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PRIMARY RESEARCH PAPER

Aquatic ecosystems of the Yucatán Peninsula (Mexico), Belize, and Guatemala

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Abstract This study presents limnological and morphological characteristics, physical and chemical properties of waters, and geochemistry of surface sediments for 63 aquatic ecosystems located on the karst Yucatán Peninsula and surrounding areas of Belize and the Guatemalan highlands and eastern lowlands. Our principal goal was to classify the aquatic systems based on their water variables. A principal component analysis (PCA) of the surface water chemistry data showed that a large fraction of the variance (29%) in water chemistry is explained by conductivity and major ion concentrations. The broad conductivity range, from 168 to 55,300 μS cm^{-1} reflects saline water intrusion affecting coastal aquatic environments, and the steep NW–S precipitation gradient, from ~450 to >3,200 mm year^{-1}. Coastal waterbodies Celestún and Laguna Rosada displayed the highest conductivities. Minimum surface water temperatures of 21.6°C were measured in highland lakes, and warmest temperatures, up to 31.7°C, were recorded in the lowland waterbodies. Most lakes showed thermal stratification during the sampling period, with the exception of some shallow (<10 m) systems. Lakes Chichancanab, Milagros, and Bacalar displayed sulfate-rich waters. Waters of sinkholes had relatively high conductivities (<3,670 μS cm^{-1}) and a broad range of δ^{18}O values (−4.1 to +3.8‰). Ca, HCO_3, and SO_4 dominated the waters of the lowland lakes, whereas Na was the dominant cation in highland lakes. Coastal aquatic ecosystems were dominated by Na and Cl. Cluster analysis based on surface water variables classified aquatic environments of the lowlands and highlands into three groups: (1) lowland lakes, ponds, wetlands, and coastal waterbodies (2) highland lakes, and (3) sinkholes and rivers. A broad trophic state gradient was recorded, ranging from the eutrophic Lake Amatitlán and the Timul sinkhole to oligotrophic Laguna Ayarza, with the highest water transparency (11.4 m). We used major and trace

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elements in surface sediments to assess pollution of waterbodies. Lakes Amatitlán, Atescatempa, El Rosario, Cayucón, Chacan-Lara, La Misteriosa, rivers Subín and Río Dulce, the wetland Jamolún, and the sinkhole Petén de Monos showed evidence of pollution and urban development. Their surface sediments displayed high concentrations of As, Cu, Fe, Ni, Pb, Se, Zn, and Zr, which suggest moderate to strong pollution.

Keywords Neotropical aquatic ecosystems · Limnology · Physical and chemical water variables · Surface sediment geochemistry · Yucatán Peninsula · Guatemala · Belize

Introduction

Here, we present results of a limnological survey across Mexico's Yucatán Peninsula, Belize, and Guatemala. The aims of this study were (1) to provide basic limnological information, characterize, and classify the aquatic ecosystems across an altitudinal and precipitation gradient from southern Guatemala to the northern Yucatán Peninsula, (2) to identify factors that influence water variables in Neotropical aquatic ecosystems, (3) to generate the first physical and chemical data for several waterbodies that were previously unstudied, (4) to assess the present trophic state, level of pollution, and human impact in the waterbodies, and (5) to contribute to the sustainable management of aquatic ecosystems and formulation of strategies for their conservation by providing baseline data for future studies.

Guatemala is diverse with respect to its lake types. Many lakes in the southern highlands of Guatemala originated from volcanic activity, while lakes of the northern lowlands are of tectonic and/or karstic origin (Brezonik & Fox, 1974). The Department of Petén, northern Guatemala, lies in the southernmost part of the limestone platform of the Yucatán Peninsula and has numerous lakes. One of them, Lago Petén Itzá, is the deepest waterbody (~165 m) in the northern lowland Neotropics. Guatemala has an area of 108,430 km^2 and about 300 lakes and lagoons (Basterrechea, 1988a). More than 7,000 solution features have been reported in the northwest, Mexican sector of the Yucatán Peninsula (Stenich, 1996). Regional studies of water chemical composition, sediment geochemistry, and aquatic species richness are scarce. Lakes Izabal, Amatitlán, and Atitlán (Nr. 1, 19, 20, Fig. 1), however, have received attention because they are of great touristic and hence economic importance for Guatemala (Clark, 1908; Meek, 1908; Brinson et al., 1974; Brinson & Nordlie, 1975; Basterrechea, 1986; Medina et al., 2010). Little attention, however, has been paid to most of the aquatic ecosystems, many of which have been polluted or have experienced recent changes in trophic state. These aquatic ecosystems provide multiple services. They are important drinking water sources, serve as sites for recreation, and are important wildlife areas, for both aquatic and terrestrial fauna.

In the last few decades, climate change and human activities have affected many lakes in the study region (Rosenmeier et al., 2004; Alcocer & Bernal-Brooks, 2010). For instance, a dramatic reduction in lake level has affected some waterbodies over the last 30 years. There are good chemical indicators of pollution and urban development (Cu, Zn, and Fe), and their values in lake sediments and waters should be monitored to protect human health. Limnology is in a nascent stage in Guatemala and Belize, whereas Mexico has made great strides in this discipline over the last few decades. For instance, Mexico established the Mexican Association of Limnology, and since 2003 has had a Master program (M.S.) in Limnology at the Universidad Michoacana (Alcocer & Bernal-Brooks, 2010). There are about 100 publications on freshwater and saline aquatic environments from the Yucatán Peninsula (Schmitter-Soto et al., 2002). The first studies on Guatemalan Lakes Amatitlán and Atitlán were carried out in the early 1900s and 1950s and focused mainly on plankton and fish taxonomy (Clark, 1908; Meek, 1908; Tilden, 1908; Peckham & Dineen, 1953). This was also the case in Mexico, where studies followed a similar approach (Alcocer & Bernal-Brooks, 2010). Comprehensive limnological studies in Guatemala were conducted first by Juday (1915), and later by Deevey (1955) and Brezonik & Fox (1974). Studies were also completed in Lake Izabal (Brinson et al., 1974; Brinson & Nordlie, 1975). Other recent contributions to Guatemalan limnology include the works of Löffler (1972), Deevey et al. (1980a, b), Basterrechea (1986, 1988a, b), Brenner (1994), and Brenner et al.

