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Scientific Research

Development of a Water Quality Index (WQI) of an Artificial Aquatic Ecosystem in Mexico

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ABSTRACT

A Water Quality Index (WQI) is a simple numeric expression reflecting the quality of water in any ecosystem at a given time. The objective of this study was to develop a WQI for the man-made dam Francisco I. Madero located in Chihuahua, Mexico. Eight points were randomly selected in the dam area and at each point water samples were collected monthly from March 2011 to February 2012 at three depths; 0.30 m, 5 m and 10 m. The following physical-chemical variables were measured: potential hydrogen (pH), electrical conductivity (EC), dissolved oxygen (DO), temperature (T), turbidity, total dissolved solids (TDS), total hardness (TH) and chlorides (Cl^-). In a first step for data analysis, an analysis of variance (ANOVA) was performed for each variable considering a factorial treatment design 12 × 3 in which factor A was the month with 12 levels (sampling months) and factor B was the depth with three levels (0.30 m, 5 m and 10 m). In a second statistical step, the WQI was calculated for each month only for the surface sampling (0.30 m) and the resulting value was classified under three categories; <2.0 as poor water, in a range of 2.0 to 2.5 as good water and, >2.5 as excellent water. The results showed the following ranges for single variables: pH of 7.63 - 10.65, EC of 190 - 320 $\mu S \cdot cm^{-1}$, DO of 1.30 - 12.1 $mg \cdot L^{-1}$, T of 11.30˚C - 30˚C, Turbidity of 0-1, 120 NTU, TDS of 170 - 220 $mg \cdot L^{-1}$, TH of 240 - 900 $mg \cdot L^{-1}$ and Cl^- of 7.28 - 7034 $mg \cdot L^{-1}$. The calculated WQI demonstrated that water quality varies seasonally and was classified as poor in the rainy season to good in winter season. We conclude that in general the water from the dam is acceptable and suitable for ecological and a broad spectrum of other purposes.

Keywords: Water Quality; Index; Chihuahua; Mexico; Ecology; Contamination

1. Introduction

Artificial water reservoirs are important for domestic activities, industry, agriculture and livestock production, especially in arid and semi-arid zones. Nowadays, anthropogenic activities have contributed to pollution of these ecosystems. Consequently, it is necessary to employ new tools and methodologies to determine the level of pollution of any ecosystem at a given time. One alternative is the estimation of the water quality index (WQI), which is a simple arithmetic tool to assess water quality [1-6]. Calculating the WQI is based on the integration of physical-chemical-biological variables to generate a single value as an indicator of water quality [7-9]. In the mid-1960s Horton [10] developed the first WQI and since then this tool has been used to determine water quality in rivers [11], lakes [12], dams [13], and groundwater [14]. In addition, some variations of the WQI have been adjusted to potable water, recreational water and fisheries [15]. In some cases, the analysis has involved modulation or forecast because of easy interpretation of results [16]. In some cases WQI values allow for identifying pollution variables, consequently for recommending preventive actions in the water ecosystem [17]. This methodology had been used in countries, such as Argentina [18], Brazil [19], Spain [20], the United States [21], Iran [22] and Malawi [23].

In the case of Mexico, there have been some studies concerning water pollution in the Conchos watershed, the

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most important watershed in the State of Chihuahua [24] as well as in tributaries like the San Pedro River [25]. The studies detected varying levels of pollution in the rivers and other water ecosystems in Chihuahua [26-28]. For instance, Gutierrez *et al*. [29] determined contamination levels in the San Pedro River and the Francisco I Madero Dam. The dam, which is ranked as the third largest in the State of Chihuahua, provides waters to the communities in south-center Chihuahua and is a tourist and recreational attraction. The objective of this study was to develop a WQI for the water of the Francisco I. Madero Dam and to assess the spatial variability of the parameters. The results will allow inhabitant sand the authorities to differentiate pollution levels to know water quality and to implement corrective or preventive actions.

2. Materials and Methods

The study was carried out at the Francisco I. Madero Dam situated in the Municipality of Rosales, Chihuahua, Mexico. The dam is commonly known as “Las Virgenes” and is located between latitude 28˚09'58.82"N and longitude 105˚37'43.95"W with an altitude 1250 m (**Figure 1**). The water reservoir is about 80 km from the city of Chihuahua and its main source is the San Pedro River, which is a tributary of the Conchos River. The dam has a capacity of 424 Mm^3 and is considered the third most important dam in the State of Chihuahua [30,31]. The waters come under the authority of Irrigation District 005 (ID-005), which is the most important in the State and one of the largest in Mexico. The region has a semiarid climate with a maximum temperature of 41.7˚C in summer and a minimum of −14.1˚C in winter. Average annual precipitation is 294.7 mm with about 61 days of rain. Dominant winds are from the southwest. The dam is located between the great northern plains and the Sierra Madre Occidental mountain range [24,30,32].

