Article

STUDY OF THE WATER QUALITY OF A TROPICAL RESERVOIR

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ABSTRACT: A study of the water quality of the Adolfo López Mateos Reservoir (ALMD) was developed through different indicators from a spatial and seasonal perspective. Variables related to the general characteristics of water quality, trophic level and ecological risk were assessed through the water Quality Index ($WQI_{NSF-BROWN}$), Trophic State Index ($TSI_{CARLSON}$) and the Ecological Risk Index ($RI_{HAKANSON}$). Using data from physical, chemical and biological parameters obtained from four sampling points in the ALMD, the water quality was assessed in each model used. The results indicated that the reservoir presents a water quality classified as "medium" ($WQI_{NSF-BROWN}$= 70), where significant variations in the concentrations of some parameters are observed. The reservoir showed a general trophic state classified as "Mesotrophic" ($TSI_{GENERAL-AVERAGE}$ = 43.04). The ecological risk analysis achieved the best classification of the methodology, discarding contamination by heavy metals in surface waters. Through this type of applied methodologies will help as decision making tools in the dam, as well as for application in other dams in the region.

Keywords: Tropical reservoir; water quality index (WQI); trophic state index (TSI); ecological risk index (ERI); ecological risk assessment (ERA)

1. Introduction

Water resources are dynamically influenced by several factors such as human, agricultural and industrial activities. For this reason waterbodies show a poor water quality [1]. The assessment of water quality is obtained through the study of physical, chemical and biological components, which are related to natural phenomena, human effects and their possible uses. The reservoirs play a fundamental role from the ecological point of view. Therefore, a poor water quality puts in risk the sustainability and survival of the ecosystems and their species [2, 3].

The contamination of waterbodies is commonly affected due to the increase in contaminant concentrations as a consequence of agrochemical abuse, upstream mining leachates, the use of herbicides in anti-narcotics campaigns, domestic waste and discharges of wastewaters, as well as the presence of species of aquatic lily produced by eutrophication in reservoirs [4, 5]. Contaminants entering a water body naturally or anthropogenically are retained in sediments and deposited at the bottom of these aquatic ecosystems, causing toxic effects on aquatic systems. These deposits are of a great scientific value since they retain a historical record of the type of pollution that has taken place in the surrounding areas. Besides, when the sediments interact with the surface water currents, they move the retained contaminants and alter the general dynamics of the water mass [6]. Thus, variations in pH, salinity and the properties of the redox potential can cause the mobilization and resuspension of chemical particles accumulated in the sediments, magnifying even its toxic effect, such as the case of heavy metals. Heavy metals are largely derived from anthropogenic sources, such as domestic, agricultural and industrial waste and constitute a danger to aquatic biota and human beings, as well as an environmental deterioration factor [7].

The monitoring and evaluation of water quality involve an analysis of various parameters that evidence the degree of alteration of natural variations of a waterbody. These variations are analyzed through indicators that quantify water quality for a given use from a holistic perspective [8, 9]. However, the efforts made in the literature only show applications from a specific perspective for each indicator, considering only partial diagnoses of water quality that can be affected by various sources of pollution such as eutrophication or contamination by heavy metals. Different mathematical tools are proposed in order to integrate indicators that show a broader diagnosis through the application of multiparameter indicators in tropical water bodies. One of them is the Water Quality Index (WQI), which represents a numerical classification involved in the decision making of water resources to diagnose the spatial and temporal variation of contaminants and facilitating the treatment and analysis of a large amount of data [10, 11]. The most commonly method used for the computation of the WQI is the one proposed by Brown and the NSF (National Sanitation Foundation) [12-15].

Another tool is the Trophic State Index (TSI), which is used to define the trophic status of a waterbody. The Carlson TSI considers the annual average values of transparency by using the depth of Secchi disk, surface concentrations of total phosphorus and chlorophyll-α [16-18]. Finally, the Ecological Risk Index (ERI), developed by Håkanson [19], is used to calculate the toxicity coefficient of various metallic elements [20-23]. The integration of metric tools in the evaluation of the water quality allows extending the assessment of water quality of aquatic ecosystems from several perspectives [24].

Multiparametric studies in water bodies show a broader picture than works that only consider water quality parameters analyzed in insolation. Due to the scarce information in the implementation of various indices in tropical water bodies, this work aims to undertake a comprehensive study of water quality by implementing the WQI, TSI and ERI indexes, considering physical, chemical and biological parameters, those concerning to eutrophication and some that represent ecological risk for the Adolfo López Mateos Reservoir (ALMD).

