Limnetica, 41(2): 269-279 (2022). DOI: 10.23818/limn.41.16

AIL

Seston and eutrophication on a tropical karst lake district: Lagunas de Montebello, Chiapas, Mexico

Mariana Vargas-Sánchez[1], Javier Alcocer[2,*] and Luis A. Oseguera[2]

[1] Programa de Posgrado en Ciencias del Mar y Limnología. Universidad Nacional Autónoma de México, Ciudad de México, México.
[2] Grupo de Investigación en Limnología Tropical, FES Iztacala, Universidad Nacional Autónoma de México, Tlalnepantla, México.

[*] Corresponding author: jalcocer@unam.mx

Received: 16/02/21 Accepted: 14/06/21

ABSTRACT

Seston and eutrophication on a tropical, karst lake district: Lagunas de Montebello, Chiapas, Mexico

Large quantities of seston are among the most important indicators of eutrophication in aquatic ecosystems. The present study aimed to elucidate the role seston plays in the general limnological dynamics of a cluster of eighteen tropical karstic lakes with different anthropic impacts (non-impacted, oligotrophic, clear-water lakes, and impacted, eutrophic, turbid-water lakes) of the "Lagunas de Montebello" National Park lake district. The seston concentration was measured twice, in the warm/rainy and the cold/dry season. Vertical profiles of temperature, dissolved oxygen, electrical conductivity, pH, and photosynthetic active radiation (PAR) were recorded at each lake. Water samples were taken along the water column to evaluate seston and chlorophyll *a* (Chl-*a*) concentration. Impacted lakes displayed higher seston (4.1-21.0 mg/L) and Chl-*a* (8.1-129.8 µg/L) concentrations, reduced euphotic zone (Z_{EU} = 2.6-6.3 m), and superficial thermo- (gradient = 0.8 ± 0.2 °C/m) and oxyclines (gradient = 4.7 ± 2.4 mg DO/m). Non-impacted lakes had lower seston (1.0-2.1 mg/L) and Chl-*a* (0.4-5.2 µg/L) concentrations, wide Z_{EU} (10.1-33.4 m), and deeper thermo- (gradient = 0.5 ± 0.1 °C/m) and oxyclines (gradient = 0.6 ± 0.4 mg DO/m). The changes reported in impacted lakes linked with the increase in the seston and Chl-*a* concentrations are most likely related to the eutrophication process associated with anthropogenic activities (agriculture, urban development, land-use change) in the NW part of the area. This research highlights the fragility of the tropical karst lake ecosystems worth protecting to preserve the aquatic ecosystem's health.

Key words: eutrophication, seston, chlorophyll, karst lakes, tropical lakes

RESUMEN

Seston y eutrofización en un distrito lacustre tropical kárstico: Lagunas de Montebello, Chiapas, México

La presencia de grandes cantidades de seston es uno de los indicadores más importantes de eutrofización en los ecosistemas acuáticos. El presente estudio tuvo como objetivo dilucidar el papel que juega el seston en la dinámica limnológica general de un grupo de dieciocho lagos kársticos tropicales con diferente impacto antrópico (lagos oligotróficos de agua clara no impactados y lagos de agua turbia eutrófica impactados) del distrito lacustre "Parque Nacional Lagunas de Montebello". La concentración de seston se midió dos veces, en las estaciones cálida/lluviosa y fría/seca. En cada lago se registraron perfiles verticales de temperatura, oxígeno disuelto, conductividad eléctrica, pH y radiación fotosintéticamente active (PAR, por sus siglas en inglés). Se tomaron muestras de agua a lo largo de la columna de agua para evaluar la concentración de seston y clorofila a *(Clor-*a*). Los lagos impactados mostraron las concentraciones más altas de seston (4.1-21.0 mg/L) y Clor-*a *(8.1-129.8 µg/L), zona eufótica reducida (Z_{EU} = 2.6-6.3 m) y termo- (∇T = 0.8 ± 0.2 °C/m) y oxiclinas (∇OD = 4.7 ± 2.4 mg OD/m) superficiales. Los lagos no impactados tuvieron las concentraciones más bajas de seston (1.0-2.1 mg/L) y Clor-*a *(0.4-5.2 µg/L), Z_{EU} anchas (10.1-33.4 m), y termo (∇T = 0.5 ± 0.1 °C/m) y oxiclinas (∇OD = 0.6 ± 0.4 mg OD/m) más profundas. Los cambios reportados en los lagos impactados se asocian con el aumento en las concentraciones de seston y Chl-*a*, *probablemente relacionado con un proceso de eutrofización fomentado por las actividades antropogénicas (agricultura, desarrollo urbano, cambio de uso de la tierra) en la parte noroeste del área. Esta investigación destaca la fragilidad de los* *ecosistemas de lagos kársticos tropicales que vale la pena proteger para preservar la salud ecosistémica.*

Palabras clave: *eutrofización, seston, clorofila, lagos kársticos, lagos tropicales*

INTRODUCTION

As most inland aquatic ecosystems worldwide, karst lakes have not escaped from water pollution and eutrophication. Although the mechanisms and effects of eutrophication on karst lakes have been studied in temperate regions (e.g., Špoljar et al., 2007; Mikac et al., 2011; Zutinić et al., 2014), tropical karst aquatic ecosystems are still poorly known. The warmer temperatures and humidity, both characteristic of the tropical climate, intensify these ecosystems' vulnerability to human activities (e.g., tropical storms and floods), favoring the dispersion of contaminants among nearby lakes (Alcocer et al., 2018).

Karst zones occupy about 20 % of the planet's surface and, in many regions, karst aquifers are the primary source of drinking water supply (Ford & Willliams, 2007). In Mexico, karstic areas cover more than 15 % of the national territory and host the most significant continental wetlands (Mora et al., 2016). The "Lagunas de Montebello" National Park (LMNP) is probably the most important karstic ecosystem in México. The LMNP takes its name from its karstic lake district (CONANP, 2007). It was declared a National Park based on its abundant hydric resources (surface and underground) surrounded by an extensive forested area. The LMNP is important for migratory and resident birds that use the wide variety of habitats, especially its wetlands recognized as a Ramsar Site, as well as for being the refuge for numerous species of small mammals, amphibians, reptiles and insects with restricted distribution. The favorable conditions (e.g., National Park, RAMSAR site, high biodiversity, aquatic resources) of the LMNP granted its designation as one of the Mexican water reserves by CONAGUA-WWF-Fundación Gonzalo Río Arronte Alliance (CONAGUA, 2011) that guarantee the flows for ecological protection, in the terms of the National Water Law. Changes have occurred in some lakes on the NW portion (i.e., from transparent blue to turbid greenish-yellow waters, the presence of white-yellowish supernatant, disgusting odors, and fish mortalities) from 2003 onwards. The deterioration of these aquatic ecosystems commenced with the increasing anthropic activities in the area like landscape fragmentation for agriculture, accelerated soil erosion, and water pollution (fertilizers, organic matter, solid residues) (SEMARNAT, 2008). The lakes serve, among other uses, as a drinking water source for the local inhabitants.