2.1. Water Sampling

Water samples were obtained randomly. In a first step, with the help of a satellite image of the dam, the area was divided into 1-km^2 quadrants using the geographic software Google™ Earth. In a second step eight quadrants

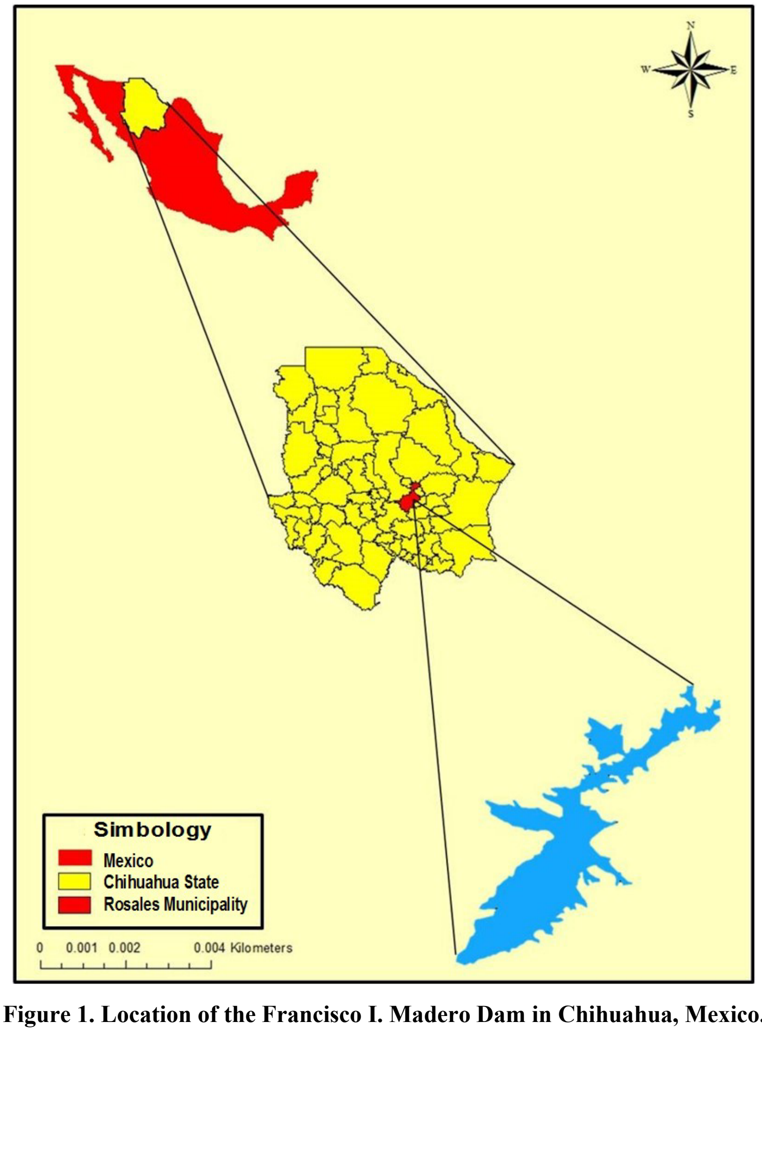

Figure 1. Location of the Francisco I. Madero Dam in Chihuahua, Mexico.

were randomly designated as sampling sites. In each sampling site, during the period of March 2011 to February 2012 monthly water samples were collected at three depths; 0.30 m, 5 m and 10 m. Water samples were obtained in 1-liter containers that were washed, sterilized and properly identified. Water samples at 5 m and 10 m were obtained with a Van Dorn bottle (Plano™). A total of 288 water samples were obtained as a product of 12 months of sampling, eight sampling sites and three depths (12 × 8 × 3). Once the samples were obtained they were kept on ice at 4˚C to be transported to the laboratory of the College of Animal Husbandry and Ecology of the Autonomous University of Chihuahua for further analysis. The water samples were collected in accordance with official Mexican standards [33].

