.41	2.97	2.82	1.81	16.36	0.00	246.68	11.37
RC-03	7.18	9.05	3.66	1.23	16.91	13.93	178.25	12.23
RC-04	7.01	8.01	1.29	1.00	16.95	71.53	401.12	10.50
RC-05	7.35	6.02	5.87	2.04	19.23	216.13	205.97	9.70
RC-06	7.38	16.64	4.06	1.73	16.90	16.30	400.66	10.30
RC-07	7.96	12.89	9.71	1.96	18.01	7.60	186.30	10.40
RC-08	7.12	14.91	56.15	32.35	21.32	1000.00	847.32	0.00
RC-09	7.30	5.83	4.27	1.30	15.65	11.82	616.86	12.60
RC-10	6.87	123.89	0.00	12.08	18.29	29.21	472.77	10.20
RC-11	7.13	12.60	3.52	2.30	19.32	258.06	198.72	8.20
RC-12	6.95	0.10	3.02	0.89	15.26	0.71	149.50	12.80
RC-13	7.71	5.29	4.67	2.84	17.41	163.40	210.22	12.20
RC-14	8.04	9.78	1.33	0.66	20.25	22.40	198.72	11.50
RC-15	7.85	6.10	0.35	1.76	23.26	15.80	128.80	9.70
RC-16	6.99	15.57	3.84	2.76	21.05	83.03	251.16	8.30
RC-17	8.20	8.14	1.55	0.31	18.59	213.50	301.30	10.70

Table A3. BMWP values.

Site Key	D	BMWP
RC-01	0.72	71
RC-02	0.67	101
RC-03	0.23	39
RC-04	0.11	102
RC-05	0.72	142
RC-06	0.09	52
RC-07	0.75	41
RC-08	0.27	37
RC-09	0.66	114
RC-10	0.78	46
RC-11	0.27	78
RC-12	0.74	75
RC-13	0.25	61
RC-14	0.76	90
RC-15	0.65	88
RC-16	0.13	30
RC-17	0.80	95

Table A4. Microbiology values.

Site Key	*Total coliform* Organisms	*Fecal coliform* Organisms	*Escherichia coli*
RC-01	2×10^3	2×10^2	2
RC-02	6×10^3	9×10^2	2
RC-03	6×10^6	1×10^4	9×10^3
RC-04	4×10^7	2×10^6	2×10^3
RC-05	9×10^6	2×10^5	9×10^3
RC-06	2×10^6	2×10^6	9×10^3
RC-07	6×10^9	8×10^8	3×10^6
RC-08	6×10^9	1×10^7	3×10^5
RC-09	2×10^5	2×10^5	2×10^3
RC-10	3×10^9	2×10^8	2×10^8
RC-11	4×10^6	2×10^5	1×10^3
RC-12	4×10^2	2	2
RC-13	2×10^6	1×10^6	2×10^4
RC-14	9×10^6	5×10^6	9×10^5
RC-15	2×10^5	1×10^4	2×10^3
RC-16	6×10^7	6×10^6	1×10^5
RC-17	9×10^5	3×10^3	3×10^1

Table A5. Values for heavy metals and As, B, and Se.