The distribution of seston (particles > 0.45 µm suspended in the water column) (Wetzel & Likens, 2000) results from the interaction of biological (production and decomposition) and physical processes (Callieri et al., 1991). Seston could be 1) lithogenic allochthonous (e.g., clays, volcanic material), 2) biogenic allochthonous (e.g., pollen, leaves, and branches), 3) lithogenic autochthonous (e.g., resuspension of sediments from the bottom and the littoral zone of lakes) or 4) biogenic autochthonous (e.g., phytoplankton production) (Lenz, 1977; Peng et al., 2004).

Seston is one of the main signals of eutrophication in water bodies (Lenz, 1977). In aquatic ecosystems, light is rapidly attenuated as depth increases (absorption and scattering) (Wetzel & Likens, 2000) and, subsequently, transformed into heat energy (Westlake, 1965). Thus, seston in aquatic ecosystems largely determines the depth of the euphotic or productive zone [Z_{EU}; the zone where there is enough photosynthetically active radiation (PAR) for photosynthesis].

There are few studies on the dynamics of seston and its effects on karst ecosystems (e.g., Špoljar et al., 2007; Alcocer et al., 2018; Han et al., 2018). Therefore, this work aimed to elucidate the role of seston in the general limnological dynamics of the LMNP lakes, particularly on the penetration of light and, consequently, on their thermal structure. Likewise, it was sought to recognize the changes in seston concentration, light penetration, and thermal structure in impacted (turbid water) lakes compared to non-impacted (clear water) ones.

This limnological information is a useful descriptive tool to evaluate the ecosystem health of these lakes. We hypothesize that if the lakes' changes originate from anthropic activities, the seston concentration in impacted lakes, largely biogenic, would be significantly higher than in non-impacted lakes, constituting a clear indicator of the alteration that occurred in the LMNP lakes. Higher seston concentration will modify the light penetration and the thermal structure of impacted lakes.

METHODOLOGY

Study Area

Our investigation was carried out in the LMNP, at the southeast region of the State of Chiapas, Mexico (16° 04' - 16° 10 'N and 91° 37' - 91° 47' W, 1500 m a.s.l) (Fig. 1 and Table 1). The total area of the LMNP is 6425 ha (CONANP 2011). The LMNP belongs to the sub-basin of the *Rio Grande de Comitán-Lagos de Montebello*. The lake district is surface fed by the *Rio Grande de Comitán*, which runs through urban and agricultural areas before flowing into the lakes. However, the primary source is groundwater. The karst system complex develops on sedimentary sequences of outcrops of marine-transitional limestone, dolomite rocks, and limestone-shale (Vázquez & Méndez, 1994; Mora et al., 2016). Limestone or river and lake sediments characterize soils in the LMNP. Predominant soils are leptosols, extremely gravelly with a high tendency to erosion.

Climate [Cb(m)(f)ig] is temperate rainy, with a long, cool, and humid summer, with a typical summer precipitation regime (García, 2004). The mean annual temperature and precipitation are 18.67 °C and 1960 mm, respectively (CONANP Automatic Meteorological Weather Station No. N15DA7496, at 16° 06' 52.5 N, 91° 43' 48.2 W).

There are more than 60 karst lakes along the regional fault and fracture system NW-SE oriented. Durán Calderón et al. (2014) divided the lakes into two groups: a) plateau lakes at the NW and b) mountain lakes at the SE. Mountain lakes are slightly higher in altitude, surrounded by forest, mostly groundwater-fed and, surface isolated. Plateau lakes are surrounded by agricultural areas, feed superficially by the *Rio Grande de Comitán* but also groundwater-fed and interconnected through a network of canals built for transportation purposes (Alcocer et al., 2018).

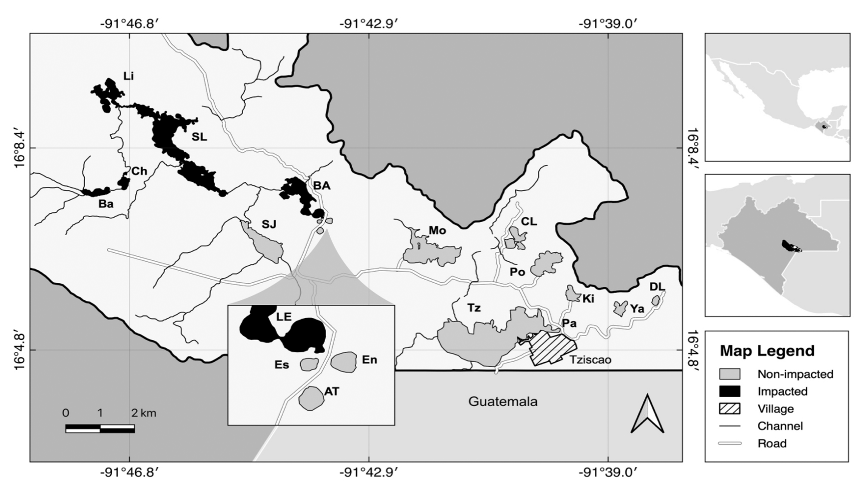

Figure 1. The "Lagunas de Montebello" National Park, Chiapas, Mexico. The lakes in this study are marked in black (impacted lakes) and grey (non-impacted lakes). The analysis was carried out including all the water bodies under study. *Parque Nacional "Lagunas de Montebello", Chiapas, México. Los lagos en estudio están marcados en negro (lagos impactados) y gris (lagos no impactados).*

Table 1. Geographical location of the LMNP lakes under study and their main geomorphological characteristics (Alcocer et al., 2016, Durán Calderón et al. (2014). (Z_{MAX} = maximum depth, Z_{MEAN} = mean depth, GC = Geomorphological classification, P = plateau lakes, M = Mountain lakes, S = Status, NI = non-impacted, I = impacted). *Ubicación geográfica de los lagos del PNLM en estudio y sus principales características geomorfológicas (Alcocer et al., 2016, Durán Calderón et al. (2014). (Z_{MAX} = profundidad máxima, Z_{MEAN} = profundidad media, GC = clasificación geomorfológica, P = lagos de planiecie, M = lagos de montaña, S = Estado, NI = no impactado, I = impactado).*