2.2. Physical-Chemical Analysis

The following variables were evaluated *in situ*; potential hydrogen (pH), electrical conductivity (EC) and temperature (T) were measured with a Hanna instruments™ (a waterproof HI-9146 pH/CE/temp. model). Dissolved oxygen (DO) was determined with a portable Hach™ model 156, while turbidity was estimated with a turbid meter HI-93703C. Total dissolved solids (TDS) were calculated with an Oakton model waterproof/TDS/Test low. The pH level is reported in pH units, EC in $\mu\cdot Sm^{-1}$, T in Celsius degree (˚C), DO in $mg\cdot L^{-1}$, turbidity is reported in nephelometric turbidity units (NTU) and TDS in $mg\cdot L^{-1}$. The following variables were evaluated in the laboratory: total hardness (TH) was estimated by EDTA titration and the results are expressed in $mg\cdot L^{-1}$ while Chlorides (Cl^-) were determined using the Mohr method. These parameters were analyzed following Mexican government standards [34-40].

2.3. Statistical Analysis and WQI Calculation

Data analysis was carried out in two steps. In the first, an analysis of variance (ANOVA) was performed for each variable. In the second step WQI was calculated. The ANOVA for each variable considered a factorial treatment design 12 × 3 where factor A was the sampling month, with 12 levels (the sampling months) and factor B was depth, with three levels (0.30 m, 5 m and 10 m). Hence, the effects of month, depth and month-depth interaction were identified. All statistical analyses were performed using a level of significance of 0.05 ($\alpha = 0.05$). When the interaction is significant, an interaction graph is shown, while a main factor graph is shown for non-significant interactions.

The WQI was calculated following the methodology recommended by Rubio *et al*. [28] which consists of three steps and was computed only for the depth of 0.30 m. In the first step, each parameter was assigned a specific weight (Wi) in a range of 1 to 4 according to the level of importance of the parameter in determining water quality. Four represented the most important and one the least important. The Wi values were assigned as follows: pH, OD and CE were assigned 4; T and turbidity were assigned 3; TDS and TH were assigned 2; and Cl^- was assigned 1. This information is present in **Table 1**. In the second step, the results of each variable obtained previously from the ANOVA were examined independently to scrutinize the specific weights of the parameters according to a range of tolerance (Pi). Pi = 1 was assigned to the variables with values in the ideal ranges while values outside the ideal range were given Pi = 2. It is important to note that the Wi and Pi values used in the present study took into account criteria from previous studies (**Table 1**). The WQI was calculated with the following Equation (1) suggested by Rubio *et al*. [28].

$$WQI = \frac{\sum_{i=1}^{n} Pi * Wi}{\sum_{i=1}^{n} Pi} K \tag{1}$$

where:

WQI = water quality index.

Wi = specific weight of each variable (1-4).

Table 1. Value assigned for water quality parameters.

Parameters	Units	Wi*	Pi**	Range Tolerance	References
pH	-	4	1	6.5 - 8.5	[18,41,42]
			2	<6.5	
			2	>8.5	
EC	$\mu S\cdot cm^{-1}$	4	1	250 - 500	[43,44]
			2	<250	
			2	>500	
DO	$mg\cdot L^{-1}$	4	1	5 - 7	[9,41]
			2	<5	
			2	>7	
T	˚C	3	1	20 - 25	[44,45]
			2	<20	
			2	>25	
Turbidity	NTU	3	1	5 - 10	[18,42,46]
			2	<5	
			2	>5	
TDS	$mg\cdot L^{-1}$	2	1	120 - 500	[17,47]
			2	<120	
			2	>500	
TH	$mg\cdot L^{-1}$	2	1	150 - 300	[17,23]
			2	<150	
			2	>300	
Cl^-	$mg\cdot L^{-1}$	1	1	250 - 300	[42,46]
			2	<250	
			2	>300	

*Wi (Specific weight), **Pi (Range tolerance).

Pi = assigned value to each variable in base to a tolerance result (1-2).

K = constant (1; 0.75; 0.50).

K represents a constant according to the level of contamination when the sample was taken. A value of one was assigned to clear water without apparent contamination; 0.75 to water with a low level of turbidity from non-natural processes; and 0.50 to contaminated water. According to this system the samples obtained from March to June were assigned a value of one, the value of 0.50 those obtained from July to October were assigned 0.50; and those from November to February were assigned 0.75.

The calculated WQIs were then classified according to the following range: >2.5 were excellent quality water; 2.0 to 2.5 good quality water; and <2.0 poor quality water.