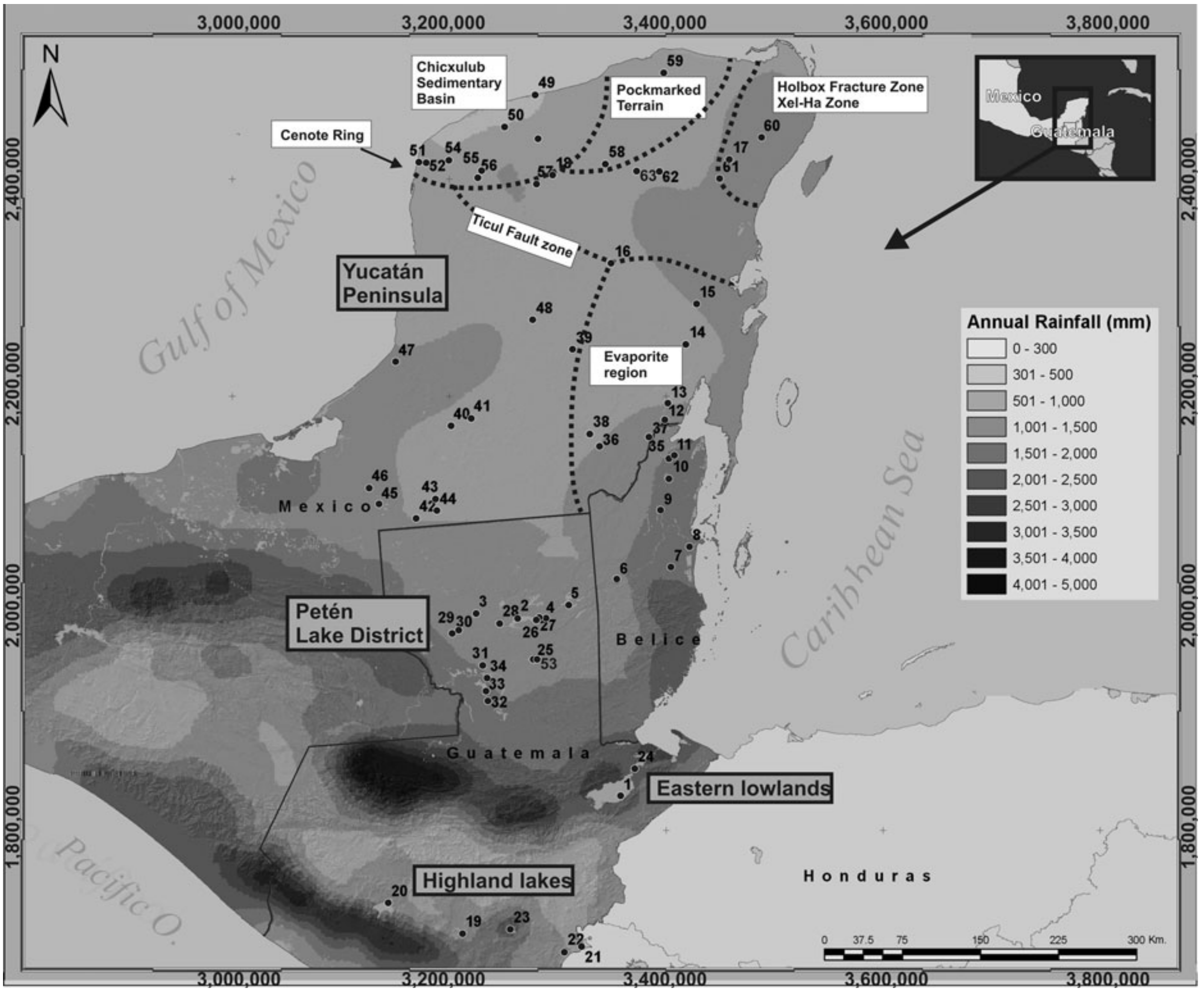


Fig. 1 Location of the 63 studied lowland and highland aquatic environments across a precipitation and altitudinal gradient on the Yucatán Peninsula and surrounding areas: *1* Izabal, *2* Petén Itzá, *3* Perdida, *4* Macanché, *5* Yaxhá, *6* Belize 1, *7* Belize 2, *8* Almond Hill, *9* Crooked Tree Lagoon, *10* Honey Camp, *11* Cenote, *12* Milagros, *13* Bacalar, *14* Nohbec, *15* Ocom, *16* Chichancanab, *17* Punta Laguna, *18* Yalahau, *19* Amatitlán, *20* Atitlán, *21* Güija, *22* Atescatempa, *23* Ayarza, *24* Río Dulce, *25* Oquevix, *26* Salpetén, *27* Río Ixlú, *28* Sacpuy, *29* La Gloria, *30* San Diego, *31* Río Subín, *32* Las Pozas, *33* Petexbatún, *34* Rosario, *35* Progreso Lagoon, *36* San José Aguilar, *37* Sabanita, *38* Chacan-Bata, *39* Chacan-Lara, *40* Silvituc, *41* Jobal, *42* San Francisco Mateos, *43* La Misteriosa, *44* Río Cuba, *45* Laguna del Cayucón, *46* Río Candelaria, *47* Río Guerrero, *48* Jamolún, *49* Laguna Rosada, *50* Xlakal, *51* Celestún, *52* Petén de Monos, *53* Pond near Oquevix, *54* San Francisco Kaná, *55* San Ignacio Chocholá, *56* Chenhá, *57* Timul, *58* Yokdzonot, *59* Loché, *60* Juárez, *61* Cobá, *62* Tekom, and *63* Ya’ax’ex. *Gray shading* on the Yucatán Peninsula denotes the precipitation gradient. *White squares* and *dashed lines* indicate the six hydrogeochemical-physiographic regions identified by Perry et al. (2002) for the Yucatán Peninsula. *Gray squares* indicate the studied areas

(2002a, c). Given the region’s large number and diversity of aquatic ecosystems, there have been relatively few limnological studies in the area and most relied on measurements made during a single visit, which makes it difficult to assess temporal patterns of lake dynamics.

The Yucatán Peninsula and surrounding regions are of great interest to tropical limnologists because they possess abundant aquatic ecosystems with diverse hydrochemical characteristics. Furthermore, the region’s aquatic ecosystems are characterized by long-term interactions with human populations

(Brenner, 1983; Brenner et al., 2002b; Alcocer & Bernal-Brooks, 2010).

Study area

The Yucatán Peninsula and surrounding areas

The biogeographic area of the northern lowland Neotropics extends from the Tropic of Cancer to the equator and includes southern Mexico, Central America, northern South America, and the West Indies (Deevey et al., 1983; Hillesheim et al., 2005). The Yucatán Peninsula, in southernmost Mexico, covers 450,000 km^2, and is surrounded by the Gulf of Mexico and the Caribbean Sea (Fig. 1). It consists of the Mexican States of Campeche, Quintana Roo, and Yucatán, as well as parts of the states of Tabasco and Chiapas. The peninsula also includes the Department of Petén in northern Guatemala and the northern half of Belize (Lutz et al., 2000; Ibarra-Manríquez et al., 2002; Rosenfeld, 2002; Rosenmeier et al., 2002a, b; Schmitter-Soto et al., 2002; Hillesheim et al., 2005; Alcocer & Bernal-Brooks, 2010).

Central America and southern Mexico display great geomorphic and geographic variability, with complex coastlines, coastal plains, high mountain ranges, interior basins, and extended plateaus. The relatively small area is characterized by a variety of tectonic, lithologic, climatic, and ecological zones. The physiographic structure of Central America is defined by the northwest–southeast trend of the Middle America Trench and Central American Volcanic Front. Guatemalan faulting and volcanism are related to subduction of the Cocos Plate beneath the Caribbean Plate, and to sliding of the Caribbean Plate eastward relative to the North American Plate (Molnar & Sykes, 1969; Marshall, 2006). The volcanic highlands of southern Guatemala were formed above this subduction zone. These highlands descend to the north onto the immense carbonate lowlands of the Yucatán Platform Province, which is the most extensive karst area on the North American continent (Marshall, 2006). The Yucatán Peninsula consists of a marine carbonate platform that ranges in altitude from sea level to about 300 m a.s.l. The age of exposed bedrock increases from north to south, ranging from Pleistocene to late Cretaceous (Hodell et al., 2004). The southern Yucatán Peninsula (Petén, Guatemala) is underlain mostly by Cretaceous limestones, containing dolomite and gypsum (Brenner et al., 2002c).

The Yucatán Peninsula, Guatemala, and Belize (Fig. 1) are rich in aquatic environments. Waterbodies vary in surface area, water depth, elevation (Tables 1, 2), trophic status, water chemistry, and surface sediment chemistry. There are no large rivers on the peninsula, rivers are completely lacking in the north, and sinkholes are abundant. There are ~12 large lakes (Back & Hanshaw, 1970; Schmitter-Soto et al., 2002; Perry et al., 2003; Suárez-Morales, 2003). Aquifers of Florida (USA) and northern Yucatán show lithologic and faunal similarities. Both peninsulas are part of a single regional geologic setting (Back & Hanshaw, 1970), and groundwater flows through networks of a large submerged cave system (Alcocer & Bernal-Brooks, 2010). Karst features such as channels and sinkholes (cenotes) are typical of the Yucatán Peninsula (Schmitter-Soto et al., 2002; Perry et al., 2003; Suárez-Morales, 2003). Cenotes were formed by dissolution and collapse of the carbonate rock. A semicircular ring of cenotes in northern Yucatán has its center near the site of the late Cretaceous Chicxulub meteorite impact. Impeded groundwater flow was forced to follow the semicircular contour, thereby contributing to dissolution and collapse of the local rock (Perry et al., 2003). Comín et al. (1996) and Schmitter-Soto et al. (2002) indicated that inland waterbodies on the Yucatán Peninsula show the strong influence of rock dissolution processes on the major ionic composition of waters. Oxygen and carbon stable isotopes in inland waters are analyzed to study groundwater throughflow, balance between precipitation and evaporation, and lake water productivity (McKenzie, 1985; Aravena et al., 1992; Socki et al., 2002).

Most of the Yucatán Peninsula is located in a humid tropical climate zone, and displays high terrestrial and aquatic biodiversity. The study area contains three of 37 hydrologic regions that have been identified in Mexico: Yucatán Oeste, Yucatán Norte, and Yucatán Este (Alcocer & Bernal-Brooks, 2010). The peninsula receives an average of ~172,000 × 10^6 m^3 of rainwater per year, of which about 85% is lost to evapo-transpiration. Precipitation on the Yucatán Peninsula is driven by the seasonal migration of the Intertropical Convergence Zone (ITCZ) and the precipitation gradient ranges from ~450 mm year^{-1} in

Table 1 Limnological and geographical characteristics of study lakes in the Yucatán Peninsula and surrounding areas