Lake	Label	Location Lat (N)	Long (W)	Alt (m a.s.l.)	Z_{MAX} (m)	Z_{MEAN} (m)	Area (ha)	GC	S
Balantetic	Ba	16°07’31.8”	91°47’35.5”	1466	3	1.7	13.6	P	I
Chaj Chaj	Ch	16°07’53.4”	91°46’58.8”	1426	12	5.3	9.2	P	I
Liquidambar	Li	16°09’01.8”	91°46’52.3”	1461	24	11.2	40.5	P	I
San Lorenzo	SL	16°07’32.2”	91°45’11.2”	1455	67	11.8	181.3	P	I
San José	SJ	16°06'34.0”	91°44'29.2”	1454	30	10.3	60.6	P	NI
Bosque Azul	BA	16°07’7.1”	91°43’44.4”	1458	58	20.0	52.5	P	I
La Encantada	LE	16°07’08.1”	91°43’37.2”	1454	89	29.4	8.2	P	I
Esmeralda	Es	16°07’03.4”	91°43’39.2”	1461	7	3.6	1.1	M	NI
Ensueño	En	16°07’02.3”	91°43’29.6”	1430	35	21.6	2.7	M	NI
Agua Tinta	AT	16°06'25.5"	91°41'19.8”	1465	24	14.7	3.0	M	NI
Montebello	Mo	16°06'32.0"	91°40'57.5”	1490	45	12.3	96.2	M	NI
Cinco Lagos	CL	16°06’35.6”	91°40’20.6”	1486	162	42.5	23.7	M	NI
Pojoj	Po	16°06'22.2”	91°40'03.3”	1499	198	35.2	43.7	M	NI
Kichail	Ki	16°05’39.5”	91°39’25.2”	1475	2	9.5	12.5	M	NI
Tziscao	Tz	16°04'59.0”	91°40'46.8”	1490	86	28.9	306.6	M	NI
Patianú	Pa	16°05’06.”	91°39’45.7”	1484	26	10.8	3.4	M	NI
Yalalush	Ya	16°05'30.3”	91°38'47.8”	1452	23	9.9	11.5	M	NI
Dos Lagos	DL	16°07’02.3”	91°43’29.6”	1427	42	25.2	5.2	M	NI

Environmental characterization

We selected 18 water bodies, including plateau and mountain lakes, which were *a priori* classified into non-impacted (blue, clear water) lakes (*Agua Tinta*, *Cinco Lagos*, *Dos Lagos*, *Ensueño*, *Esmeralda*, *Kichail*, *Montebello*, *Patianú*, *Pojoj*, *San José*, *Tziscao*, and *Yalalush*), and impacted (green, turbid water) lakes (*Balantetic*, *Bosque Azul*, *Chaj Chaj*, *La Encantada*, *Liquidambar*, and *San Lorenzo*) (Table 1). Most lakes are deep, warm monomictic (thermally stratified in summer and circulate in winter), while a few shallow, warm polymictic (Alcocer et al., 2016). Sampling was performed in the warm/rainy season (May 2014, summer, stratification) and in the cold/dry season (February 2015, winter, circulation) to better represent the expected maximum differences in lakes' hydrodynamics then in seston concentration and vertical distribution.

Physical and chemical parameters measured in the LMNP lakes were temperature (T), dissolved oxygen (DO), electrical conductivity (K_{25}), pH, and PAR. The measurements were conducted at the central and most profound part of each lake with a Hydrolab DS5 multiparameter water quality sonde (T, DO, K_{25}, and pH) and a Biospherical PNF-300 profiling natural fluorometer (PAR). Position, width (top/ceiling and bottom/floor), and T gradient (∇T) was calculated for each thermocline. The mixing layer (Z_{MIX}) was estimated according to the vertical profiles of T and DO. The Z_{EU} was estimated from the surface down to the depth at which PAR reach 0.1 % of PAR at the surface (SPAR) (Palmer et al., 2013).

Seston and chlorophyll-*a*

Between one and five water samples were taken along the water column, depending on each lake's maximum depth, with a 5 L UWITEC water sample bottle. Water samples of each depth (800 in turbid waters to 1200 ml in clear waters) were filtered through previously prepared (dry and pre-weighted) GF/F Whatman filters (47 mm diameter, 0.7 µm of nominal pore opening). Seston was obtained gravimetrically after filter desiccation to 60 °C for 24 h (Weyhenmeyer, 1997; Wetzel & Likens, 2000; Jellison & Melack, 2001), with a Mass Comparator Balance (Mettler Toledo).

Water samples for chlorophyll-*a* (Chl-*a*) concentration analysis were filtered through Whatman filters (GF/F, nominal pore opening of 0.7 µm). After filtration, the pigments were extracted with 90 % acetone at 4 °C overnight. Subsequently, the samples were centrifuged, and the fluorescence of the supernatant was measured in a Turner Designs 10-AU fluorometer (EPA method 445.0, Arar & Collins, 1997).

Since phytoplankton contributes a substantial proportion to the total mass of seston in an aquatic body and this presents a close relationship to the dynamics of Particulate Organic Carbon (POC) (Jellison & Melack 2001, Punning et al., 2003), the POC was taken as the equivalent of the organic fraction of seston (S_O). Equation (1) could be used to derive POC empirically from available Chl-*a* data (Legendre & Michaud, 1999):

$$log\,[POC] \approx 1.3 + 0.5\,log\,[POC_{phyto}] \approx 1.3 + 0.5\,log\,[Chl\text{-a}] \quad (1)$$

The difference of the seston concentration minus the POC concentration (eq. 2) was employed to estimate the proportion of inorganic (S_I) and organic material in the seston concentration as follows:

$$S_I = seston - POC \quad (2)$$

Statistical analysis

The physicochemical variables (T, DO, pH, K_{25}, and Z_{EU}) were transformed into another set of new intercorrelated variables through a principal component analysis (PCA). The analysis was performed with each variable's average value for each lake and each sampling season. The PCA revealed the internal data structure and detected data clusters (groups), outliers, and trends.

Subsequently, the group, season, and its interaction effects were tested by two-way ANOVA analyses. ANOVA was performed following an F distribution ($\alpha < 0.05$). The multiple pairwise-comparisons were performed by Tukey HSD tests. Finally, we evaluated the linear correlation between seston and Z_{EU} logarithmically transformed data to promote linearity in the two variables' relationship. All statistical analyzes were run with R Core Team (2016).