2. MATERIALS Y METHODS

2.1. .Study area

Adolfo López Mateos (ALMD) is located in the state of Sinaloa to the north of Mexico (25° 05' 25" North Latitude and 107° 23' 00" West Longitude). ALMD is one of the most important tropical reservoirs in the region and contributes to the water supply for the production of agricultural foods, being the region with the largest export in the country. This reservoir is the largest in surface extension (11.354 Ha) and has a conservation capacity of 3.087 Mm^3. Therefore, this reservoir is essential for irrigating the most important agricultural valley in Mexico [25]. The modification of the environment by the construction of hydraulic systems for the control of avenues, logging and accelerated deforestation, construction of roads, dismantling and diversion of currents can change the water quality of the reservoir [26].

This work was carried out using data provided by the National Water Commission of Mexico (government agency which is the watershed operator). This information was obtained every six months in ALMD through the National Monitoring Network. For this work, the physicochemical and biological data consisting of the period of 2012-2017 were used. The monitoring was conducted biannually at 4 sampling points of the ALMD (Figure 1). The sampling, transportation and preservation of samples were carried out in accordance with standard methods. The samples were analyzed in an accredited laboratory by the Mexican Accreditation Entity, based on international standard methods for water analysis [27].

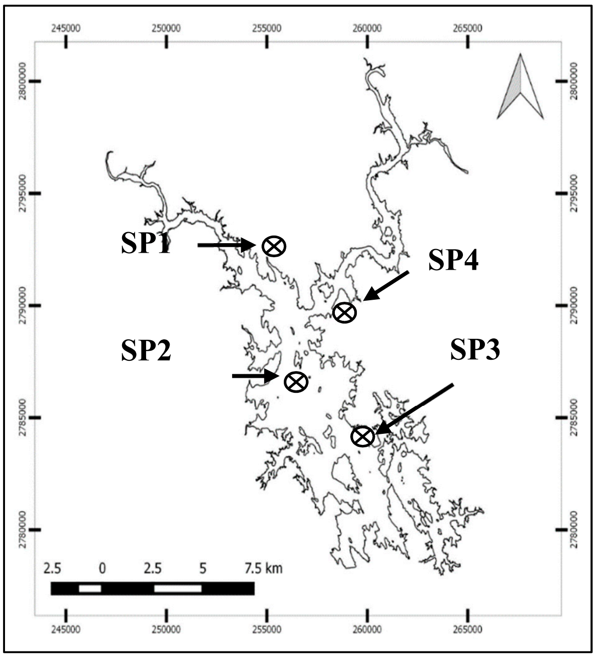

Figure 1. Sampling points of the PALM.

2.2. Water Quality Index

To simplify the interpretation of the physicochemical and biological parameters of ALMD, the NSF-brown Water Quality Index ($WQI_{NSF-BROWN}$) was used [28]. The $WQI_{NSF-BROWN}$ showed the water quality state of the reservoir by using the averages of the concentrations obtained from 9 parameters of water quality for seven years (2012-2017) in 4 sampling points (SP1-SP4). A linear mathematical model (Equation 1) was used in order to calculate $WQI_{NSF-BROWN}$. This model involves the use of nine water quality parameters: Fecal coliforms (FC), Biochemical oxygen Demand (BOD_5), nitrates (NO_3), phosphates (PO_4-), hydrogen potential (pH), dissolved oxygen (DO), total dissolved solids (TDS), temperature (Tem) and turbidity (Tur). Weights (w_i) were assigned for each parameter and the quality distributions (Sub_i) were used based on the established by the aforementioned methodology.

$$WQI_{NSF-BROWN} = \sum_{i=1}^{9}(Sub_i * w_i) \tag{1}$$

Where w_i is the relative weight assigned to each parameter weighted between 0-1. The sum of the 9 weights must be equal to 1 (Table 1). The value Sub_i represents the score obtained as a function of water quality parameter. This value depends on the probability distribution for each parameter.

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The mean value of each water quality parameter represents a score between 0 and 100. The higher the score is, the better the quality of water. The index result was classified according to the scale proposed by the National Sanitation Foundation (NSF) (Excellent = 91-100; Good = 71-90; Fair = 51-70; Marginal= 26-50; Poor = 0-25) [28].

Table 1. Water quality variables used in the WQINSF-BROWN calculation.

Parameter	Units	Weight (wi)
FC	CFU/100 mL	0.15
pH	pH units	0.12
BOD_5	mg/L	0.1
NO_3^-	mg/L	0.1
PO_4^-	mg/L	0.1
Tem	°C	0.1
Tur	NTU	0.08
TDS	mg/L	0.08
DO	mg/L	0.17