3. Results and Discussion

Table 2 shows the descriptive statistics of the eight variables during the sampling period. The value of the coefficient of variation (CV) demonstrates the heterogeneous concentration during the evaluation period. This variability can be explained by the presence of an atypical drought that the State of Chihuahua experienced, which was considered the most persistent in the last 50 years. **Table 3** shows the Pearson's matrix, indicating the correlation between EC and pH ($r = 0.000$), as well as OD and T ($r = 0.013$) and SDT ($r = 0.000$). Coletti *et al*. [18] reported similar results between pH and EC, while Jindal and Sharma [8] also noted a positive tendency between SDT and EC, which is comparable to our results. In addition, Rosli *et al*. [48] pointed out a strong relationship for these variables, explaining that low concentrations of EC indicate low concentrations of soluble salts. Likewise, Lai *et al*. [49] noted that there is a strong relationship between suspended solids and flooding. Therefore, it can be affirmed that our TDS and EC results could be the result of flooding caused by several tributaries of the dam under study.

3.1. Physical-Chemical Variables: pH, T, EC, DO, TDS, Turbidity, TH and Cl^-

For pH, the ANOVA detected statistical differences for the month ($P < 0.05$) and depth ($P < 0.05$) but not for the month-depth interaction ($P > 0.05$). The mean was 8.49 ± 0.03, indicating that water in this ecosystem can be classified as slightly alkaline. This result can be explained by both anthropogenic and natural processes [50,51]. The values in general are within the acceptable limits for potable water [41]. However, from **Figure 2(a)** it is evident that values were higher in July and August, which may affect the physiology of some aquatic organisms [44]. Logsdon *et al*. [52], Horvatincic *et al*. [53] and Srivastava *et al*. [17] have all noted that precipitation events increase pH levels in aquatic ecosystems due to the runoff of alkaline substances. On the other hand, low pH levels were noted in December (**Figure 2(a)**), which can be explained by the absence of agricultural activities in the region as well as reduced flows of water. Other studies in the same area, like those of Gutierrez *et al*. [25] and Rubio *et al*. [28] reported similar values.

The ANOVA for T showed statistical differences for the month ($P < 0.05$), the depth ($P < 0.05$) and the interaction between them ($P < 0.05$). **Figure 2(b)** shows the interaction effect where the general mean for T was 19.64˚C ± 0.32˚C. These values behaved consistently for a temperate zone where values are low in winter (December to February) and high in summer. It is well known that variation in temperature affects the availability of dissolved oxygen in aquatic ecosystems, because of which it is essential to know the level of this variable [4,44]. According to Moss [54] aquatic life depends on the stratification produced by temperature and light, so that different species have evolved to survive in specific temperature ranges. In other words, temperature governs the different functions of organisms, as well as the dis-

Table 2. Descriptive statistics of physiochemical parameters at eight sampling sites during the period March 2011 to February 2012 at the Francisco I. Madero Dam in Chihuahua, Mexico.

Parameter	Units	Mean	±	SE	Min	Max	CV	Quantity
pH	-	8.49	±	0.03	7.63	10.65	6.59	288
EC	$\mu S \cdot cm^{-1}$	250	±	1.35	190	320	9.01	288
DO	$mg \cdot L^{-1}$	6.27	±	0.15	1.30	12.1	38.25	264*
T	˚C	19.64	±	0.32	11.30	30	27.93	288
Turbidity	NTU	32.54	±	4.22	0	1120	219.90	288
TDS	$mg \cdot L^{-1}$	187.26	±	0.60	170	220	5.49	288
TH	$mg \cdot L^{-1}$	501.60	±	5.09	240	900	17.21	288
Cl^-	$mg \cdot L^{-1}$	27.38	±	0.93	7.28	70.34	57.38	288

*The parameter DO has only 264 samples because values were not obtained for the first month of sampling; SE: Standard Error; Min: Minimum Value; Max: Maxim Value; CV: Coefficient Variation expressed in %.

Table 3. Pearson's correlation matrix for the physicochemical parameters at the Francisco I. Madero Dam in Chihuahua, Mexico.

Parameter	pH	EC	T	DO	TDS	TH	Cl^-
EC	0.000*						
T	0.001*	0.000*					
DO	0.085	0.463	0.013*				
TDS	0.000*	0.000*	0.000*	0.000*			
TH	0.109	0.000*	0.000*	0.116	0.020*		
Cl^-	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	
Turbidity	0.090	0.001*	0.418	0.071	0.051	0.000*	0.015*

*Correlation is significant at the level of 0.05.