RESULTS

Environmental characterization

The samplings were carried out in May 2014 (warm/rainy) and February 2015 (cold/dry). During the warm/rainy season, the mean atmospheric T was 18.9 ºC and the mean precipitation was 238.4 mm. During the cold/dry season, the mean atmospheric T was 15.35 ºC and precipitation was 77.4 mm. The mean T in water was 20.1 ± 1.4 °C during the warm/rainy season. 14 lakes presented thermal stratification, while four (Ba, Ch, Es, and Ya) were circulating. During the cold/dry season, the average T in water was 18.3 ± 0.9 °C, and all lakes showed homogeneous temperatures throughout the entire water column indicating

Table 2. Physical and chemical parameters in four groups of LMNP, Chiapas, Mexico. (IS = impacted shallow, ID = impacted deep, NIS = non-impacted shallow and NID = non-impacted deep, X = mean, S.D. = standard deviation, - = no data available, * = entire water column). *Parámetros fisicoquímicos de los cuatro grupos de lagos del PNLM, Chiapas, México. (IS = impactado somero, ID = impactado profundo, NIS = no impactado somero y NID = no impactado profundo, X = media, S.D. = desviación estándar, - = no hay valor disponible, * = toda la columna de agua).*

Warm/rainy season														
Group	**T (°C)**		**DO (mg/L)**		**K_{25} (µS/cm)**		**pH (units)**		**Z_{EU} (m)**		**Z_{MIX} (m)**		**Chl-a (µg/L)**	
	X	**S.D.**	**X**	**S.D.**	**X**	**S.D.**	**X**	**S.D.**	**X**	**S.D.**	**X**	**S.D.**	**X**	**S.D.**
IS	23.0	0.4	4.3	1.2	670	23	7.5	0.1	2.6	1.1	7.5	6.4	29.9	17.2
ID	19.9	0.73	2.0	0.8	680	244	7.3	0.1	3.5	0.6	5.3	1.5	8.1	7.2
NIS	22.1	1.9	5.8	0.1	307	50	7.6	0.1	10.1	4.3	15.0	11.3	0.4	0.2
NID	20.6	1.1	4.5	1.4	317	201	7.6	0.2	33.4	21.3	14.0	7.1	2.2	4.5
Cold/dry season														
Group	**T (°C)**		**DO (mg/L)**		**K_{25} (µS/cm)**		**pH (units)**		**Z_{EU} (m)**		**Z_{MIX} (m)**		**Chl-a (µg/L)**	
	X	**S.D.**	**X**	**S.D.**	**X**	**S.D.**	**X**	**S.D.**	**X**	**S.D.**	**X**	**S.D.**	**X**	**S.D.**
IS	19.4	1.8	13.0	7.2	986	58	8.7	0.1	-	-	3.5*	2.5	129.8	26.3
ID	17.6	0.3	7.5	9.0	589	148	8.0	0.1	6.3	3.3	16.5*	8.2	20.0	26.7
NIS	18.4	0.8	6.7	0.41	339	50	8.2	0.0	23.0	-	6.8*	4.5	0.4	0.3
NID	18.2	0.7	6.4	1.4	328	188	8.2	0.3	28.0	12.2	20.2*	13.3	5.2	14.6

the lakes were circulating. The DO concentration ranged from 0 (i.e., below the detection limit) to 25.7 mg/L with an average of 4.0 ± 1.7 mg/L in the warm/rainy season. All lakes exhibited anoxia except Es and Ya, indicating they were circulating. In the cold/dry season, the DO concentration was in a range of 0 to 18.2 mg/L with an average of 7.2 ± 4.4 mg/L.

According to the thermal dynamics, the lakes were separated into two groups: warm monomictic (14 deep lakes: AT, BA, CL, DL, En, LE, Ki, Li, Mo, Pa, SJ, SL, Po, and Tz) and warm polymictic (4 shallow lakes: Ba, Ch, Es, and Ya).

The PCA allowed us to identify two different lakes groups: non-impacted and impacted. This classification matched well with the *a priori* two-group characterization: transparent/blue (non-impacted) and turbid/green (impacted) lakes. The first two principal components account for 82.8 % and 73.0 % of the total variance for the warm/rainy and cold/dry seasons, respectively. The analysis showed that DO and pH had the strongest correlation with the first component and T and Chl-*a* with the second one during the warm/rainy season (Fig. 2). On the other hand, during the cold/dry season, Chl-*a* and K_{25} had the strongest correlation with the first component and pH and Z_{EU} with the second one. However, the most useful variable for identified differences is Z_{EU} and Chl-*a* concentration.

This classification criterion, added to the classification by thermal dynamics (deep and shallow), allowed us to separate the eighteen lakes into four groups; a) impacted deep (ID) b) impacted shallow (IS), c) non-impacted deep (NID), and d) non-impacted shallow (NIS), and thus identify differences between them.

The pH was alkaline and similar (Table 2) in the four groups ($F_{(3,26)} = 1.94$, $p = 1.14$), but the difference between seasons was significant ($F_{(3,26)} = 79.19$, $p < 0.05$) with the cold/dry season having higher values.

K_{25} was higher (Table 2) in the impacted (IS and ID) lakes than in the non-impacted (NIS and

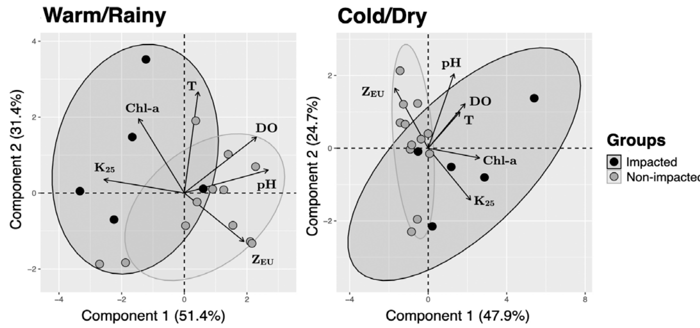

Figure 2. Two-dimensional representation of the PCA for the water quality variables [water temperature (T), dissolved oxygen (DO), pH, electric conductivity (K_{25}), euphotic zone (Z_{EU}) and, chlorophyll-*a* (Chl-*a*)] for the warm/rainy season (left) and the cold/dry season (right). The analysis was carried out including all the water bodies under study. *Representación bidimensional del ACP para las variables fisicoquímicas [temperatura del agua (T), oxígeno disuelto (OD), pH, conductividad eléctrica (K_{25}), zona eufótica (Z_{EU}) y clorofila* a *(Chl-*a*)] durante la estación cálida/lluviosa (izquierda) y la estación fría/seca (derecha). El análisis se realizó incluyendo todos los cuerpos de agua en estudio.*

NID) lakes ($F_{(3,26)} = 10.87$, $p < 0.05$) in both seasons. Although the K_{25} was higher in the cold/dry than in the warm/rainy season there were no significant differences ($F_{(3,26)} = 0.28$, $p = 0.60$).