2.3. Trophic State Index

The criteria for evaluating eutrophication in a waterbody consider the analysis of nutrient concentrations, the amount of chlorophyll a (Chla) and total phosphorus (TP), as well as the transparency (Tra) with Secchi Disk [29, 30]. The classification of trophic state is based on the nutrient that represents a primary production limitation. In most of the cases, the limiting nutrient is phosphorus in waterbodies, in particular in those located in tropical regions [11, 31-33]. The evaluation of eutrophication in ALMD was carried out using the Carlson Trophic State Index [34] ($TSI_{CARLSON}$). The scale of the $TSI_{CARLSON}$ varies between 0-100, where; $TSI_{CARLSON} < 30$ = oligotrophic, $30 < TSI_{CARLSON} < 60$ = Mesotrophic, $60 < TSI_{CARLSON} < 90$ = eutrophic and $90 < TSI_{CARLSON} < 100$ = hypertrophic. $TSI_{CARLSON}$ is obtained by calculating the mathematical equations established in Equations 2 to 5 using the mean values of the parameters that compose the index; Transparency (TSI_{Tra}) determined by measuring the Secchi Disk depth, while chlorophyll concentration (TSI_{Chla}) and Total Phosphorus (TSI_{TP}) were carried out using standard methodologies [27]. Ln is the calculation of the natural logarithm.

$$TSI_{Chla} = 9.81\ Ln\ [Chla\ \left(\frac{mg}{L}\right)] + 30.6 \tag{2}$$

$$TSI_{Trans} = 60 - 14.4\ Ln\ [Tra\ (m)] \tag{3}$$

$$TSI_{TP} = 14.42\ Ln\ [TP\ \left(\frac{mg}{L}\right)] + 4.15 \tag{4}$$

$$TSI_{CARLSON} = \frac{[TSI_{Chla} + TSI_{Tra} + TSI_{TP}]}{3} \tag{5}$$

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2.4. Ecological Risk Index

The pollution produced by high levels of heavy metals in water bodies has been a major concern for the scientific community because of the impact of toxicity levels on aquatic ecosystems ecology [35, 36]. The content of harmful metals in the water increases significantly due to the discharge of industrial waste, the combustion of fossil fuels, domestic wastewater, water transport and agricultural irrigation [37]. An ecological risk assessment is the process used to verify how the environment is affected as a result of exposure to one or more environmental stressors such as chemicals, land change, disease, invasive species and climate change [38]. When an aquatic ecosystem is exposed to contaminants, waterbodies should be analyzed from various components, including physical, chemical and biological parameters, and the amount of metals influenced by some hydrological factors such as dispersion, advection and dilution or by some geochemical processes such as adsorption-desorption, precipitation and diffusion [39]. In this study, the Ecological Risk Index (ERI) was used as a fast and practical tool for environmental risk assessment in ALMD. This methodology is proposed by Håkanson [19] and suggests the classification of contamination in a waterbody and the identification of the toxic substances in order to take actions for the control and mitigation of this contamination [40-42]. Ecological Risk Index is based on the Equations 6 and 7:

$$RI_{\text{HÅKANSON}} = \sum_{i=1}^{5} Er^i = \sum_{i=1}^{5} Tr^i * C_f^i \tag{6}$$

$$C_d = \sum_{i=1}^{5} C_f^i = \sum_{i=1}^{5} \frac{\bar{C}^i{}_{0-1}}{C_n^i} \tag{7}$$

Where RIHAKANSON is the ERI presented by the waterbody, Er^i the factor of the potential ecological risk and Tr^i the toxic response factor of a given substance (i = mg/L). ERI is defined as the sum of all the risk factors (Er^i). On the other hand, it is also necessary to calculate the degree of pollution (C_d) by obtaining the factor of pollution of each metal (C_f^i). This factor is obtained by the ratio between the mean concentration of the metal ($\bar{C}^i{}_{0-1}$) and the reference concentration given by the Standard Preindustrial Impact (C_n^i) (Table 2).

Table 2. Rating scale for Er^i and RI_{HAKANSON}.

$Er^{i.}$	**Potential ecological risk for substance**
< 40	Low
$40 \leq Er^i < 80$	Moderate
$80 \leq Er^i < 160$	Considerable
$160 \leq Er^i < 320$	High
≥ 320	Very high
RI	**Ecological risk for lake/basin**
< 150	Low
150 ≤ RI < 300	Moderate
300 ≤ RI < 600	Considerable
RI ≥ 600	Very high

For the calculation of each Tr^i value, the equations of the toxic-response of the methodology were considered (HG = 40 * 5/BPI, Cd = 30 * √ 5/√ BPI, As = 10, Pb = Cu = 5 and Cr = 2 * √ 5/√ BPI. Each C_f^i was obtained by dividing the mean concentration of the heavy metals ($\bar{C}^i{}_{0-1}$), where the reference values given by the methodology (C_n^i) were: Hg = 0.25, Cd = 1.0, As = 15, Pb = 70 and Cr = 90).