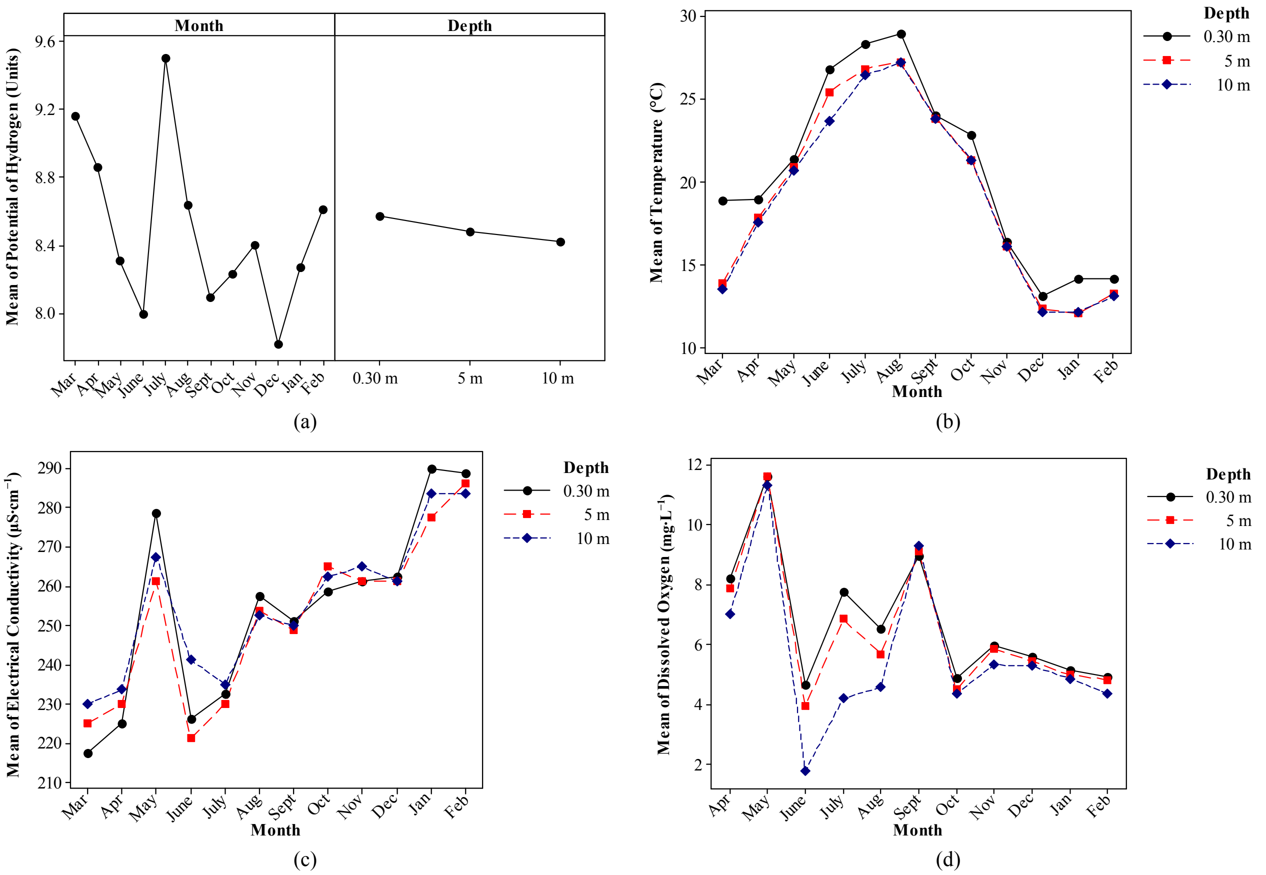

Figure 2. Levels of the parameters pH, T, EC and DO in water samples obtained in the Francisco I. Madero Dam in Chihuahua, Mexico.

tribution of their populations [55]. For instance, a drastic change in temperature can cause hepatic or skin problems in species like *Oreochromis* spp., while small changes in temperature might origin species succession [56].