Z_{EU} in non-impacted lakes (NIS and NID) was > 13 m, while in impacted lakes (IS and ID) was < 4 m in both seasons (Table 2). In general, the impacted lakes presented Z_{EU} values about five times lower in contrast to the non-impacted ones ($F_{(3,26)} = 7.38$, $p < 0.05$), which showed greater transparency in their waters. The difference between sampling seasons was not significant ($F_{(1,26)} = 0.003$, $p = 0.95$).

NID lakes displayed wider (19.0 ± 16.9 m) thermo- and oxyclines at greater depth (4-25 m) than ID lakes. This group showed a ∇T of 0.5 ± 0.1 °C/m and a ∇DO of 0.6 ± 0.4 mg DO/m. This group also recorded a deep (9-70 m) and wide (21.6 ± 11.36 m) halocline with a ∇K_{25} of -0.1 ± 0.07 µS cm^{-1} m^{-1}.

The ID lakes showed shallow (0-1 m) and wide thermo/oxyclines (6.0±2.0 m and 4.0±1.7 m, respectively) in the warm/rainy season. In ID lakes, the ∇T and ∇DO in the metalimnion were 0.8 ± 0.2 ºC/m and 3.9 ± 2.4 mg DO/m, respectively. Despite showing homothermic profiles, the ID lakes presented anoxic bottom in the cold/dry season. These lakes also showed a superficial (0-6 m) and narrow (6.6 ± 3.6 m) halocline with a gradient of 0.2 ± 0.5 µS cm^{-1} m^{-1}.

Table 3. The concentration of seston (mg/L) during warm/rainy season and cold/dry season in the different established groups of the LMNP (X = mean, S.D. = standard deviation). *Concentración de seston (mg/L) durante la temporada cálida/lluviosa y fría/seca en los diferentes grupos establecidos del PNLM (X = media, S.D. = desviación estándar).*

Group	Seston (mg/L) Warm/rainy X	Warm/rainy S.D.	Cold/dry X	Cold/dry S.D.
IS	21.0	4.2	11.0	0.5
ID	5.2	1.7	4.1	2.5
NIS	1.5	0.9	1.0	0.7
NID	2.1	1.8	1.8	1.7

Z_{MIX} was higher in impacted than non-impacted lakes, the difference between groups was significant ($F_{(3,26)} = 3.13$, $p < 0.05$). Z_{EU}:Z_{MIX} ratio was > 1 in the NID lakes, < 0.7 in ID and NIS lakes and, < 0.4 in IS lakes during the warm/rainy season. During the cold/dry season, the Z_{MIX} comprises the entire water column due to the mixing process.

Chl-*a* concentration in IS lakes showed the highest values while NIS lakes presented the lowest ones. The Chl-*a* concentration was different

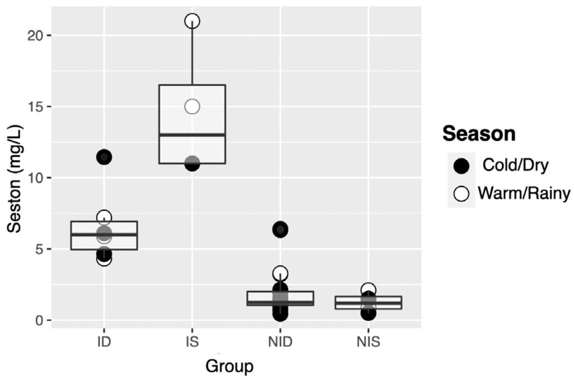

Figure 3. Scatter and boxplots of in the four preset groups. (IS = impacted shallow, ID = impacted deep, NIS = non-impacted shallow and NID = non-impacted deep). The difference between sampling seasons was not significant (black and white points, $F_{(1,26)} = 1.39$, $p = 0.25$) but there were significant differences between the established groups ($F_{(3,26)} = 50.69$, $p < 0.05$). *Diagramas de caja y dispersión de la concentración de seston en los cuatro grupos preestablecidos. (IS = impactado somero, ID = impactado profundo, NIS = no impactado somero y NID = no impactado profundo). No existen diferencias significativas entre temporadas de muestreo (puntos blancos y negros, $F_{(1,26)} = 1.39$, p = 0.25) pero si entre los grupos establecidos ($F_{(3,26)} = 50.69$, p < 0.05).*

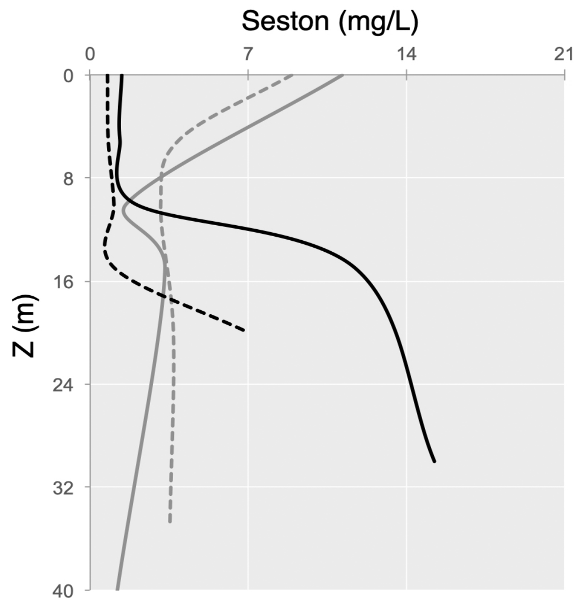

Figure 4. Vertical distribution of seston in NID lakes (black) and ID lakes (grey) during warm/rainy (solid line) and cold/dry season (dotted line). *Distribución vertical de seston en lagos NIP (negro) y lagos IS (gris) durante la estación cálida/lluviosa (línea continua) y la estación fría/seca (línea punteada).*

between groups and seasons so, the interaction between factors was significant ($F_{(3,26)} = 68.54$, $p < 0.05$).

Seston concentration in IS lakes ranged 15.0-21.0 mg/L and 10.9-11.2 mg/L in the warm/rainy and cold/dry season, respectively, with no significant ($F_{(1,26)} = 1.39$, $p = 0.25$) differences between seasons (Table 3). In general, this group showed the highest seston concentrations ($F_{(1,26)} = 59.82$, $p < 0.05$, Fig. 3).

Seston concentration in ID lakes ranged from 4.3 to 7.2 mg/L in the warm/rainy season and 4.6 to 11.5 mg/L in the cold/dry season, with no significant ($F_{(1,26)} = 1.65$, $p = 0.2$) differences between seasons (Table 3). The maximum seston concentration was close to the surface (Fig. 4). ID lakes showed lower concentrations than IS lakes ($F_{(1,26)} = 12.23$, $p < 0.05$, Fig. 3).