3. RESULTS AND DISCUSSION

3.1. Selection of parameters

ALMD is under the supervision of the national militia to safeguard the integrity of the reservoir with the support of CONAGUA, which is the operator responsible for the control of facilities and the monitoring of the water quality parameters. The water quality data were analyzed from a temporal and spatial perspective studying the behavior of the parameters for the determination of each index. By integrating components that define the health of reservoirs using multiparameter measurements from various perspectives, a better diagnosis is obtained in the extension of the water quality assessment. Unlike recent classical non-multiparameter studies that only evaluate WQI, TSI and ERI from a specific point of view [43-45], the proposed multiparametric study opens the gap by considering a panorama that deepens the understanding of those natural intrinsic processes or anthropogenic that impact on the quality of reservoir water over time from a global context. Due to the nulls efforts to integrate multiparameter parameter analysis tools, a series of physical, chemical and biological parameters (Table 3) were used for the computation of $WQI_{NSF-BROWN}$. Aspects related to the eutrophication of the reservoir were addressed in $TSI_{CARLSON}$ and the toxicity of some heavy metals was assessed through the ecological risk analysis ($RI_{HÅKANSON}$). A Pearson correlation analysis was also carried out to identify the degree of correlation between variables with respect to the water quality of ALMD. The bold numbers represent the variables that had more significant correlation ($P < 0.05$) (Table 4).

Table 3. Parameters of water quality used in the ERA.

Ecological indexes	Parameter	Units	Temporal variation average						Spatial variation average				Mean	Max value	Min value	Standard deviation
			2012	2013	2014	2015	2016	2017	SP1	SP2	SP3	SP4				
WQI$_{\text{NSF-BROWN}}$	FC	CFU/100 mL	206	2127	221	598	127	992	729	661	851	759	834	5794	1	1275.5
	pH	pH units	7.58	7.37	7.76	7.71	8.26	9.25	8.05	7.98	8.07	8.01	7.91	9.5	7.07	0.62
	BOD_5	mg/L	6.02	2.66	5.38	3.03	2.0	3.46	3.63	3.64	3.53	3.43	3.45	9.7	2	2.3
	NO_3^-	mg/L	0.01	0.24	0.04	0.02	0.01	0.02	0.07	0.07	0.04	0.07	0.06	0.59	0.001	0.15
	PO_4^-	mg/L	0.04	0.03	0.02	0.03	0.01	0.02	0.03	0.03	0.02	0.02	0.02	0.09	0.001	0.02
	Tem	°C	32.4	31.2	29.1	28.8	30.7	29.2	29.9	30.1	29.8	30.1	29.69	33.8	24.5	2.73
	Tur	NTU	2.1	22.1	1.8	1.6	2.2	3.3	6.5	8.9	2.5	5.4	6.31	74	0.88	13.10
	TDS	mg/L	119	117	147	97	109	101	119	116	111	115	115	156	82	21.45
	DO	mg/L	3.65	5.07	7.28	6.77	9.63	9.90	7.50	7.20	7.54	7.22	7.3	12.1	2.93	2.62
TSI$_{\text{CARLSON}}$	Chla	mg/m^3	2.4	18.1	4.03	12.7	4.2	3.5	8.5	7.62	11.3	6.07	9.2	37.3	0.05	9.5
	Tra	m	2.4	0.63	1.8	2.7	1.12	1.39	1.51	1.65	1.71	1.62	1.6	3.4	0.4	0.86
	TP	mg/L	0.07	0.25	0.06	0.08	0.10	0.04	0.10	0.11	0.09	0.11	0.11	0.52	0.02	0.12
RI$_{\text{HÅKANSON}}$	As	mg/L	0.0014	0.0028	0.0023	0.0014	0.0014	0.0036	0.0014	0.0032	0.0014	0.0022	0.0020	0.0127	0.0014	0.0024
	Cd	mg/L	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	1.37E-19
	Cr	mg/L	0.0003	0.0067	0.0003	0.0003	0.0011	0.0003	0.0014	0.00153	0.00181	0.0022	0.0017	0.0154	0.0003	0.0037
	Hg	mg/L	0.0001	0.0005	0.0001	0.0002	0.0001	0.0001	0.00016	0.00016	0.0003	0.00015	0.00019	0.0013	0.0001	0.00025
	Pb	mg/L	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	8.78E-19

Table 4. Pearson correlation matrix for water quality parameters.

Parameter	**Chla**	**Tra**	**TP**	**FC**	**BOD$_5$**	**NO$_3^-$**	**pH**	**TDS**	**DO**	**PO$_4^-$**	**Tur**
Tra	-0.0714										
TP	0.1035	**-0.3557**									
FC	0.1865	**-0.4641**	**0.5241**								
BOD$_5$	-0.0096	**0.3272**	-0.1678	-0.1757							
NO$_3^-$	0.1508	**-0.3848**	**0.89**	**0.6818**	-0.0806						
pH	-0.1622	-0.2232	**-0.3966**	0.0392	-0.213	**-0.3271**					
TDS	-0.2484	-0.0968	-0.031	-0.1798	0.2839	0.0908	**-0.3352**				
DO	-0.2632	-0.1937	-0.174	-0.1482	-0.1767	-0.2293	**0.7597**	**-0.3385**			
PO$_4^-$	**0.3632**	**0.3133**	**0.3395**	0.1128	0.2151	**0.4045**	-0.2635	0.0561	**-0.3643**		
Tur	0.1846	**-0.4621**	**0.7583**	**0.826**	-0.0798	**0.8493**	-0.2597	0.0237	-0.2985	0.2702	
Tem	-0.1783	-0.2145	0.1391	-0.0985	-0.3134	0.0526	**-0.3628**	**0.4309**	**-0.4706**	-0.0406	0.0617