Area	Code	ID-Nr.	Name of waterbody	Country	Coordinates		Averaged annual precipitation (mm year^{-1})	Altitude (m a.s.l.)	Depth[a] (m)	Surface area (km^2)	Secchi depth (m)	Stratification
					N	W						
Guatemalan highlands	AMA	19	Amatitlán	GUA	14°26′03.7″	90°32′58.6″	2,847	1,200	23 (33[b])	15.2	0.1–0.8	Yes
	ATI	20	Atitlán	GUA	14°42′34.8″	90°15′59.4″	2,500	1,560	340	126	6.6	Yes
	AYA	23	Ayarza	GUA	14°25′39.3″	90°08′11.6″	2,900	1,414	250	14	11.4	Yes
	GÜI	21	Güija	GUA	14°15′43.7″	89°32′11.3″	2,116	433	21.5	45	1.4	Yes
	ATE	22	Atescatempa	GUA	14°13′01.1″	89°41′39.2″	2,216	587	2	1.1	0.1	No
Guatemalan eastern lowlands	IZA	1	Izabal	GUA	15°29′24.5″	89° 8′32.7″	2,881	4	14.8	645	–	No
Guatemalan lowlands	OQU	25	Oquevix	GUA	16°39′14.2″	89°44′26.1″	2,578	148	10	1.6	0.4	–
	SAL	26	Salpetén	GUA	16°58′38.2″	89°40′30.9″	2,077	114	38	2.9	0.8	Yes
	MAC	4	Macanché	GUA	16°57′60.0″	89°38′06.5″	2,036	165	80	2.5	–	Yes
	YAX	5	Yaxhá	GUA	17°03′48.9″	89°24′27.1″	2,036	219	22	7	1.8	Yes
	ITZ	2	Petén Itzá	GUA	17°00′02.0″	89°51′16.4″	2,176	115	165	100	7.5	Yes
	SAC	28	Sacpuy	GUA	16°58′46.4″	90°00′52.2″	2,304	122	6	3.5	0.5	Yes
	PER	3	Perdida	GUA	17°04′00.7″	90°12′41.7″	2,260	75	4	11	0.7	Yes
	GLO	29	La Gloria	GUA	16°57′07.5″	90°22′36.1″	2,452	132	65	3.6	0.6	Yes
	DIE	30	San Diego	GUA	16°55′59.5″	90°24′54.5″	2,480	134	8.1	3.8	0.6	Yes
	POZ	32	Las Pozas	GUA	16°21′02.4″	90°10′28.9″	3,161	146	35	2.0	1.8	Yes
	PET	33	Petexbatún	GUA	16°26′11.8″	90°11′46.0″	3,042	115	40	5.6	0.6	Yes
	ROS	34	El Rosario	GUA	16°31′31.4″	90°09′36.2″	2,908	117	3	0.02	–	–
Mexican lowlands	MIL	12	Milagros	MEX	18°30′41.5″	88°25′35.8″	1,304	1	4	3.1	1.0	No
	BAC	13	Bacalar	MEX	18°39′54.0″	88°23′27.0″	1,239	1	16	51	10.3	No
	NOH	14	Nohbec	MEX	19°08′8.54″	88°10′46.6″	1,209	1	0.6	8.5	0.6	No
	OCO	15	Ocom	MEX	19°28′28.6″	88°03′17.9″	1,249	1	10	0.25	5.5	Yes
	CHI	16	Chichancanab	MEX	19°52′43.2″	88°46′06.5″	1,120	2	14	5.1	2.8	Yes
	PUN	17	Punta Laguna	MEX	20°39′00.6″	87°38′28.2″	1,295	3	20	0.9	4.7	Yes
	JOS	36	San José Aguilar	MEX	18°22′04.5″	89°00′41.2″	1,187	107	3	2.0	0.6	–
	SAB	37	Sabanita	MEX	18°24′03.2″	88°34′20.6″	1,306	38	2.5	0.02	0.5	No
	BAT	38	Chacan-Bata	MEX	18°28′42.1″	89°05′13.9″	1,150	91	–	2.9	–	–
	LAR	39	Chacan-Lara	MEX	19°11′21.8″	88°10′17.0″	1,072	90	3	1.2	0.7	No
	JOB	41	Jobal	MEX	18°41′40.7″	90°06′45.4″	1,210	74	3		–	No
	FRA	42	San Francisco Mateos	MEX	17°53′55.9″	90°39′22.8″	1,578	52	5	0.1	–	No
	MIS	43	La Misteriosa	MEX	18°02′40.3″	90°29′14.0″	1,462	57	5.8	5.0	2.1	No
	CAY	45	Cayucón	MEX	18°02′34.3″	90°58′33.0″	1,520	69	8	2.0	?	–
	YAL	18	Yalahau	MEX	20°39′25.9″	89°13′02.0″	1,099	2	11	0.25	1.1	Yes
	COBA	61	Cobá	MEX	20°29′40.2″	87°44′19.2″	1,282	7	–	0.35	0.9	–
Belizean lowlands	ALM	8	Almond Hill Lagoon	BZ	17°27′49.0″	88°18′31.6″	2,006	1	1.9	1.5	1.7	No
	CRO	9	Crooked Tree Lagoon	BZ	17°46′42.8″	88°31′37.4″	1,705	2	3.3	23	2.0	No
	HON	10	Honey Camp Lagoon	BZ	18°02′44.5″	88°26′20.5″	1,586	1	8	3.9	1.8	No

The ID-Nr. corresponds to the sampling sites in Fig. 1

[a] Maximal sampled water depth

[b] Deevey (1955)

Table 2 Limnological and geographical characteristics of additional studied aquatic environments in the Yucatán Peninsula and surrounding areas

Aquatic environment	Code	ID-Nr.	Name of waterbody	Country	Coordinates		Averaged annual precipitation (mm year^{-1})	Altitude (m a.s.l.)	Depth[a] (m)	Surface area (km^2)	Secchi depth (m)
					N	W					
Cenotes	XLA	50	Xlacah	MEX	21°05′27.6″	89°35′53.3″	712	6	45	<0.01	5
	MON	52	Petén de Monos	MEX	20°50′59.6″	90°19′13.8″	851	25	1.5	<0.01	1.5
	IGN	55	San Ignacio Chochola	MEX	20°45′00.9″	89°50′03.2″	928	7	4	<0.01	4
	CHE	56	Chenhá	MEX	20°41′23.0″	89°52′34.5″	928	3	2	<0.01	3.5
	TIM	57	Timul	MEX	20°35′38.8″	89°21′23.7″	1,079	9	–	0.03	0.2
	YOK	58	Yokdzonot	MEX	20°42′24.6″	88°43′52.0″	1,191	13	45	<0.01	7
	JUA	60	Juarez	MEX	20°48′09.6″	87°20′23.8″	1,357	14	25	0.03	1.6
	YAA	63	Yaa'x ek	MEX	20°37′15.4″	88°24′56.0″	1,200	27	47	<0.01	0.8
	KAN	54	San Francisco Kana	MEX	20°51′22.2″	90°07′04.5″	824	3	–	0.01	0.3
	TEK	62	Tekom	MEX	20°36′08.1″	88°15′52.5″	1,198	18	1.5	<0.01	1.5
Coastal water bodies	PRO	35	Progreso	BZ	18°13′05.2″	88°24′35.2″	1,485	5	3.2	7.2	1.3
	CEN	11	Cenote Little Belize	BZ	18°13′36.9″	88°22′55.57″	1,497	7	11.1	0.06	5.5
	ROSA	49	Rosada	MEX	21°20′11.3″	89°18′01.9″	668	4	0.5	2.3	0.5
	CEL	51	Celestún	MEX	20°51′20.8″	90°22′39.2″	861	14	1.5	28	0.5
Rivers	SUB	31	Subin	GUA	16°38′11.6″	90°11′00.3″	2,908	141	1	–	0.5
	IXL	27	Ixlú	GUA	16°58′27.3″	89°53′27.8″	2,091	110	1	–	1
	DUL	24	Río Dulce	GUA	15°40′25.3″	88°57′49.3″	3,019	4	7	–	0.5
	CUB	44	Cuba	MEX	17°56′55.4″	90°28′39.1″	1,521	80	0.5	–	0.5
	CAN	46	Candelaria	MEX	18°11′02.4″	91°02′59.6″	1,435	44	1.5	–	1.0
	GUE	47	Guerrero	MEX	19°12′41.6″	90°43′47.6″	1,187	5	1	–	0.5
Wetland	JAM	48	Jamolún	MEX	19°27′58.3″	89°29′45.1″	1,041	115	1.5	–	0.5
Ponds	TÜM	53	Near Oquevix	GUA	16°40′31.7″	89°44′18.1″	2,578	179	1	<0.01	–
	LOC	59	Loché	MEX	21°25′04.3″	88°08′30.8″	1,015	20	1	<0.01	0.2
	SIL	40	Silvituc	MEX	18°38′23.2″	90°17′35.2″	1,245	59	2.5	<0.01	–
	BZ1	6	Belize 1	BZ	17°14′33.5″	88°58′19.7″	1,665	77	1.5	<0.01	–
	BZ2	7	Belize 2	BZ	17°18′17.9″	88°29′18.9″	2,020	33	1	<0.01	–

The ID-Nr. corresponds to the sampling sites in Fig. 1

[a] Maximal sampled water depth

the northwest to >3,200 mm year^{-1} in the south (Schmitter-Soto et al., 2002). Aguilar et al. (2005) determined changes in precipitation and temperature in Central America and northern South America between 1961 and 2003. Precipitation indices showed low correlation with the El Niño-Southern Oscillation, but there was a higher correlation between precipitation and tropical Atlantic sea surface temperatures.

Regional and local characteristics of rainfall distribution in Central America are influenced, in part, by topography. Large spatial variability in precipitation in Central America is related to the region's position and altitudinal variations, and configuration of coastlines relative to seasonal storm patterns (Hastenrath, 1967). There are only a few meteorological stations at high-altitude sites in Guatemala, making studies of rainfall variation across elevations difficult. Nevertheless, the existence of an altitudinal belt of maximum precipitation is obvious in Guatemala.