NIS lakes exhibited seston concentrations between 0.9 and 2.1 mg/L in the warm/rainy season (Fig. 3), while during the cold/dry season, the concentrations ranged from 0.5 to 1.5 mg/L with a homogeneous vertical profile (variation < twice the value of SD). There were no significant differences between seasons ($F_{(1,27)} = 1.39$, $p = 0.25$, Fig 3 and Table 3). NIS lakes presented the lowest seston concentrations of the LMNP lakes.

Seston concentration in NID lakes ranged from 0.7 to 6.3 mg/L in the warm/rainy season and 0.4 to 6.4 mg/L in the cold/dry season (Table 3). These lakes displayed the maximum concentration close to the bottom (Fig. 4). NID lakes showed higher seston concentrations compared than NIS lakes ($F_{(1,26)} = 12.23$, $p < 0.05$, Fig. 3), without significant differences between seasons ($F_{(1,26)} = 1.39$, $p = 0.25$).

There was a significant correlation between seston and Chl-*a* [warm/rainy season, seston = 0.47(Chl-*a*) + 1.62, $R^2 = 0.82$; cold/dry season, seston = 0.076(Chl-*a*) + 2.00, $R^2 = 0.71$; Fig 5], and between seston and Z_{EU} [warm/rainy season, $Log_{10}Z_{EU} = -0.06(seston) + 1.39$, $R^2 = 0.50$; cold/dry season, $Log_{10}Z_{EU} = -0.1(seston)+1.53$, $R^2 = 0.72$; Fig 5] in both seasons.

During the warm/rainy season the $Seston_I$ predominated in the four groups of lakes (Ses-

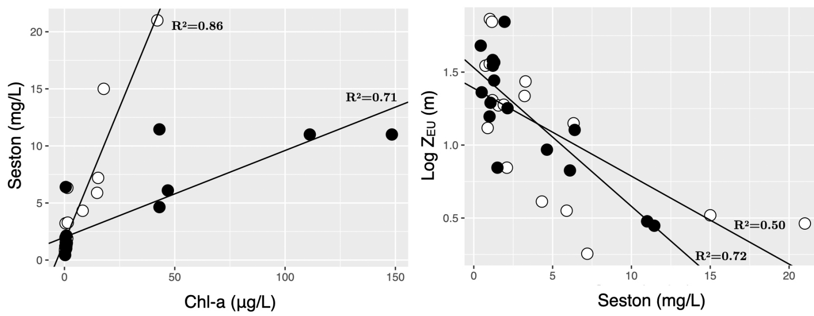

Figure 5. Linear correlations between the Chl-*a* and seston concentration (left) and the seston concentration and the depth of the Z_{EU} (right) throughout warm/rainy (white points) and cold/dry (black points) season. *Correlaciones lineales entre la concentración de Chl-*a *y seston (izquierda) y la concentración de seston y la profundidad de la* Z_{EU} *(derecha) durante la estación cálida/lluviosa (puntos blancos) y fría/seca (puntos negros).*

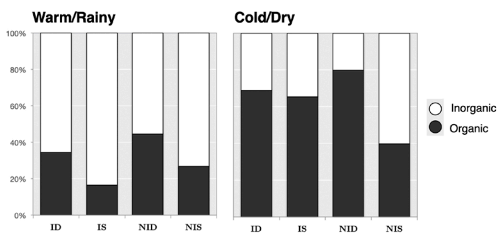

Figure 6. Percentage contribution of inorganic (white) and organic (black) material in the total composition of the seston in the four groups studied (IS = impacted shallow, ID = impacted deep, NIS = non-impacted shallow, and NID = non-impacted deep) during the two sampling seasons. *Contribución porcentual del material inorgánico (blanco) y orgánico (negro) en la composición total del seston en los cuatro grupos estudiados (IS = impactado somero, ID = impactado profundo, NIS = no impactado somero y NID = no impactado profundo), durante las dos temporadas de muestreo.*

ton_I:$Seston_O$ > 1). The IS lake group was the one with the highest ratio $Seston_I$:$Seston_O$ = 5.01 (Fig. 6). On the other hand, during the cold/dry season the $Seston_O$ predominated in three of the four groups of lakes ($Seston_I$:$Seston_O$ < 1), only in the NIS lakes did the SI predominate (Seston_I:$Seston_O$ > 1, Fig.6).

DISCUSSION

The seston concentration was measured in eighteen lakes throughout the LMNP in two contrasting seasons (warm/rainy and cold/dry); seston turned out to be a key variable to understand the changes registered in the LMNP water bodies.

The environmental characteristics, both local and regional, cause an ample spatial variation in seston concentration ($p < 0.05$) that has significant consequences in Z_{EU} and the thermal structure of the lakes. Seston concentration had a strong significant correlation with Z_{EU} (negative) and Chl-*a* (positive) in both seasons.

The correlation between seston and Chl-*a* suggests that the high primary productivity is responsible for the biogenic turbidity in IS and ID lakes. Based on Chl-*a* concentration and according to the Cooperation Program on Eutrophication (OECD, 1982), NIS and NID lakes were classified as ultra-oligotrophic (< 2.5 µm/L) or oligotrophic (2.5-8 µm/L), while IS and ID lakes as eutrophic (25-75 µm/L) or hypereutrophic (> 75 µm/L).

Seston concentrations in IS and ID lakes (4.1-21.0 mg/L) were in the range of similar eutrophic lakes [e.g., Hongze (38.9-66.0 mg/L) in China, Cao et al., 2017; Chapultepec (20-117 mg/L) in Mexico, Rodríguez Giraldo, 2017], and much higher than in the non-impacted ones (1.0-2.1 mg/L), where the concentrations were close to oligotrophic lakes [e.g., El Sol (0.7-3.4 mg/L) and La Luna (0.3-1.5 mg/L) in Mexico, Hernández, 2008; Imja Khola Valley (0.63-6.69 mg/L) in Nepal, Giardino et al., 2010].

The strong correlation between Z_{EU} and seston indicates the light extinction among lakes increases with particulate matter augment, resulting in a thinner Z_{EU}, a reducing Z_{EU}:Z_{MIX} ratio, and an increasing portion of Z_{MIX} located below Z_{EU}, as observed in IS and ID lakes. In this case, the phytoplankton can move through the Z_{MIX} and, therefore, reach the aphotic zone where respiration is not offset by photosynthesis (Kalff, 2002).

The ID lakes displayed narrow and superficial thermoclines (reduced Z_{MIX}). The larger concentration of seston close to the surface of ID lakes causes rapid light absorption and its transformation into heat (Wetzel, 2001). The thermoclines are then more superficial and with a higher ∇T (0.8 ± 0.2°C). Z_{EU} reaches the bottom of the metalimnion (Z_{EU}>Z_{MIX}) in NID lakes during the warm/rainy season mirroring the low seston concentration (2.1 mg/L) and consequently the high transparency.