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3.2. Water Quality Index

To calculate the WQI$_{NSF-BROWN}$, each subscript (Sub_i) of the nine parameters that compose the methodology [28] was calculated through the probability distributions that express the water quality related to the concentration means obtained each year (Table 5) and for each sampling point (SP) (Table 6). The value obtained from probability distribution (Sub_i) was multiplied by the weight (W_i). WQI$_{Value}$ (Sub_i*w_i) was calculated for each parameter and these values were added ($\sum$ WQI$_{Value}$) to calculate the WQI$_{NSF-BROWN}$ (Table 7).

Table 5. Determination of ICA$_{value}$ by year.

Year	Sub	Parameters								
		FC	pH	BOD$_5$	NO$_3^-$	PO$_4^-$	Tem	Tur	TDS	DO
2012	Sub_{2012}	83.89	100	30.12	100	100	10	94.48	65.47	17.42
	$Sub_{2012}*w_i$	12.58	12	3.01	10	10	1	7.56	5.24	2.96
2013	Sub_{2013}	*12.49*	100	58.85	100	100	10	62.21	66.24	45.34
	$Sub_{2013}*w_i$	1.87	12	5.89	10	10	1	4.98	5.30	7.71
2014	Sub_{2014}	82.65	100	34.22	100	100	10	96.8	56.65	77.56
	$Sub_{2014}*w_i$	12.40	12	3.42	10	10	1	7.74	4.53	13.19
2015	Sub_{2015}	56.90	100	54.67	100	100	12.14	99.22	73.68	71.34
	$Sub_{2015}*w_i$	8.54	12	5.47	10	10	1.21	7.94	5.89	12.13
2016	Sub_{2016}	90.78	87.38	67.12	100	100	10	93.26	69.08	96.81
	$Sub_{2016}*w_i$	13.62	10.49	6.71	10	10	1	7.46	5.53	16.46
2017	Sub_{2017}	38.5	52.28	50.14	100	100	10	87.15	71.99	98.04
	$Sub_{2017}*w_i$	5.78	6.27	5.01	10	10	1	6.97	5.76	16.67

Table 6. Determination of WQI$_{value}$ by sampling point (SP).

SP		Parameters								
		FC	pH	BOD$_5$	NO$_3^-$	PO$_4^-$	Tem	Tur	TDS	DO
SP1	Sub_{SP1}	49.97	97.44	48.50	100.00	100.00	10.00	77.31	65.79	80.02
	$Sub_{SP1}*w_i$	7.50	11.69	4.85	10.00	10.00	1.00	6.19	5.26	13.6
SP2	Sub_{SP2}	53.42	100.00	48.50	100.00	100.00	10.00	73.11	66.81	76.64
	$Sub_{SP2}*w_i$	8.01	12.00	4.85	10.00	10.00	1.00	5.85	5.35	13.03
SP3	Sub_{SP3}	44.26	96.43	49.48	100.00	100.00	10.00	91.49	68.46	80.46
	$Sub_{SP3}*w_i$	6.64	11.57	4.95	10.00	10.00	1.00	7.32	5.48	13.68
SP4	Sub_{SP4}	48.51	100	52.32	100.00	100.00	10.00	78.77	67.12	76.05
	$Sub_{SP4}*w_i$	7.28	12.00	5.23	10.00	10.00	1.00	6.30	5.37	12.93

Table 7. Temporal and spatial TSI of ALMD.

Parameters	**Temporal variation**						**Spatial variation**			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**SP1**	**SP2**	**SP3**	**SP4**
TSI$_{Chla}$	**39.53**	**59.01**	**44.27**	**55.60**	**44.69**	**42.93**	**51.65**	**50.53**	**54.44**	**48.29**
TSI$_{Tra}$	**47.31**	**66.48**	**51.53**	**45.23**	**58.30**	**55.24**	**54.02**	**52.73**	**52.26**	**53.00**
TSI$_{TP}$	**22.38**	**40.31**	**19.68**	**24.53**	**26.88**	**14.54**	**27.46**	**28.52**	**26.37**	**28.01**
TSI$_{CARLSON}$	**36.41**	**55.27**	**38.50**	**41.79**	**43.29**	**37.57**	**44.37**	**43.92**	**44.36**	**43.10**
TSI$_{SPATIAL-AVERAGE}$	**43.94**									
TSI$_{TEMPORAL-AVERAGE}$	**42.14**									
TSI$_{GENERAL-AVERAGE}$	**43.04**									