As tropical latitudes display small intra-annual variations in radiation and temperature, seasonality in the tropics is often manifested by differences in precipitation, with alternating dry and rainy seasons (Hastenrath, 1967). On the Yucatán Peninsula, the wet season occurs from late May to October, and the dry season lasts from November to April (Hodell et al., 2005). There are occasional brief showers from November to February. Highest precipitation typically occurs in September and is often associated with tropical storms or hurricanes (Schmitter-Soto et al., 2002). In summer, the ITCZ is located at its northernmost position over Yucatán. Dry conditions prevail when the ITCZ is located south of the lowlands (Enfield, 1996; Enfield & Alfaro, 1999; Magaña et al., 1999; Haug et al., 2001, 2003; Poore et al., 2004). The mean annual air temperature is 26.1°C. Vegetation of the Yucatán Peninsula changes along with the precipitation gradient. The steep, increasing northwest-to-south gradient in rainfall is associated with greater soil development and higher forest stature. Tropical rain forest characterizes the southernmost Yucatán Peninsula, while the north is dominated by scrub forest, along with seasonal semi-deciduous and deciduous forests. Vegetation in the Yucatán Peninsula is still relatively intact compared to other regions in Mexico (Alcocer & Bernal-Brooks, 2010). There is a diverse plant community (~2,400 spp.), however, endemism is low. The highlands are characterized by conifer and oak forests (Ibarra-Manríquez et al., 2002; Islebe & Leyden, 2006).

Materials and methods

Fieldwork

Two field trips to the Yucatán Peninsula and surrounding areas were carried out during the dry season. Between 21 November 2005 and 25 February 2006, we sampled 18 aquatic environments. Forty-five additional aquatic environments were sampled between 6 February and 24 March 2008 (Fig. 1). Deep and shallow lakes, sinkholes (cenotes), ponds, wetlands, rivers, and coastal waterbodies were included in the sampling campaigns. Six aquatic environments in the Guatemalan highlands were also sampled. Tables 1 and 2 provide brief geographical and limnological descriptions of the studied environments. Average annual precipitation was obtained from the CRU TS 2.1 database (Mitchel & Jones, 2005; Correa-Metrio, pers. comm.). Sampling was conducted mainly during the dry season to facilitate lake access, but powerful Hurricanes Emily (July) and Wilma (October) in 2005 affected the region in summer and fall (Klotzbach et al., 2007) and made sampling in some lakes in Mexico difficult. We selected the most accessible lakes along the precipitation gradient and collected surface sediments and ostracodes from the littoral zone and the deepest part of each waterbody. Water samples for major ion and physical and chemical variable analysis were collected from different water depths, in most cases at a site in the lake above its deepest point. Water samples were collected from at least three depths in the water column (surface, middle, and bottom). We collected only surface waters in sinkholes without obtaining information about thermal stratification in those basins. In smaller aquatic environments such as ponds, rivers, and wetlands, surface waters were collected only near the shore. Physical and chemical variables in waters, including dissolved oxygen, pH, conductivity, and temperature, were measured with a WTW Multi Set 350i. This was done mostly at the same time of day to enable comparison of physico-chemical characteristics such as pH. Sampling was carried out from a rubber boat, using an Echosounder Eagle Mach 1 to locate the deepest part of the lake. A Ruttner water sampler and an Ekman grab attached to a 170-m-long UWITEC Handwinch were used to collect samples of water and surface sediments, respectively. Only the uppermost few centimeters of sediment taken with the Ekman grab were collected for analysis. We used a Secchi Disk to determine water transparency, and a GPSmap 60C to determine the sampling location. Protocols for sampling, preservation and analyses of water and surface sediment samples are described in Pérez et al. (2010).

Water analysis

Water samples for stable oxygen and carbon isotopes were measured using a VG/Micromass PRISM Series II isotope ratio mass spectrometer and a Finnigan-MAT DeltaPlus XL isotope ratio mass spectrometer with a GasBench II universal on-line gas preparation device. Stable isotopes were measured in the Department of Geological Sciences, University of Florida. Measurements of major anions (Cl, SO_4, and HCO_3) and cations (Ca, K, Mg, and Na) in water samples were carried out using a 761 Compact IC Methrom, and an ICP-OES Jobin Yvon JY 50 P. We were unable to determine chloride and sulfate concentrations in some lake waters due to bacterial and algal growth during transport to the laboratory. In such cases, we present results from previous studies (Brezonik & Fox, 1974; Basterrechea, 1988a; Perry et al., 2002). In cases for which complete ion analyses were done, we tested the validity of our results by checking the ion balance. This was accomplished by subtracting the total anion charges (sum of Cl, SO_4, and HCO_3) from the total cation charges (sum of Ca, Mg, Na, and K) and dividing by the total charges in solution (Murray & Wade, 1996). Percent difference between the total positive and negative charges was always $\leq$10%. Water chemistry analyses were carried out at the Institut für Umweltgeologie (IUG), Technische Universität Braunschweig, Germany.

Sediment analysis

Color, texture, odor, and other characteristics of surface sediments were described. Wet sediments were homogenized and water content, organic matter, carbonate and non-carbonate inorganic matter were determined by loss-on-ignition as described in Heiri et al. (2001). Whole surface sediment samples were analyzed, without any wet sieving to remove selected size fractions. After pulverizing the dried samples (105°C), major and trace elements (As, Br, Cu, Fe, Ni, Pb, Rb, Se, Sr, Y, Zn, and Zr) were quantified using energy-dispersive X-ray fluorescence (XRF) spectrometry (Cheburkin et al., 1997). We present major and trace element concentrations in surface sediments collected during our second field trip. We used the index of geoaccumulation (I_{geo}, Müller, 1979) to assess pollution in lake sediments. The I_{geo} has six levels of pollution (classes): (0) practically unpolluted, (1) practically unpolluted to moderately polluted, (2) moderately polluted, (3) moderately to strongly polluted, (4) strongly polluted, (5) strongly to very strongly polluted, and (6) very strongly polluted. An elemental analyzer (HEKAtech GmbH, Euro EA 3000) was used to determine total C, N, and S concentrations in sediments. Geochemical analyses were done at the Institut für Umweltgeologie.

Total carbon (TC) and total inorganic carbon (TIC) in sediments were measured in the laboratories of the Physische Geographie, Freie Universität, Berlin, Germany. TC was determined by combustion at 1,000°C in an oxygen-supersaturated atmosphere with a Woesthoff Carmhograph C-16-D. The carbon dioxide (CO_2) formed is absorbed in NaOH and the change in conductivity represents TC. TIC was determined similarly, with the Woesthoff Carmhograph, but hot (80°C) phosphoric acid (45%) was added to the sample to evolve CO_2. Analyses for TC and TIC on each sample were completed twice. Total organic carbon (TOC) was calculated as TC minus TIC. Standard deviations on replicate samples were $\leq$10% for all analyses.

Numerical analysis

We used principal component analysis (PCA) and a correlation matrix to examine the chemistry data set of surface waters. Prior to multivariate analysis, 13 water variables (conductivity, pH, temperature, dissolved oxygen, $\delta^{18}O_{\text{SMOW}}$, $\delta^{13}C_{\text{DIC}}$, Ca, Na, Mg, K, HCO_3, Cl, and SO_4) were standardized by subtracting the mean value and dividing by the standard deviation. This method enables comparison of variables expressed in different units (Leyer & Wesche, 2007). Aquatic ecosystems at Celestún and Laguna Rosada, in the NW Yucatán Peninsula, were excluded from multivariate analysis (PCA and cluster analysis) because samples were identified as outliers. Surface waters displayed much higher conductivities (55.3 mS cm^{-1}) than the other aquatic environments. This precluded effective visualization in the scatter biplot and dendrogram. Cluster analysis (Ward's method, Euclidean distance) was used to classify and define groups of aquatic environments based on their physical and chemical variables. The program Past, version 1.89, was used for all statistical analyses.

Results

Physical and chemical variables of the aquatic ecosystems

Our study covered the area from 14°13′ to 21°25′N latitude and from 87°20′ to 91°02′W longitude (Fig. 1). It ranged across a precipitation gradient from ~700 to 3,200 mm $year^{-1}$. Lake Atitlán in the Guatemalan highlands was the highest (~1,560 m a.s.l.) and deepest (~340 m) lake sampled. Most of the aquatic environments we studied are located in the lowlands ($\leq$400 m a.s.l.) and displayed water depths <40 m, with the exception of Lakes La Gloria (65 m), Macanché (~80 m), and Petén Itzá (~165 m). The largest lakes were Izabal (645 km^2), Atitlán (126 km^2), and Petén Itzá (100 km^2). The rest of the aquatic systems had smaller surface areas ($\leq$45 km^2).

Cenotes displayed small surface areas ($\leq$0.03 km^2), but some were relatively deep (up to 65 m). Water transparency was high in Lakes Ayarza (11.4 m), Bacalar (10.3 m), and Petén Itzá (7.5 m). Low water transparency ($\leq$0.8 m) was measured in Lakes Amatitán, Salpetén, Sacpuy, Perdida, La Gloria, San Diego, Petexbatún, Nohbec, San José Aguilar, Sabanita, and Chacan Lara. Eighteen lakes exhibited thermal stratification and oxygen depletion in deep waters (Fig. 2). Exceptions included Atescatempa, Izabal, Milagros, Bacalar, Nohbec, Sabanita, Chacan Lara, Jobal, San Francisco Mateos, La Misteriosa, and the lowland lakes of Belize. In systems from which we collected surface waters only from the littoral zone (Table 2), we do not provide limnetic water column temperatures or oxygen profiles.