There were statistical differences for the variable EC for the month ($P < 0.05$) and for the month-depth interaction ($P < 0.05$) but not for the sampling depth ($P > 0.05$). The average was 250 ± 1.35 µS·cm^{-1} which is below the standard limits proposed by Srebotnjak *et al.* [44] of <500 µS·cm^{-1}. **Figure 2(c)** presents the interaction effect. These results can be explained by the drought that occurred this year. Miyamoto *et al.* [57], Kannel *et al.* [58] and Sanchez *et al.* [20] have noted that during droughts in arid zones the accumulation of salts and other contaminates increase and as a consequence EC levels also increase. Moreover, it is well documented that EC values are good indicators that have been used to calculate WQI, especially where high EC values indicate heavy levels of inorganic contamination [2,3,28].

The DO variable was different for the month ($P < 0.05$), depth ($P < 0.05$) and the interaction between month and depth ($P < 0.05$). **Figure 2(d)** shows the interaction effect. It can be from the figure that OD levels varied according to depth, which is due to variations in temperature [44]. The average was 6.27 ± 0.15 mg·L^{-1}, which means that in relation to this variable the water is acceptable and within the permitted range of 5 - 7 mg·L^{-1} [9]. Additionally, the values indicate that water in this ecosystem can maintain aerobic organisms and plants with a good auto depurative capacity [59]. It is important to keep in mind that DO is an important indicator of the health of an ecosystem because of its effect on aquatic life and physical-biological processes [13,48,60]. OD levels are higher after precipitation events because of organic matter transported by runoff from agricultural and animal production activities in the higher areas of the watershed.

The difference in TDS was statistically significant for the month and the interaction between the month and depth (P < 0.05) but not for the depth (P > 0.05). In **Figure 3(a)** it can be noted the interaction and the values were in a range of 175.41 - 199.98 mg·L^{-1} indicating that the water is acceptable because it is within the permissible limits of 120 - 500 mg·L^{-1} [17]. Khalil *et al*. [61] specified that TDS accounts for both organic and inorganic matter present in water. Our results are lower than those reported by Contreras [62] who found an average TDS of 612 mg·L^{-1} in the Luis L. Leon Dam, which is located downstream from the dam in our study. Turbidity was statistically different for the month and depth (P < 0.05) but not for the interaction (P > 0.05). The average was 32.54 ± 4.22 NTU and the highest values were during and after the rainy season. However, in December there were higher levels that can be explained by winter precipitation levels. On the right side of **Figure 3(b)** an increase can be noted due to depth that can be explained by precipitated solids. Several authors have noted that runoff increases turbidity in aquatic ecosystems, and as a consequence, raises contamination levels [5,63-65]. Hurley *et al*. [4] established that the variable of turbidity was of relevance in calculating WQI for similar studies.

The ANOVA for TH only found statistical differences for the sampling month (P < 0.05), where the general average was 501.60 ± 5.09 mg·L^{-1}. The maximum level was in December with 606.66 ± 18.32 mg·L^{-1}, while the lowest level was in June with 444.16 ± 8.51 mg·L^{-1}. **Figure 3(c)** shows the TH found in this study. The sampled waters can be considered very hard because the ideal levels are in a range of 150 - 300 mg·L^{-1} [23]. With respect to Cl^- concentrations, the ANOVA only found sta-