The mean spatial (SP1-SP4) and temporal (2012-2017) variations of the WQI$_{NSF-BROWN}$ classify the water quality of ALMD as ¨medium¨ (WQI$_{NSF-BROWN}$ =70) (Table 7). The superficial reservoirs that have a "medium" classification for water quality present a moderate increase in the concentration of pollutants [46]. In the temporal variation, fluctuations of the WQI$_{NSF-BROWN}$ of 59-81% are observed during the 6 year period of study. This significant variation is due to the significant increase in the mean values of CF (2127 CFU/100 mL), Tur (22.18 NTU) and DO (5.07 mg/l). The best water quality was observed in 2016, with a $WQI_{NSF-BROWN}$ of 81 (CF = 127 CFU/100 mL, Tur = 3.34 NTU and DO = 9.63 mg/L) (Table 3). The presence of high warm temperatures significantly influences the decrease in the score for the sub_i, both in the lower condition found (2013; Tem = 31.28 °C) as the highest one (2016; Tem = 30.7 °C) (Table 3). From a temporal point of view, a significant variation was observed in this study (2016 $WQI_{NSF-BROWN} = 81$; 2017 $WQI_{NSF-BROWN} = 67$), which is attributed to the increase in the concentrations of FC (992 CFU/100 mL) and BOD_5 (3.46 mg/L) (Table 3). In years 2012 ($WQI_{NSF-BROWN} = 64$), 2013 ($WQI_{NSF-BROWN} = 59$) and 2017 ($WQI_{NSF-BROWN} = 67$), water quality of ALMD was classified as "medium", while in 2014 ($WQI_{NSF-BROWN} = 74$), 2015 ($WQI_{NSF-BROWN} = 73$) and 2016 ($WQI_{NSF-BROWN} = 81$), this reservoir showed a "Good" water quality (Table 7). NO_3^- showed a variation of 0.01-0.24 mg/L and $PO_4^-$of 0.01-0.04 mg/l (Table 3). The parameters with the highest value of sub_i during the period of study were pH and Tur, with a mean value of 89.94% and 88.85%, respectively. On the other hand, the lower mean percentages were attributed to Tem (10.35%), BOD_5 (49.18%), FC (60.86%) and TDS (67.18%) (Table 5).

Water quality index values ($WQI_{NSF-BROWN}$) ranged from 70 to 71 (Table 7) in the four sampling points. A slight increase in the concentrations of FC was observed in the four sampling points (Table 3). The reservoir showed a homogeneous distribution of contaminants in the 4 sampling points for BOD_5 parameters (3.25-3.63 mg/L) and TDS (111-119 mg/L). Warm temperatures were also observed in AMLD, ranging from 29.79 to 30.05 °C (Table 3). Due to the homogeneous behavior of water quality parameters from a spatial point of view, the water quality was maintained as "medium" classification according to Brown et al., [28]. On the other hand, due to the decrease of Tur (2.54 NTU) and TDS (111 mg/L), and the increase of OD concentration (7.54 mg/L) (Table 3), the reservoir was classified as "Good" in SP3 (Table 7). Turbitidy and TDS are related to the dissolved solids and particulate matter. Therefore, a reduction of these parameters increases the penetration of sunlight that originates the photosynthetic processes and the balance of primary productivity, improving the health conditions in the oxygenation of the reservoir [47]. The reservoirs classified in the category "Good" represent suitable conditions for the proper functioning of the ecosystem and the trophic chain [48]. The variables with the highest score in the spatial evaluation are attributed to NO_3-and PO_4. Values of 100% were found for the sub_i of each sampling point. This situation could be related to the low levels of these nutrients found in AMLD.

In AMLD, the main pollutants distributed along the water body correspond to particulate matter originated by organic material and toxic inorganics coming from natural or anthropogenic activities [49]. This type of contaminants that are scattered evenly in the four sampling points and with significant variations in the temporal evaluation are regulated by the diffusion-advection processes [50]. In this way, the spatial and temporal analysis show that the parameters with the most significant changes in the index are due to the variation of the concentration of FC, BOD_5, Tur, TDS and Tem. On the other hand, the parameters that showed the highest scores in the sub_i obtained were; NO_3-and PO_4-, with concentrations less than 0.24 mg/L and 0.04 mg/L, respectively (Table 3).