Site Key	Total Cadmium (mg/L)	Total Beryllium (mg/L)	Total Aluminum (mg/L)	Total Chrome (mg/L)	Total Copper (mg/L)	Total Iron (mg/L)	Total Mercury (mg/L)	Total Nickel (mg/L)	Total Lead (mg/L)	Total Zinc (mg/L)	Total Arsenic (mg/L)	Total Boron (mg/L)	Total Selenium (mg/L)
RC-01	<0.01	<0.01	0.11	0.798	0.015	4.959	<0.01	0.287	9.2	7.938	0.006	6.483	0.046
RC-02	<0.01	<0.01	149.3	1.32	0.015	0.19	<0.01	0.178	8.177	4.952	0.006	11.54	0.377
RC-03	<0.01	<0.01	21.575	1.042	0.015	0.741	<0.01	0.275	3.657	56.952	0.006	10.865	0.239
RC-04	<0.01	0.03	13.075	1.897	0.015	1.765	<0.01	0.588	9.315	77.285	0.006	12.3	0.045
RC-05	<0.01	<0.01	28.185	1.361	0.015	0.163	<0.01	3.115	3.105	16.893	0.006	9.57	0.124
RC-06	<0.01	<0.01	271.925	0.956	0.015	0.687	<0.01	0.242	4.773	20.55	0.006	11.878	0.041
RC-07	<0.01	<0.01	573.12	<0.01	<0.010	0.042	<0.01	<0.010	9.89	<0.010	<0.001	<0.5	<0.01
RC-08	<0.01	<0.01	2302.58	3.757	2.412	3.401	<0.01	2.789	25.415	429.138	0.006	10.07	0.12
RC-09	<0.01	<0.01	0.015	0.737	0.015	0.407	<0.01	0.108	3.795	19.646	0.006	8.193	0.061
RC-10	<0.01	<0.02	317.58	0.01	0.01	0.339	<0.01	0.048	33.27	47.653	0.229	75.76	0.463
RC-11	<0.01	<0.01	21.99	0.01	0.01	0.026	<0.01	0.01	8.441	2.517	0.001	0.5	0.01
RC-12	<0.01	<0.01	42.84	0.554	0.015	0.067	<0.01	0.468	9.074	30.927	0.006	6.765	0.397
RC-13	<0.01	<0.01	12.65	<0.01	<0.010	0.075	<0.01	<0.010	<0.01	5.239	<0.001	<0.5	<0.01
RC-14	<0.01	<0.01	217.23	<0.01	<0.010	0.059	<0.01	2.54	19.65	<0.010	<0.001	389.12	<0.01
RC-15	<0.01	0.316	3.73	1.87	4.599	0.544	<0.01	5.055	6.866	10.398	0.006	7.078	0.032
RC-16	<0.01	0.041	25.755	0.977	0.015	0.162	<0.01	1.116	5.474	18.809	0.006	11.865	0.091
RC-17	<0.01	0.05	8.5	0.981	0.015	1.281	<0.01	0.997	9.775	24.373	0.52	7.633	0.015

Table A6. Toxicity values.

Site Key	Determination of *Vibrio fischeri*
RC-01	≤10
RC-02	≤10
RC-03	34,581
RC-04	4574
RC-05	3489
RC-06	45,631
RC-07	3246

Table A6. *Cont.*

Site Key	Determination of *Vibrio fischeri*
RC-08	2378
RC-09	269
RC-10	847
RC-11	34,789
RC-12	348
RC-13	3456
RC-14	3487
RC-15	1278
RC-16	3489
RC-17	3423

Table A7. Results obtained for the IIWQ in the Cupatitzio River.

Sampling Sites	Index					IIWQ	
	IWQ	BMWP Roldan, 2003	Microbiology: Levels of *Escherichia coli* Organisms	Metals (ICP ISO 11885)	Toxicity (UT)		
RC-01	25.8	19.8	19.2	40	10	114.8	Good
RC-02	27.3	24.3	19.2	40	10	120.9	Good
RC-03	25.4	13.0	4.5	36	1.5	80.4	Fair
RC-04	20.1	24.6	7.8	36	3.2	91.7	Fair
RC-05	20.1	30.0	4.6	36	3.5	94.2	Fair
RC-06	20.8	16.1	4.5	36	1.2	78.5	Fair
RC-07	22.4	13.5	0.0	40	3.5	79.5	Fair
RC-08	9.0	12.5	0.0	32	3.7	57.2	Bad
RC-09	21.1	28.2	7.5	36	5.6	98.3	Good
RC-10	19.2	14.7	0.0	32	4.4	70.3	Fair
RC-11	19.4	20.8	7.9	32	1.4	81.5	Fair
RC-12	25.2	20.3	19.2	36	5.5	106.3	Good
RC-13	20.1	18.3	3.7	32	3.5	77.6	Fair
RC-14	24.5	22.5	0.0	40	3.5	90.6	Fair
RC-15	26.9	22.5	7.6	36	3.9	96.7	Good
RC-16	22.4	10.5	0.0	36	3.5	72.4	Fair
RC-17	21.1	23.3	15.3	36	3.5	99.2	Good

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