The $Seston_I$ predominance was possibly due to greater runoff and land contribution in the warm/rainy period (increasing soil erosion and causing turbid enhancement). On the other hand, during the cold/dry season, $Seston_O$ predominated. The latter is surely associated with higher primary production favored by the recirculation of nutrients, while the terrestrial contribution was lower. NIS is the only group that presented $Seston_I$:$Seston_O$ > 1 in both seasons, this could be related to the dragging of materials from the lakeshore and/or the proximity to human settlements.

It is worth mentioning that in the NID lakes, although the $Seston_I$:$Seston_O$ is the lowest of the four groups during the two seasons, the total concentration of seston is considerably low and the depth of the Z_{EU} is high. The high Z_{EU} in NID lakes allows the development of deep chlorophyll maxima (DCM) at the metalimnion (25-30 m) and consequently higher $Seston_O$ concentrations at the DCM.

In the last 20 years, there has been an important increase in agricultural activity (23.9 %) in previously forested areas (reduction of 51.6 %; CONANP, 2007). Soils in the NW zone of the LMNP are mostly phaeozems and luvisols with a high content of OM and nutrients that favor the regional agriculture activities. Differently, the soils of the SE zone are very shallow rendzinas on calcareous rocks, extremely gravelly and with high calcium content that immobilize nutrients (IUSS, 2007). Apparent, the land-use change (from forested to agricultural areas) has favored the deterioration of the impacted lakes through nutrients' enrichment (Alcocer et al., 2018).

Our results attest that seston was a key factor regulating Z_{EU}, which is related to the higher photosynthetic activity encouraged by the higher tropical T and higher nutrients inputs to impacted lakes. The impacted lakes in the NW zone of the LMNP receive the surface discharge of the *Río Grande de Comitán* and leachates from the surrounding agricultural areas, which results in nutrient enrichment (Juárez, 2014). On the contrary, the non-impacted lakes located in the SE portion (groundwater-fed) have remained in their original ultraoligo- or oligotrophic status (pristine).

This paper suggests that changes in impacted lakes are associated with a high seston concentration most likely connected with a eutrophication process. The significantly higher concentrations recorded in the IS and ID lakes compared to the NIS and NID ones have consequences on their transparency and thermal structure. These factors must be considered in the management plans of the LMNP lakes due to the importance of light penetration and primary production in lake ecosystems.

CONCLUSION

This study points out the importance of seston concentration and its vertical distribution in the water column, and its relationship with eutrophication in tropical karst lakes. Seston was a key factor regulating the Z_{EU} and Z_{MIX} of lakes. The higher T (> 20 ºC) in these tropical lakes and the external (agriculture, urban, land-use changes) nutrients inputs encourage photosynthetic activity and, therefore, an increase in Chl-*a* and seston concentrations, particularly during the stratification season. There were lower seston concentrations during the circulation season, apparently associated with lower light availability (Z_{EU}:Z_{MIX} < 1), and relatively lower T (< 20 °C).

Growing anthropic activities and eutrophication are the main problems facing impacted lakes of LMNP, being OM and nutrients inputs (punctual through the *Río Grande de Comitán* and diffuse through agricultural drainage) the primary cause of its deterioration. Eutrophication alters water bodies by 1) reducing water transparency (reduced Z_{EU} due to increased seston) and 2) modifying the thermal structure by the rapid absorption of light and its transformation into heat on the surface layer.

This research highlights the fragility of tropical lake karstic ecosystems worth protecting to preserve the aquatic ecosystem's health.

ACKNOWLEDGMENTS

This research was funded by the Fondo Sectorial de Investigación y Desarrollo Sobre el Agua (Sectorial Fund for Water Research and Development) (CONAGUA-CONACYT) through the project 167603 *Estudio hidrológico y de Calidad del Agua del sistema Lagunar de Montebello, en el Estado de Chiapas* and by *Dirección General de Asuntos del Personal Académico* (UNAM-DGAPA-PAPIIT) through the projects IN219215 *Factores que determinan el estado trófico de los lagos de Montebello, Chiapas* and and IV200319 *Área Experimental de Lagos Tropicales*. We thank René Morales Hernández for support during the fieldwork. We also thank the Parque Nacional Lagunas de Montebello, Comisión Nacional de Áreas Naturales Protegidas (CONANP) (Jesús A. León and Roberto Castellanos), the local community, and the Comisariados Ejidales from Antelá, Cárdenas, Miguel Hidalgo, Ojo de Agua and Tziscao for facilitating access to the lakes. We also thank the Comité de Administración de Tziscao (Sergio Marcos and Miguel A. Tomas), Presidente del Comité de Turismo de Tziscao (Armando Hernández), Comisario Ejidal de Tziscao (Enrique M. Hernández) and personnel of the Villas Tziscao Hotel (Rosemberg F. Jorge, Juan G. Espinoza and Gemuel P. Hernández) for offering their support and facilities for this study. Finally, we acknowledge the comments and suggestions of two anonymous referees that significantly improved this paper.

REFERENCES

Alcocer, J., Merino-Ibarra, M., Oseguera, L.A. & Escolero, O. (2018). Anthropogenic impacts on tropical karst lakes: "Lagunas de Montebello," Chiapas. *Ecohydrology*, e2029. DOI: 10.1002/eco.2029

Alcocer, J., Oseguera, L., Sánchez, G., González, C., Martínez, J. & González, R. (2016). Bathymetric and morphometric surveys of the Montebello Lakes, Chiapas. *Journal of Limnology*, 75, 56-65. DOI: 10.4081/jlimnol.2016.1343

Arar, E. J. & Collins, G. (1997). In vitro determination of chlorophyll-*a* and pheophytinain marine and freshwater algae by fluorescence (445.0). US Environmental Protection Agency.

Callieri, C., Bertoni, C, De Marco, C. & Contesini, M. (1991). Settling flux and sinking velocity of seston in Lago Di Mergozzo (Northern Italy) and influence of microbial activity on the decomposition of entrapped organic material. *Hydrobiologia*, 213, 155-165. DOI: 10.1007/BF00015002

Cao, Z., Duan, H., Feng, L., Ma, R. & Xue, K. 2017. Climate- and human-induced changes in suspended particulate matter over Lake Hongze on short and long timescales. *Remote Sensing of Environment*, 192, 98–113. DOI: 10.1016/j.rse.2017.02.007

Comisión Nacional del Agua (CONAGUA). (2011). *Identificación de reservas potenciales de agua para el medio ambiente en México*. CONAGUA, SEMARNAT. México.