3.3. Trophic State Index

The mean concentrations of Chla and TP, and the Tra values were used to obtain the $TSI_{CARLSON}$ (Table 8) by using the Eq. 2 – Eq. 5 [51]. According to these equations, the trophic level of ALMD is "Mesotrophic" ($30 < TSI_{CARLSON} < 60$). Spatial ($TSI_{SPATIAL-AVERAGE} = 43.94$) and temporal ($TSI_{TEMPORAL-AVERAGE} = 42.14$) values are consistent with this classification. A spatial analysis showed that $TSI_{CARLSON}$ does not present significant variation between the four sampling points analyzed. These values oscillated between 43.10 and 44.37, with a difference of 1.27%. Chla is a key biochemical component in the cellular process of biomass production through the consumption of nutrients (nitrogen and

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phosphorus) responsible for the photosynthesis process [52, 53]. The variation of Chla was from 6.07 to 11.3 mg/m^3, with a significant increase of 46% in this concentration between samples points SP3 and SP4. The values of Tra varied between from 1.51 to 1.71 m (Table 3). A positive Pearson correlation was observed between Chla and PO_4, (Table 4). Despite the high variation of Chla, low concentrations of TP (0.09 – 0.11 mg/L) and NO_3-(0.04 – 0.07 mg/L) were observed (Table 3). This situation limited the overproduction of biomass from the reservoir, which explains the slight variation observed for the spatial Trophic Status Index: SP4 (43.10) < SP2 (43.92) < SP3 (44.36) < SP1 (44.37). The trophic status of AMLD at each sampling point is mainly attributed to; TSI_{Tra} (53) > TSI_{Chla} (51.22) > TSI_{TP} (27.59).

Table 8. Temporal and spatial evaluation of $WQI_{NSF-BROWN}$ in ALMD.

Parameters	Temporal variation						Spatial variation			
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**SP1**	**SP2**	**SP3**	**SP4**
FC	12.58	1.87	12.40	8.54	13.62	5.78	7.50	8.01	6.64	7.28
pH	12	12	12	12	10.49	6.27	11.69	12	11.57	12
BOD_5	3.01	5.89	3.42	5.47	6.71	5.01	4.85	4.85	4.95	5.23
NO_3^-	10	10	10	10	10	10	10	10	10	10
PO_4^-	10	10	10	10	10	10	10	10	10	10
Tem	1	1	1	1.21	1	1	1	1	1	1
Tur	7.56	4.98	7.74	7.94	7.46	6.97	6.19	5.85	7.32	6.3
TDS	5.24	5.3	4.53	5.89	5.53	5.76	5.26	5.35	5.48	5.37
DO	2.96	7.71	13.19	12.13	16.46	16.67	13.60	13.03	13.68	12.93
$WQI_{NSF-BROWN}$	64	59	74	73	81	67	70	70	71	70
$WQI_{SPATIAL-AVERAGE}$	70									
$WQI_{TEMPORAL-AVERAGE}$	70									
$WQI_{GENERAL-AVERAGE}$	70									

On the other hand, the temporal variation showed that the year with the highest incidence in the index occurred in 2013 ($TSI_{CARLSON} = 55.27$), with a difference of 18.86% compared with the highest score; 2012 ($TSI_{CARLSON} = 36.41$). The lowest values of TSI_{Chla} (59.01), TSI_{Tra} (66.48) and TSI_{TP} (40.31) were obtained in 2013, while the optimal values are attributed to 2012 ($TSI_{Chla} = 39.53$), 2015 ($TSI_{Tra} = 45.23$) and 2017 ($TSI_{TP} = 14.54$). PT showed significant correlation ($p < 0.05$) with FC (0.5241), NO_3-(0.89), pH (-0.3966), PO_4-(0.3395) and Tur (0.7583), while Tra was significantly correlated with PT (-0.3557), FC (-0.4641), BOD_5 (0.3272), NO_3-(-0.3848), PO_4-(0.3133) and Tur (-0.4621) (Table 4). TP is often correlated with Tra and therefore, a doubling in the TP concentration is attributed to a reduction of half the depth of Secchi Disk. A similar behavior is observed for Chla [34]. Thus, the increase in concentrations of some pollutants related to nitrogenous and phosphorous compounds, as well as biodegradable particulate matter and bacteria, increase the turbidity in the water [54]. The increase of turbidity prevents biochemical processes of natural self-purification, which needs the solar light [49]. The main contaminants that indirectly influence the trophic status of ALMD are due to diffuse sources attributed to productive activities generated in the region as livestock (FC = 2127 CFU/100 mL), biodegradable and non-biodegradable particulate material product of soil erosion and vegetation deforestation ($BOD_5 = 6.02$ mg/L), as well as the use of fertilizers in agriculture (NO_3-= 0.24 mg/L) that originate the turbidity in the water of ALMD (Tur = 22.1 NTU) (Table 3). A high positive significant correlation between FC and Tur (0.826) and a medium correlation between FC and NO_3- were found in this study. This last correlation could be explained as following: these bacteria are thermotolerant fecal coliform organisms and are responsible for performing biochemical metabolism to degrade organic matter and produce the nitrogen by releasing NO_3-in water [55]. The coliform density in ALMD during 2012 (206 CFU/100 ml) and 2013 (2127 CFU/100 ml) increased the presence of NO_3- from 0.01 to 0.24 mg/L from 2012 to 2013 (Table 3).