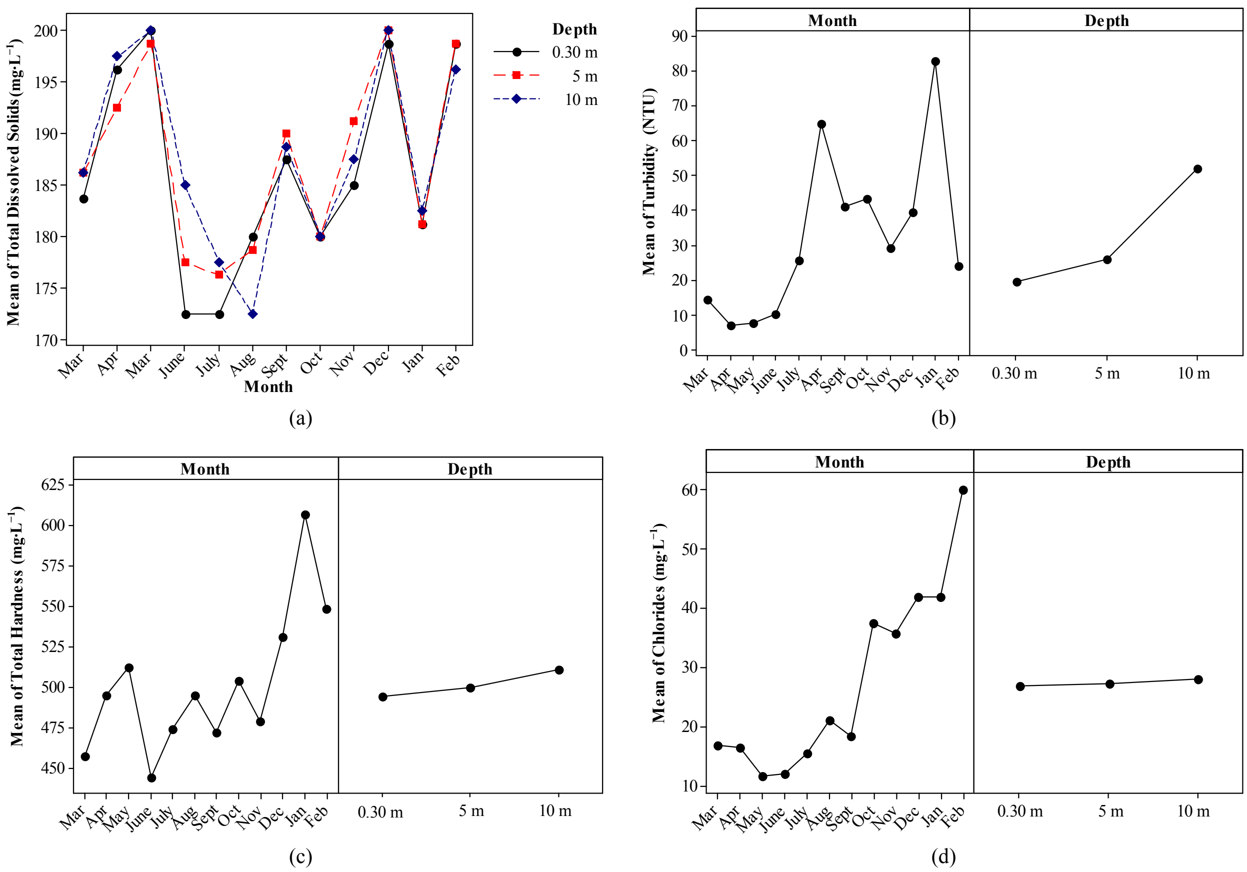

Figure 3. Levels of the parameters TDS, turbidity, TH and Cl^- in water samples from the Francisco I. Madero Dam in Chihuahua, Mexico.

tistical differences for the sampling month ($P < 0.05$), the effect of which is shown in **Figure 3(d)**, where the general average is 27.38 ± 0.93 mg·L^{-1}. The highest concentration was in February 2012 with 60.03 ± 1.43 mg·L^{-1}, while the lowest was in May with 11.62 ± 0.62 mg·L^{-1}. Jindal and Sharma [8] noted that Cl^- levels are affected by precipitation because in some cases rain contains acids or high concentrations of salts. Previous research in the same area found similar values for this variable [28, 66]. Our results indicate a good level of water for this variable given that the recommended limit is 250 mg·L^{-1} [46].

3.2. Water Quality Index (WQI)

The WQIs were different among the sampled months, with a general mean of 2.1, indicating that water from the dam can be considered acceptable. Nevertheless, during July, August and September the water was poor because the index was below 2.0. These values were observed in the rainy season, despite the severe drought affecting northern Mexico [67]. In other words, the best WQI levels were noted in the spring while the worst were in summer and autumn. The results are shown in **Table 4** and **Figures 4(a)** and **(b)**. It is important to note that variables assigned with higher Wi values presented high levels during the rainy season while DO was below the permissible limits [41]; hence, a certain level of contamination was noted [68]. Our results clearly show low water quality during the summer because in the sense that variables outside the Pi range are vulnerable, the water quality is low. Qian *et al*. [11] found an increase in the physical-chemical variables during the rainy season, and consequently low levels of water quality. This is because some rain is acidic or can have more diluted contaminants [27]. Varnosfaderany *et al*. [50] estimated a WQI for an ecosystem of an arid zone and found lower levels in August, which they attributed to agricultural activities that increase FC and DBO concentrations in water. In another study He *et al*. [16] developed a WQI in Victoria, Australia for different watersheds of semiarid areas using DO, FC and pH as the main variables. Their results showed seven watersheds as "very poor", one as "poor", one as "regular" and only one as "excellent". They attributed their results to spatial and temporal variability. Srivastava *et al*. [17] reported a decline in WQI values for the Mahi River in India before and after the rainy season. This effect was explained due to runoff that comes from agricultural and industrial zones.