Tables 3 and 4 contain the physical and chemical variables for all the studied waterbodies. Surface water temperature in the aquatic environments ranged from 21.6 to 32.0°C and dissolved oxygen ranged from 0.9 to 18.7 mg l^{-1}. Shallow lakes were generally warmer. Waters were neutral (pH 6.9) to alkaline (pH 9.4). Conductivities covered a wide range, from 126.6 µS cm^{-1} to 55.3 mS cm^{-1} near the coast. SO_4 concentration varied from 6.4 to 2,410 mg l^{-1}, Cl from ~3 to 1,602 mg l^{-1}, and HCO_3 from 55 to 617 mg l^{-1}. Ca ranged from 19 to 801 mg l^{-1}, K from <1 to 22 mg l^{-1}, Mg from 2 to 351 mg l^{-1}, and Na from ~1 to 367 mg l^{-1}. Figure 3 compares the oxygen and carbon stable isotope composition of all analyzed waters. Lake Güija had the most negative values of $\delta^{13}C_{DIC}$ (−20.8‰) and Cenote Timul the highest (+13.6‰). A small pond, Loché, displayed the highest values of $\delta^{18}O$ (+8.2‰) and large Lake Güija the lowest (−5.1‰).

Most of the sampled cenotes displayed $\delta^{18}O$ values around −4.0‰, similar to weighted mean rainfall. Rivers displayed negative $\delta^{13}C_{DIC}$ (<−7.3‰). Waters of aquatic environments located in the lowlands showed variable oxygen (−4.3‰ to +5.0‰) and carbon (−19.4‰ to +7.4‰) isotopic compositions.

PCA was used to determine the factors that contribute the most to the variability in the chemical composition of surface waters (Fig. 4). All environmental variables (water temperature, dissolved oxygen, pH, conductivity, $\delta^{18}O$ and $\delta^{13}C_{DIC}$, SO_4, Cl, HCO_3, Ca, K, Mg, and Na) were included in the analysis. We present results only from the first and second components, which explain >15% of the total variance in the data. These two components accounted for 48% of the variance, which is almost half of the variation in the entire data set. Conductivity and related variables, i.e., concentrations of principal cations and anions, explained 29% of the variance of axis 1 (eigenvalue = 3.8). This indicates that the aquatic ecosystems fall along a conductivity gradient. Values for pH were positively correlated with dissolved oxygen, $\delta^{18}O$, $\delta^{13}C$ values and temperature, and accounted for 19% of the explained variation (eigenvalue = 2.5). Therefore, this study is focused mainly on the conductivity gradient in the area.

Classification of aquatic environments in the study area is difficult because many factors play an important role in regional water chemistry composition. Cluster analysis, however, was used to identify similar groups of waterbodies based on the same 13 physical and chemical variables used for PCA analysis. A dendrogram with seven groups of aquatic environments can be reduced to three main groups (Fig. 5):

Lowland lakes, ponds, wetlands, and coastal waterbodies

Groups I, V, VI, and VII consist mainly of waterbodies in the lowlands of Guatemala, Belize, and Mexico. Surface water temperatures were somewhat higher ($\leq$32°C) than waters from highland lakes (~27°C). Aquatic environments were relatively shallow (<15 m), with the exception of Lago Petén Itzá (~165 m), and several other karst lakes in the Department of Petén, northern Guatemala (Table 1). Water chemical composition is similar among lowland aquatic environments. Waters are mainly dominated by SO_4, HCO_3, Ca, and Mg, whereas aquatic habitats close to the coast have waters dominated by Cl and Na. Conductivities in the lowlands are higher, up to 5,960 µS cm^{-1}, than in the highlands ($\leq$1,770 µS cm^{-1}). Likewise, $\delta^{18}O$ values are generally higher in the lowland lakes, reaching values of +5.0‰.

Highland lakes

Groups IV and V include lakes at altitudes >430 m a.s.l. Surface water temperatures are colder ($\leq$27°C) than those in the lowlands ($\leq$32°C). The highest

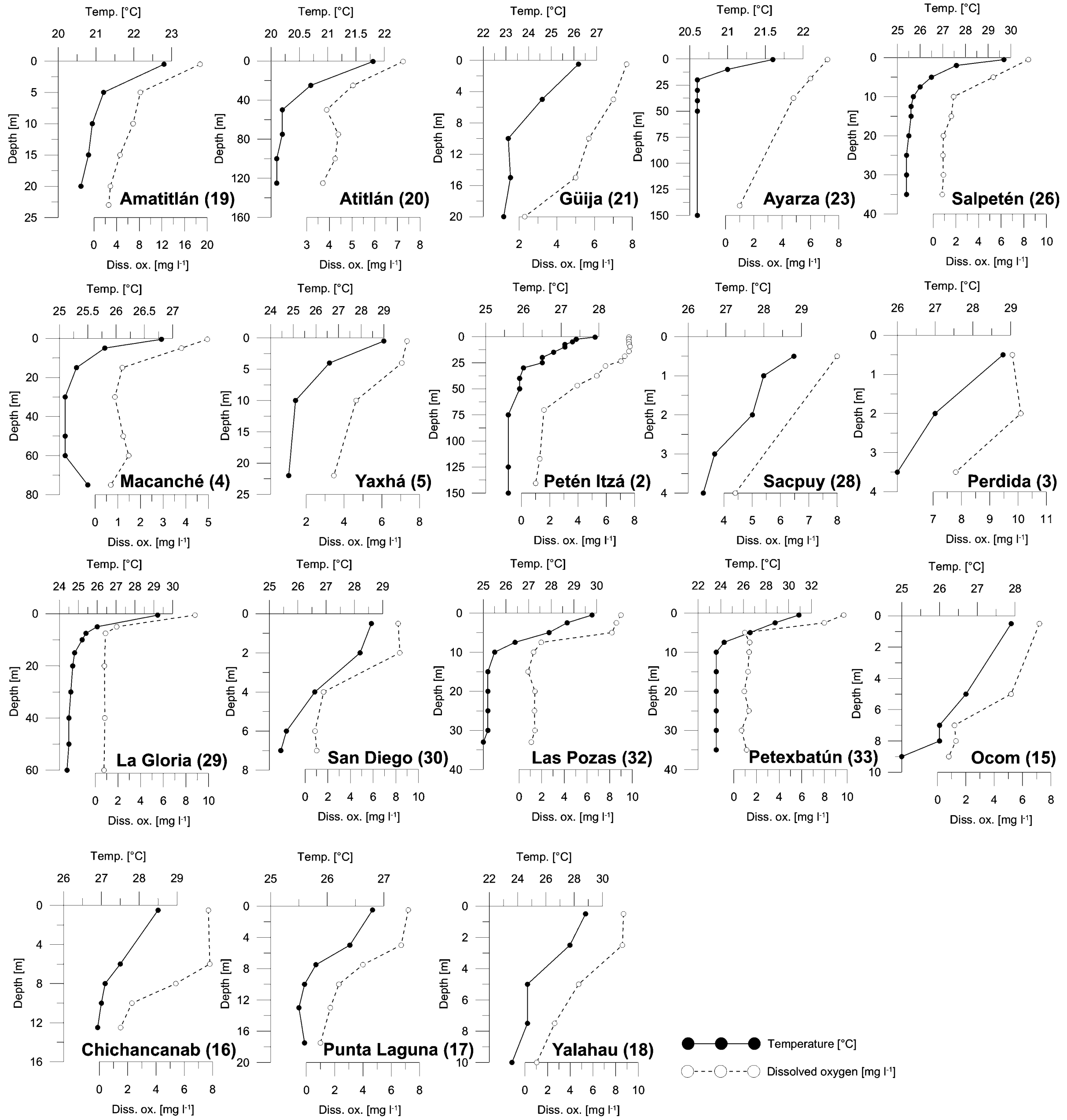


Fig. 2 Temperature and dissolved oxygen profiles of 18 lakes showing stratification during sampling. The *numbers* after each lake name indicate their location in Fig. 1. Deepest thermoclines, between 20 and 40 m, were measured in Lakes Atitlán and Petén Itzá, Guatemala

dissolved oxygen concentration (18.7 mg l^{-1}) among all studied waterbodies was measured in highly productive Lake Amatitlán, and reflects photosynthetically driven supersaturation. Waters of highland lakes were slightly alkaline, up to pH 9.3, and dominated by sodium and bicarbonate. Conductivities were <1,770 μS cm^{-1}. Lakes in the highlands displayed dramatic differences in trophic status. For instance, Lake Amatitlán was eutrophic, which is reflected in its low-water transparency (0.1–0.8 m). Laguna de Ayarza was oligotrophic, with a water transparency of 11.4 m, the highest among the sampled aquatic

Table 3 Main physical and chemical variables and water chemistry of lake surface waters