3.4. Ecological Risk Index

The degree of pollution (C_d) of a substance is determined by calculating the pollution factor (C^i_f) for each heavy metal analyzed (Table 9). Subsequently, the potential ecological risk factor (Er^i) was calculated to quantitatively express the temporal and spatial response of ALMD by means of Ecological Risk Index (*RI*) (Table 10).

Table 9. Determination of ERI in ALMD.

Parameter	Tr^i	**Degree of contamination (C_d)**		
		Temporal (2012-2017)	**Spatial (SP1-SP4)**	**General**
As	15	0.00086	0.00054	0.00140
Cd	1	0.0012	0.0008	0.0020
Cr	90	0.0001	0.00007	0.00017
Hg	0.25	0.0044	0.0030	0.0074
Pb	70	0.00012	0.00008	0.00021

Table 10. Determination of *RI* in ALMD

Parameter	**Temporal variation**						**Spatial variation**			
$(Tr_r^i * C_f^i)$	2012	2013	2014	2015	2016	2017	SP1	SP2	SP3	SP4
As	0.0009	0.0018	0.0015	0.0009	0.0009	0.0024	0.0009	0.0021	0.0009	0.0014
Cd	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060
Cr	0.000007	0.00014	0.000007	0.000007	0.00002	0.000007	0.00003	0.00001	0.00004	0.00005
Hg	0.016	0.08	0.016	0.032	0.016	0.016	0.0256	0.0256	0.048	0.024
Pb	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
$\sum Er^i$	0.0230	0.0881	0.0236	0.0390	0.0230	0.0245	0.0326	0.0338	0.0550	0.0316
RI_{SPATIAL}	0.1530									
RI_{TEMPORAL}	0.2212									
RI_{GENERAL}	0.3742									

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Each pollution factor (C^i_f) was multiplied by the toxic Response (Tr^i) (Eq. 6 and Eq. 7) (Table 10). The average of the data concentrations show that: Hg (0.00019 mg/L) < Cd (0.0002 mg/L) < Pb (0.0015 mg/L) < Cr (0.0017 mg/L) < As (0.0020 mg/L) (Table 3). Temporal and spatial evaluation also showed that Hg was the heavy metal with the highest importance in Ecological Risk Index (Hg = 0.0044 > Cd = 0.0012 > Cr = Pb = 0.0001 > As = 0.00086). Cr and Pb represent a major toxic (Tr^i) response between the heavy metals analyzed, their concentration in ALMD was low.

The result of Er^i shows that there is a greater potential risk factor in 2013 than the ones observed in others years (2013 = 0.0881 > 2015 = 0.0390 > 2017 = 0.0245 > 2012 = 2016 = 0.0230). From a spatial point of view, the SP4 site presents a slightly lower value (0.0316) followed by SP1 (0.0326) < SP2 (0.0338) < SP3 (0.0550). However, the ecological risk potential of each substance was found below the "Low" classification (Er^i < 40) in both evaluations (temporal and spatial assessment). The general Ecological Risk Potential Index ($RI_{GENERAL}$) of ALMD was 0.3742. The results obtained for AMLD reservoir are well, and below the lower category in the classification "Low" (RI < 150). This classification represents very low threat for ALMD due to pollution caused by heavy metals.

4. CONCLUSIONS

In this study, the application of ecological indexes was carried out for obtaining a diagnosis in an integrated way about the water quality, trophic status and the ecological risk for heavy metals pollution of ALMD, a tropical reservoir with greater agricultural importance in Mexico. This assessment was carried out from a spatial and temporal point of view that can be applied in other dams of the region, even in dams of other countries that present characteristics similar to those of the study area. The implementation of the indexes identified the most significant parameters, based on their importance for each model used. This type of applied methodologies related to multiparametric integrative analysis helps as a global decision making tools unlike non-multiparameter studies, that only consider a part of the components that define water quality in reservoirs. According to the results, it was obtained that the ALMD reservoir presents a WQINSF-BROWN = 70, classifying the water quality of the reservoir as "medium". This reservoir is affected mainly by the organic biodegradable material (BOD5), diffuse fecal contamination (FC) and dissolved particulate matter (TDS), which cause variations in water turbidity (Tur). Trophic state of ALMD reservoir is located in the category of "Mesotrophic", with a TSIGENERAL-AVERAGE = 43.04. The parameter that most affected the score of the TSI index was transparency, followed by chlorophyll-a and finally the phosphorus as a limiting nutrient. Because the reservoir showed low concentrations of AS, Cd, Cr, Hg, and Pb, ALMD did not present a potential ecological risk. Heavy metals concentrations found in the reservoir do not represent a negative effect or endanger to the health of the reservoir and needed in order to discard the ecological risk assessment in a broader manner. However, they are studies are also needed on the heavy metals accumulated in the sediments to discard the ecological risk assessment in a broader way. Finally, based on the results obtained in this study, it was concluded that the water of ALMD is suitable for agricultural use.

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