Comisión Nacional De Áreas Naturales Protegidas (CONANP). (2007). *Programa de conservación y manejo Parque Nacional Lagunas de Montebello, México*. 9-10.

Comisión Nacional De Áreas Naturales Protegidas (CONANP). (2011). P*rograma de Monitoreo de Calidad del Agua, Estudio para monitorear los parámetros de calidad del agua de las lagunas de Montebello*. 17-29.

Durán Calderón, I., Escolero Fuentes, O.A., Muñoz Salinas, E., Castillo Rodríguez, M. & Silva Romo, G. (2014). Cartografía geomorfológica a escala 1:50,000 del Parque Nacional Lagunas de Montebello, Chiapas (México). *Boletín de la Sociedad Geológica Mexicana*, 66, 263–277.

Ford, D. & William, P. (2007). *Karst hydrogeology and geomorphology*. Wiley. London, England.

García, E. (2004). *Modificaciones al sistema de clasificación climática de Köppen*. Universidad Nacional Autónoma de México. México.

Giardino, C., Oggioni, A., Bresciani, M., & Yan, H. 2010. Remote Sensing of Suspended Particulate Matter in Himalayan Lakes. *Mountain Research and Development*, 30(2), 157-168. DOI: 10.1659/MRD-JOURNAL-D-09-00042.1

Han, Q., Wang, B., Liu, C., Wang, F., Peng, X. & Liu, X. (2018). Carbon biogeochemical cycle is enhanced by damming in a karst river. *Science of the Total Environment*, 616–617. DOI: 10.1016/j.scitotenv.2017.10.202

Hernández, B. (2008). Dinámica del seston y clorofila “a” en dos lagos tropicales de alta montaña, El Sol y La Luna, Nevado de Toluca, México. Biology Thesis. Universidad Nacional Autónoma de México.

IUSS WRB. 2007. Base Referencial Mundial del Recurso Suelo. Primera actualización 2007. Informes sobre Recursos Mundiales de Suelos No. 103. FAO. Rome. Italy.

Jellison R. & Melack, J. M. (2001). Nitrogen limitation and particulate elemental ratios of seston in hypersaline Mono Lake, California, U.S.A. *Hydrobiologia*, 466, 1-12. DOI: 10.1023/A:1014525805934

Juárez, E. (2014). Análisis hidrogeoquímico de la cuenca del Río Grande de Comitán. Bacherlor Thesis. Universidad Nacional Autónoma de México.

Kalff, J. (2002). *Limnology: Inland Water Ecosystems*. Prentice Hall. N.J. USA.

Legendre, L. & Michaud, J. (1999). Chlorophyll a to estimate the particulate organic carbon available as food to large zooplankton in the euphotic zone of oceans. *Journal of Plankton Research*, 21(11), 2067–2083. DOI: 10.1093/plankt/21.11.2067

Lenz, J. 1977. Seston and its main components. In: *Microbial ecology of brackish water environmental*. G. RHEINHERMER (ed.): Ecological studies. Spinger Verlag.

Mikac I., Fiket, Z., Terzić, S., Barešić, J., Mikac, N. & Ahel, M. (2011). Chemical indicators of anthropogenic impacts in sediments of the pristine karst lakes. *Chemosphere*, 84, 1140-1149. DOI: 10.1016/j.chemosphere.2011.04.027

Mora L., Bonifaz, R. & López-Martínez, R. (2016). Unidades geomorfológicas de la cuenca del Río Grande de Comitán, Lagos de Montebello, Chiapas-México. *Boletín de la Sociedad Geológica Mexicana*, 683, 377–394.

Organisation For Economic And Cooperative Development (OECD). 1982. *Eutrophication of waters: Monitoring, assessment and control*. Report of the OECD Cooperative programme on Eutrophication.

Palmer, A., Van Dijken, G., Mitchell, B., Seegers, B., Lowry, K., Mills, M. & Arrigo, K. (2013). Light and nutrient control of photosynthesis in natural phytopankton populations from the Chukchi and Beaufort seas, Artic Ocean. *Limnology and Oceanography*, 58, 2185-2205. DOI: 10.4319/lo.2013.58.6.2185

Parra, O., Valdovinos, C., Urrutia, R., Cisternas, M., Habit, E. & Mardones, M. (2003). Caracterización y tendencias tróficas de cinco lagos costeros de Chile Central. *Limnetica*, 22, 51–83. DOI: 10.23818/limn.22.04

Peng D., Johnson, D. L. & Effler, S. (2004). Characterization of inorganic particles in selected reservoirs and tributaries of the New York City water supply. *Journal of the American Water Resources Association S/V*, 663-676. DOI: 10.1111/j.1752-1688.2004.tb04451.x

Punning, J. A., Jaanus, T., Koff, T. & Alliksaar, T. (2003). Seasonal fluxes of particulate matter in a small closed lake in northern Estonia. *Water, Air, and Soil Pollution*, 149, 77-92.

Rodríguez-Giraldo, L. (2017). Calidad del agua y productividad primaria fitoplanctónica en los tres lagos del Bosque de Chapultepec, Ciudad de México. Biology Thesis. Universidad Industrial de Santander.

Secretaría De Medio Aambiente Y Recursos Naturales (SEMARNAT). 2008. *Catálogo tipológico de humedales lacustres y costeros del estado de Chiapas*. 7-41.

Špoljar, M., Primc-Habdija, B. & Habdija, I. (2007). Transport of seston in the karstic hydrosystem of the Plitvice Lakes (Croatia). *Hydrobiologia*, 579, 199-209. DOI: 10.1007/s10750-006-0409-4

Vázquez, M. A. & Méndez, E. (1994). *Aspectos generales de la región: Lagos de Montebello. Reporte del trabajo para el curso de conservación de naturaleza y recursos naturales*. Master’s Thesis, ECOSUR Chiapas, México.

Westlake, D. E. (1965). Some problems in the measurement of radiation under water: A review. *Photochemestry Photobiology*, 4, 849-868.

Wetzel, R. & Likens, G. (2000). *Limnological Analyses*. Springer. NY. USA.

Wetzel, R. (2001). *Limnology. Lake and River Ecosystems*. Academic Press. San Diego. USA.

Weyhenmeyer, G. A. (1997). Quantification of resuspended particles in sedimentation traps. Internationale *Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*, 26:2, 271-27. DOI: 10.1080/03680770.1995.11900716

Zutinić, P., Gligora-Udović, M., Kralj Borojević, K., Plencović-Moraj, A. & Padisák, J. (2014). Morpho-functional classifications of phytoplankton assemblages of two deep karstic lakes. *Hydrobiologia*, 740, 147-166. DOI: 10.1007/s10750-014-1950-1