Area	Code	ID-Nr.	Temp. (°C)	Diss. oxygen (mg l^{-1})	pH	Cond. (μS cm^{-1})	$\delta^{18}O_{VSMOW}$ (‰)	$\delta^{13}C_{DIC}$ (‰)	SO_4	Cl	HCO_3	Ca	K	Mg	Na
Guatemalan highlands	AMA	19	22.8	18.7	9.3	630	−2.6	−14.7	18^{a}	163^{a}	235	23	15^{a}	17	124
	ATI	20	21.8	7.3	8.4	465	−1.6	−4.4	33^{a}	19^{a}	281	34	8^{a}	30	64
	AYA	23	21.6	7.2	8.4	1,770	+1.2	−0.9	–	–	189	31	–	12	367
	GÜI	21	26.2	7.7	8.4	206	−5.1	−20.8	–	–	122	27	–	8	17
	ATE	22	27.3	6.7	8.0	283	−2.2	−8.5	22^{b}	4^{b}	183	23	8^{b}	11	23
Guatemalan eastern lowlands	IZA	1	26.4	7.6	8.3	215	−3.8	−8.6	8	7	120	26	2	7	8
Guatemalan lowlands	OQU	25	31.4	6.9	7.7	238	+1.3	–	–	–	189	62	–	4	4
	SAL	26	29.7	8.4	8.2	4,310	+4.6	−15.7	3,000^{a}	111^{a}	122	801	23^{a}	351	142
	MAC	4	26.8	5.0	8.0	850	+3.3	−8.4	242	42	287	45	5	71	22
	YAX	5	29.0	7.3	8.7	232	+4.4	−2.6	7	13	118	23	4	5	10
	ITZ	2	27.6	8.9	8.5	533	+2.9	−5.2	158	13	115	57	5	19	12
	SAC	28	28.8	8.0	8.4	285	+2.9	−9.5	–	–	171	52	–	6	12
	PER	3	28.8	9.8	8.8	232	+0.5	−1.3	15.2	4	131	43	4	2	3
	GLO	29	29.2	8.8	8.6	187	+2.4	−1.3	–	–	134	40	–	5	5
	DIE	30	28.6	8.2	8.6	179	+1.6	+2.4	–	–	140	36	–	3	4
	POZ	32	29.8	9.0	8.4	292	+1.0	−14.1	–	–	250	44	–	31	3
	PET	33	30.9	9.7	8.0	568	−2.9	−7.9	–	–	293	75	–	40	5
	ROS	34	28.3	7.6	7.1	1,020	−4.3	+7.4	–	–	470	133	–	47	3
Mexican lowlands	MIL	12	27.9	12.4	8.1	2,720	+1.1	−10.0	1,296	125	120	404	17	101	110
	BAC	13	27.0	7.9	7.8	1,220	−2.4	−4.3	1,374	83	190	452	1	84	64
	NOH	14	29.2	9.4	8.5	1,230	+1.4	−9.1	553	550	73	161	6	42	244
	OCO	15	27.9	7.2	8.0	774	+1.0	−6.0	657	143	141	150	3	45	127
	CHI	16	28.5	7.7	8.0	2,060	+2.7	−3.8	2,410	235	120	595	20	156	158
	PUN	17	26.8	7.2	8.0	754	−1.3	−11.0	337	156	280	96	6	31	130
	JOS	36	–	4.8	8.0	488	+2.1	−3.1	–	–	244	47	–	7	55
	SAB	37	27.5	8.1	8.0	139	+0.2	−0.6	–	–	73	19	–	4	7
	BAT	38	26.3	2.2	7.0	146	+1.2	−9.2	–	–	85	23	–	3	12
	LAR	39	28.1	6.0	7.5	174	−0.8	−8.1	–	–	104	20	–	4	20
	JOB	41	31.7	10.9	8.3	241	+1.1	−8.2	–	–	171	42	–	4	2
	FRA	42	24.8	0.9	7.3	474	+0.9	−9.0	–	–	189	93	–	6	12
	MIS	43	26.7	7.7	8.0	1,410	+2.5	−3.8	–	–	104	351	–	15	23
	CAY	45	25.3	3.3	7.4	127	+1.3	−2.7	–	–	85	28	–	4	4
	YAL	18	28.8	8.7	8.9	2,350	+3.0	−1.5	340	189	617	23	17	99	213
	COBA	61	28.9	8.7	8.5	1,210	+2.2	−19.1	31^{c}	281^{c}	256	100	–	5	127
Belizean lowlands	ALM	8	27.5	6.4	7.1	1,720	−1.7	−11.6	138	400	55	58	4	25	236
	CRO	9	28.5	6.9	7.8	330	−1.7	−19.4	52	17	116	44	1	4	11
	HON	10	25.9	9.1	8.5	1,480	+5.0	−4.9	264	228	179	69	0.4	49	166
Min			21.6	0.9	7	127	−5.1	−20.8	7	4	55	19	0.4	2	2
Max			31.7	18.7	9.3	4,310	+5.0	+7.4	2,410	550	617	801	20	351	367

Anion and cation concentrations are given in mg l^{-1}. The ID-Nr. corresponds to the sampling sites in Fig. 1

[a] Brezonik & Fox (1974)

[b] Basterrechea (1988a)

[c] Perry et al. (2002)

Table 4 Main physical and chemical variables and water chemistry of surface waters of additional studied aquatic environments

Aquatic environment	Code	ID-Nr.	Temp. (°C)	Diss. oxygen (mg l^{-1})	pH	Cond. (µS cm^{-1})	$\delta^{18}O_{VSMOW}$ (‰)	$\delta^{13}C_{DIC}$ (‰)	SO_4	Cl	HCO_3	Ca	K	Mg	Na
Cenotes	XLA	50	27.9	4.0	7.0	1,450	−4.0	−10.2	–	–	482	115	–	40	169
	MON	52	26.6	1.4	6.9	3,670	−4.1	−9.7	–	–	482	23	–	115	781
	IGN	55	27.4	2.7	6.9	2,110	−4.1	−13.2	147[a]	370[a]	500	169	–	35	326
	CHE	56	28.3	10.4	7.6	2,520	−3.7	−10.6	–	–	476	217	–	59	382
	TIM	57	30.4	11.4	9.1	1,470	+3.8	+13.6	–	–	604	116	–	81	209
	YOK	58	25.2	5.3	7.4	949	−4.0	−9.7	–	–	421	80	–	28	78
	JUA	60	27.9	8.7	8.1	643	−0.9	−14.2	–	–	293	68	–	23	53
	YAA	63	26.4	10.6	8.0	793	−2.6	−8.8	–	–	287	71	–	19	61
	KAN	54	30.7	9.7	8.2	1,750	+0.4	−1.2	–	–	311	192	–	17	244
	TEK	62	25.5	6.7	7.3	958	−3.8	−11.2	–	–	415	121	–	17	55
Coastal water bodies	PRO	35	26.4	7.0	8.2	2,040	+0.2	−16.8	–	–	213	203	–	16	265
	CEN	11	25.8	8.3	8.2	5,960	−1.0	−8.6	533	1,602	331	131	22	125	930
	ROSA	49	28.1	10.5	8.7	55,300	+3.2	−7.2	–	–	244	–	–	–	–
	CEL	51	24.9	5.2	7.8	38,200	+1.0	−5.0	262[a]	657[a]	348	150[a]	12[a]	73[a]	375[a]
Rivers	SUB	31	26.2	4.2	7.4	720	−3.3	−10.5	–	–	329	164	–	12	9
	IXL	27	25.9	6.7	7.5	1,030	−3.9	−17.6	–	–	433	238	–	60	64
	DUL	24	27.6	6.5	7.6	192	−3.7	−14.6	–	–	153	36	–	13	6
	CUB	44	24.9	7.3	7.8	2,040	−2.8	−12.0	–	–	250	575	–	19	32
	CAN	46	26.9	1.9	7.7	1,560	−3.3	−13.9	–	–	384	359	–	44	17
	GUE	47	26.2	3.6	7.7	2,700	−1.4	−7.3	–	–	421	330	–	117	303
Wetland	JAM	48	25.7	2.9	7.3	2,520	−0.6	−9.0	–	–	189	45	–	7	13
Ponds	TÜM	53	25.9	9.4	9.3	168	+5.6	–	–	–	85	26	–	1	7
	LOC	59	32.0	14.4	9.4	4,340	+8.2	−0.4	–	–	482	99	–	109	908
	SIL	40	30.2	7.7	8.2	183	+0.9	−5.9	–	–	122	27	–	3	11
	BZ1	6	28.2	5.8	7.3	192	+0.3	−7.7	7	12	98	12	5	2	20
	BZ2	7	27.4	7.5	8.0	244	−0.04	−10.8	6	3	180	45	2	2	4
Min			24.9	1.4	6.9	168	−4.1	−17.6	6	3	85	12	2	25	1
Max			32	14.4	9.4	55,300	+8.2	+13.6	533	1,602	604	575	22	32	14

Anion and cation concentrations are given in mg l^{-1}. The ID-Nr. corresponds to the sampling sites in Fig. 1

[a] Perry et al. (2002)

ecosystems. The deepest sampled lakes were Atitlán and Ayarza, with 340 and 250 m, respectively.

Cenotes and rivers

Groups II and III comprise cenotes and rivers. Both types of waterbodies displayed slightly negative $\delta^{18}O$ values, around −4.0‰. Cenote Timul, however, had a high $\delta^{18}O$ value (+3.8‰), dissolved oxygen concentration (11.4 mg l^{-1}), and pH (9.1). The $\delta^{13}C$ values were extremely high (+13.6‰). The highest conductivity recorded in cenotes was 3,670 µS cm^{-1}, and rivers registered values up to 2,700 µS cm^{-1}. Concentrations of HCO_3 reached >600 mg l^{-1} and were higher in cenotes and rivers (430 mg l^{-1}) than in other studied aquatic environments. Ca and Na were the dominant cations in waters of cenotes. Dissolved oxygen concentration was variable in cenotes (1.4–11.4 mg l^{-1}) and in rivers (1.9–6.7 mg l^{-1}). The pH of river water was around 7.5. Cenotes displayed more variable pH values (7.0–9.1).