Rubio *et al*. [28] developed a WQI for the Luis L. Leon Dam located in northern Mexico using physical and chemical variables. According to the calculated WQI values, these researchers classified the water as "poor" in August and November, which is the rainy season in that region. It is clear that "poor" water indicates an aquatic ecosystem with high levels of variables such as turbidity and organic matter that can represent a risk for the envi-

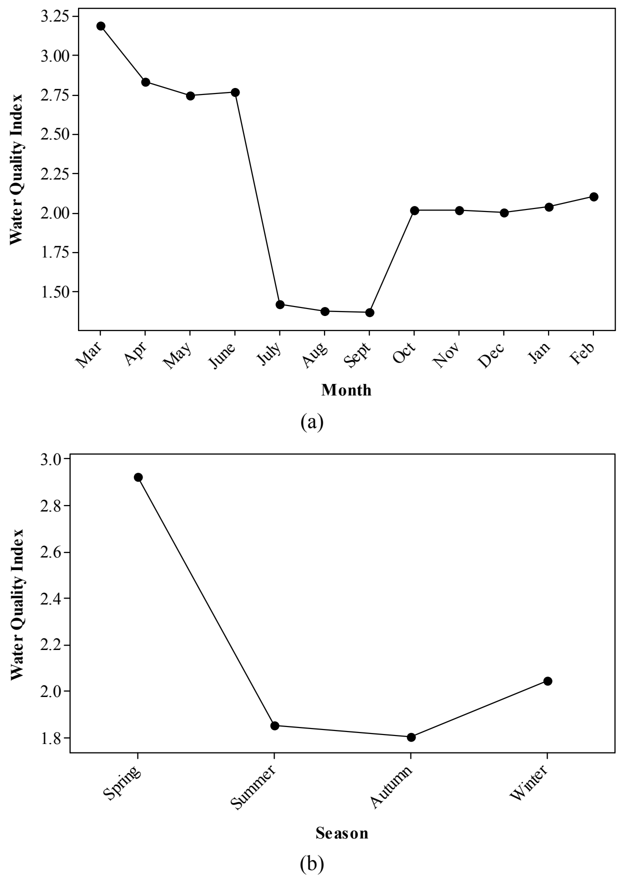

Figure 4. WQI values calculated over several months and seasons at the Francisco I. Madero Dam in Chihuahua, Mexico.

Table 4. WQI values per months at the Francisco I. Madero Dam from March 2011 to February 2012.

Month	WQI*	Water Quality
March	3.19	Excellent
April	2.84	Excellent
May	2.74	Good
June	2.77	Good
July	1.42	Poor
August	1.38	Poor
September	1.37	Poor
October	2.02	Good
November	2.02	Good
December	2.00	Good
January	2.04	Good
February	2.10	Good
Average	2.15	Good

*WQI value was determined based on the methodology employed by Rubio *et al.* [28].

ronment and human health [18].

There is strong evidence that precipitation directly affects water in aquatic ecosystems [17]. In addition, variations in WQI values are explained by both specific and general contamination, such as mining operations, industry, agriculture, livestock production and domestic activties that in turn affect water bodies [1,9,65]. Agriculture activities in particular play an important role in lowering WQI values, especially in areas where practices are inappropriate.

Our results show that the best water quality was in March and April 2011 when the water was classified as excellent (**Table 4**). Rejith *et al*. [69] also reported high WQI values in the spring. Our results demonstrate that WQI values increased in the rainy season and then declined once more to be stabilized in autumn and winter. It is important to note that in December there were few precipitation events, which explains the increase in pH levels and turbidity and as a consequence the WQI value. During the period of October 2011 to March 2012, activities in ID-005 were low and consequently runoff was also low, resulting in better quality surface waters. Wanda *et al*. [23] found acceptable levels in water during winter in an African ecosystem, while Rubio *et al*. [28] also reported good levels of water in winter.

4. Conclusion

Most parameters increased during the rainy season. The variables of turbidity and TH were beyond the permissible limits according to Mexican and international standards. The calculated WQI determined excellent water quality for the spring, good quality for autumn and winter and poor for summer. Our results show that the water of this ecosystem of this ecosystem can be used without any problem for ecological purposes as well as for fishing, agriculture and livestock production. It is highly recommend to continue monitoring water and to employ other methodologies like the WQI using additional variables.

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