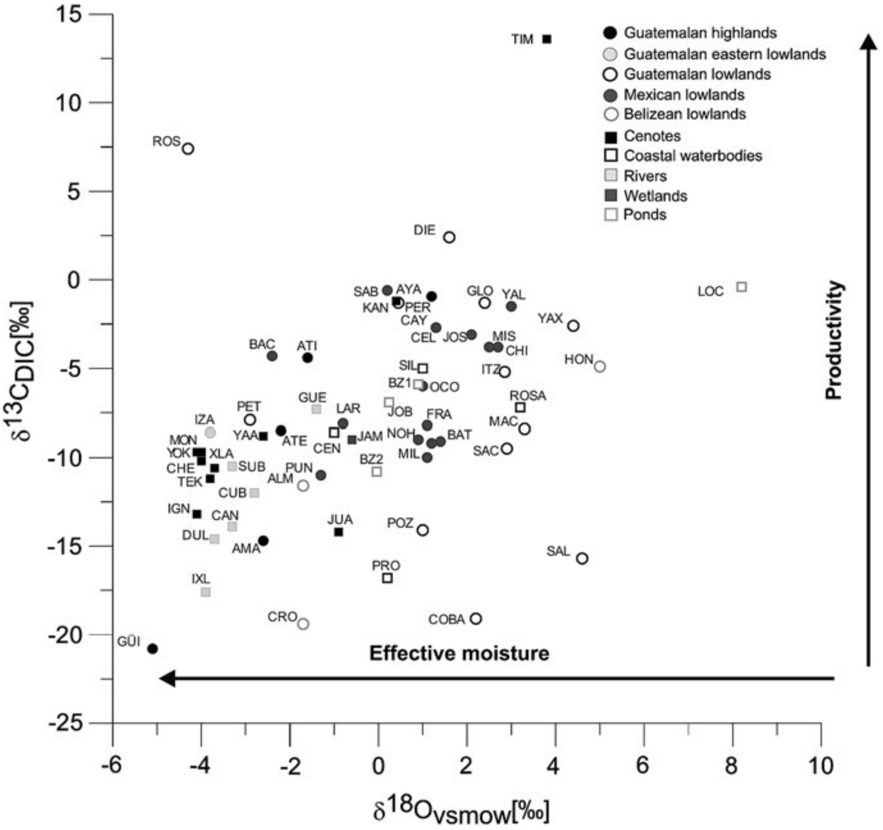
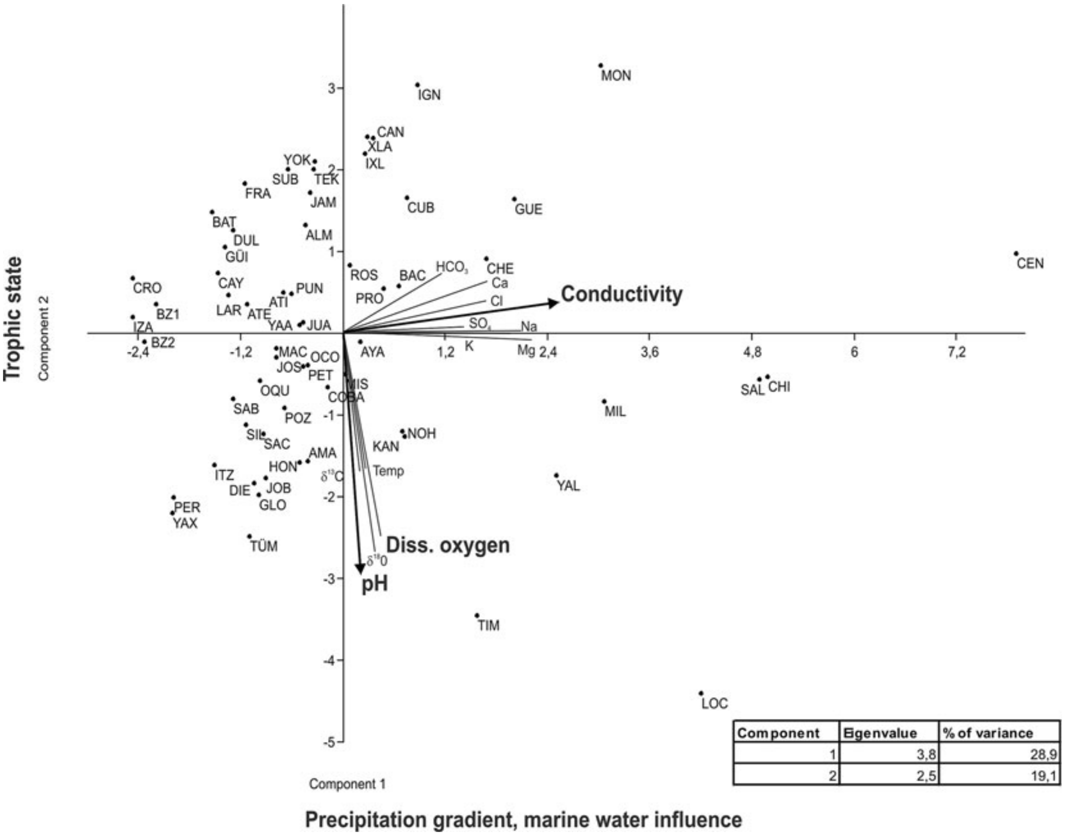


Fig. 3 Stable oxygen and carbon isotopic composition of waterbodies reflecting effective moisture (precipitation–evaporation) and lake water productivity

Geochemical characteristics of surface sediments

Surface sediment descriptions and results of geochemical analyses are shown in Tables 5 and 6. We present results of sediment samples retrieved from the deepest site in lakes and from the littoral zone of other sampled aquatic ecosystems (rivers, ponds, coastal waterbodies, sinkholes, and wetlands). Tables 5 and 6 show the water depths from which surface sediments were retrieved. The deepest-water surface sediment sample we retrieved came from Lago Petén Itzá. Lake sediments were composed mainly of clayey silts that smelled strongly of H_2S. Water content in surface sediment samples from lakes ranged from 52 to 97%, TC from 1.7 to 44.5%, TOC from 0.3 to 44.4%, and TIC from 0.1 to 10.3%. TN concentrations displayed values $\leq$2.7%, and *S* values were $\leq$1.9% (Table 5). The highest concentration of TIC in surface sediment of lakes was determined in Lake Bacalar. The other aquatic environments (Table 6) had surface sediments with water contents that varied from 15 to 97%, TC ranged from 0.3 to 37.3%, TOC from 0.2 to 37.2%, and TIC from 0.1 to 11.2%. The highest TIC concentration was measured in sediments of Cenote San Ignacio. Total nitrogen had concentrations $\leq$4.4%, and total sulfur was $\leq$0.7%.

Major and trace elements (Tables 7, 8) were quantified to further characterize surface sediments from aquatic environments. Heavy metal concentrations provide information on the degree of pollution in aquatic sediments. The highest concentration of arsenic (As) in lakes (Table 7) was found in Lake Amatitlán (201 ppm, I_{geo} = class 4). Among the lakes, Laguna San Diego displayed the highest bromine (Br) concentration (177 ppm). This lake also displayed the highest concentrations of nickel (Ni, 447 ppm, I_{geo} = class 3) and yttrium (Y, 53 ppm). Copper (Cu) concentrations in lacustrine sediments were $\leq$81 ppm (I_{geo} = class 1). Lake Chacan-Lara had the highest concentrations of Cu, lead (Pb, 41 ppm, I_{geo} = class 1), zinc (Zn, 209 ppm, I_{geo} = class 1), and zirconium (Zr, 253 ppm). Iron (Fe) ranged from <1 to over 7% and the highest values were detected in sediments from Laguna Atescatempa. Rubidium (Rb) was high in Jamolún



Component	Eigenvalue	% of variance
1	3,8	28,9
2	2,5	19,1

Fig. 4 Principal component analysis (PCA) based on 13 physical and chemical variables of aquatic environments sampled across the Yucatán Peninsula and surrounding areas. Complete names of waterbodies are shown in Tables 1, 2. Conductivity explained the highest variance (29%) among all studied variables, whereas pH explained only 19% of the data variance

(131 ppm). Selenium (Se) was detected only in sediments from Laguna Rosario, southern Petén (3 ppm, I_{geo} = class 2). Strontium (Sr) ranged from 17 to 1,914 ppm. Among the additional studied aquatic environments (Table 8), River Subín, Petén displayed the highest concentrations of As (26 ppm, I_{geo} = class 1), Cu (60 ppm, I_{geo} = class 0), Fe (7.6%), Pb (36 ppm, I_{geo} = class 1), Y (66 ppm), and Zr (324 ppm). Br concentration was highest in Celestún (229 ppm). Río Dulce had highest concentrations of Ni (1,095 ppm, I_{geo} = class 4) among all studied aquatic environments. Rb was high in the Guerrero River (74 ppm). Cenote Petén de Monos was the only waterbody that contained Se in sediments (21 ppm, I_{geo} = class 5). The coastal waterbody, Laguna Rosada showed the highest Sr concentration (2,436 ppm). Zn was high in Cenote Timul (229 ppm, I_{geo} = class 1).

Discussion

Regional limnology

The study of continental waters in this area is complex because limnological features are influenced by multiple factors including precipitation, basin origin, geographic and geologic setting, topography, orography, climate change, and human impact. Chemical characteristics of our study lakes are influenced by (1) bedrock geology, (2) climate, and (3) saltwater intrusion at coastal sites.

Southern Guatemala is characterized by mountains and volcanoes. The highest sampled lakes, Amatitlán, Atitlán, and Ayarza (Nr. 19, 20, 23, Fig. 1), are located in the Guatemalan highlands at elevations ≥1,200 m a.s.l. These lakes share many features. For instance, they are volcanic lakes characterized by

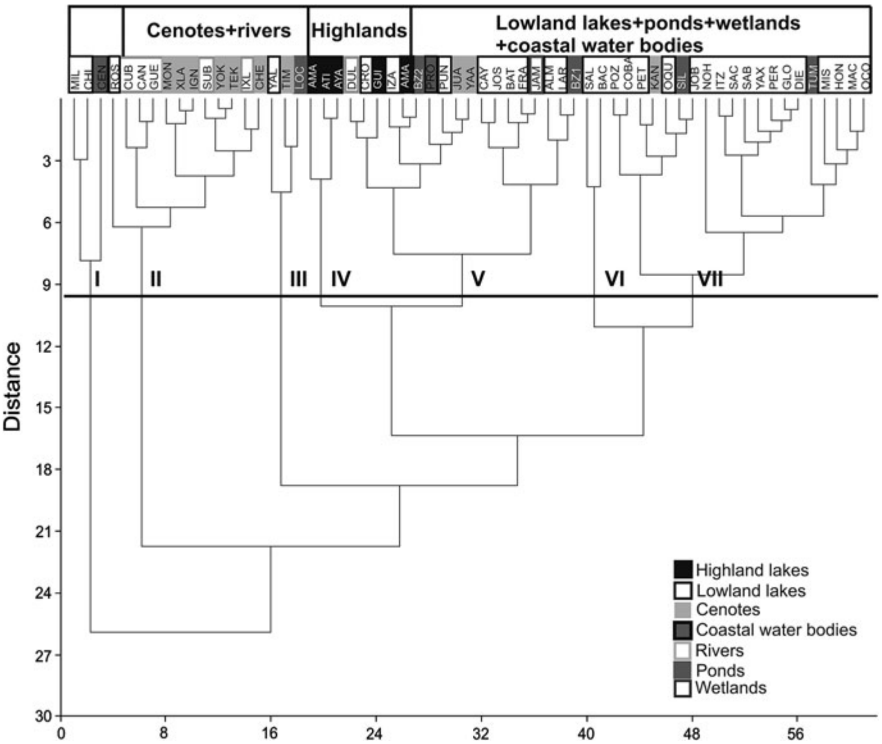


Fig. 5 Dendrogram of cluster analyses based on 13 physical and chemical variables using Ward's method. *Bold line* shows the cut-off criterion for cluster partitioning. Seven groups were identified in three main groups: (1) lowland lakes, ponds, wetlands, coastal waterbodies, (2) highland lakes, and (3) cenotes and rivers. Complete names of waterbodies are shown in Tables 1, 2. *Shading* indicates type of aquatic environment

great depths, up to 350 m, and are located in the Chortis Volcanic Front physiographic province (Marshall, 2006). Our altitudinal gradient ranged from 1,560 to 1 m a.s.l., extending from the Guatemalan highlands down to the northern karst lowlands of the Yucatán Peninsula.

Most of the waterbodies were small (surface area <45 km^2), except for Lakes Izabal (645 km^2), Atitlán (126 km^2), Petén Itzá (100 km^2), and Güija (45 km^2). Mexico has eight lakes with areas >100 km^2 (Alcocer & Bernal-Brooks, 2010). Lake Izabal (Nr. 1, Fig. 1) is Guatemala's largest lake, with the Río Polochic being the largest input river of 18 tributaries (Medina et al., 2010). The main outlet is Río Dulce, which drains to the east. Lake Atitlán, in the Guatemalan highlands, is a large caldera lake and was the deepest (~340 m) sampled lake. Lake Petén Itzá (Nr. 2, Fig. 1) is the deepest (~165 m) lake in the northern Central American lowlands. The lake owes its origin and great depth to tectonism and limestone dissolution. Lake Güija (Nr. 21, Fig. 1) is located on the border between Guatemala and El Salvador, and owes its origin to lava obstruction of the Ostúa and Angue rivers. The lava derived from eruptions of nearby volcanoes San Diego, Vega de la Cana, and Masatepeque (Sapper, 1925). Cenotes display high-relative depths (maximum depth/mean diameter), and are typically fed by groundwater. This is reflected in the oxygen isotopic composition of their water, which is discussed below. Except for Cenotes San Ignacio Chocholá and Tekom, all sampled sinkholes were open.

Surface water temperatures among all studied aquatic environments ranged only from 21.6 to 32.0°C, illustrating the small difference in water temperatures between sea level and higher elevations (~1,560 m a.s.l.). In parts of Mexico, this difference can be greater, which is typical of sites located in the northern hemisphere. High mountain lakes display temperatures ~0°C and lower-altitude lakes have temperatures of 30°C (Alcocer & Bernal-Brooks, 2010). Most of the lakes showed thermal stratification in the water column and the thermocline was well defined (Table 1, Fig. 2). The depth of the thermocline, however, varied among lakes. Heat distribution and hence the position of the thermocline can be influenced by basin morphometry, meteorological conditions, surrounding vegetation, hydrology, and light penetration. To determine the influence of each environmental factor, frequent lake monitoring is

Table 5 Description and geochemistry of lacustrine surface sediments retrieved in the Yucatán Peninsula and surrounding areas

Area	Code	ID-Nr.	Sediment description	Sample water depth (m)	Water content (%)	TC (%)	TOC (%)	TIC (%)	N (%)	S (%)
Guatemalan highlands	AMA	19	Dark brown clayey silts	23	95	10.8	8.9	1.9	1.0	1.5
	ATI	20	Brown clayey silts with gravels	44	49	1.7	0.8	0.9	0.1	0.2
	AYA	23	Gravels	–	–	–	–	–	–	–
	GÜI	21	Light brown clayey silts	21.5	52	2.0	1.9	0.1	0.3	0.2
	ATE	22	Grayish brown clayey silts	0.5	48	2.4	0.3	2.1	0.3	<0.1
Guatemalan eastern lowlands	IZA	1	Pale yellowish brown clayey silts	14	86	4.0	3.5	0.5	–	–
Guatemalan lowlands	OQU	25	Dark brown clayey silts	0.5	76	10.1	8.8	1.3	1.0	0.2
	SAL	26	Light brown clayey silts	37.5	70	15.5	9.2	6.3	1.0	0
	MAC	4	Olive gray clayey silts	75	96	21.9	15.8	6.1	–	–
	YAX	5	Light olive gray clayey silts	22	81	7.1	6.8	0.4	–	–
	ITZ	2	Olive gray clayey silts	165	92	13	10	3	0	0.4
	SAC	28	Light brown clayey silts	5	93	16.7	15.7	1.0	1.8	1.1
	PER	3	Dusky yellowish brown clayey silts	3.5	91	17.8	17.7	0.1	–	–
	GLO	29	Grayish brown clayey silts	64	88	7.9	7.6	0.3	0.9	0.5
	DIE	30	Olive brown clayey silts	8.1	87	20.0	19.8	0.2	1.8	0.4
	POZ	32	Grayish brown clayey silts	35	93	16.0	13.1	2.9	1.2	0
	PET	33	Light grayish brown clayey silts	2.1	75	10.1	4.0	6.1	0.5	0
	ROS	34	Olive brown, highly organic	2.1	83	28.7	25.1	3.6	2.7	0
Mexican lowlands	MIL	12	Yellowish gray clayey silts with gravels	3.5	65	12.8	3.6	9.2	–	–
	BAC	13	Yellowish gray clayey silts	13	59	13.6	3.3	10.3	–	–
	NOH	14	Light olive gray clayey silts	0.5	93	21.9	18.5	5.1	–	–
	OCO	15	Pale orange clayey silts with gravels	9	97	44.5	44.4	0.1	–	–
	CHI	16	Brownish black clayey silts	12.5	95	26.8	24.5	2.3	–	–
	PUN	17	Dark yellowish brown clayey silts	17.5	96	30.1	25.9	4.2	–	–
	JOS	36	Brown sandy clayey silts	2.5	30	14.9	8.3	6.6	0.9	0
	SAB	37	Light brown sandy clayey silts	0.5	61	4.3	4.2	0.1	0.4	0
	BAT	38	Brown sandy clayey silts	0.5	71	15.8	9.8	6.0	1.1	0
	LAR	39	Dark grayish brown clayey silts	0.5	91	11	10.8	0.2	1.1	0
	JOB	41	Dark grayish brown clayey silts	0.5	62	6.5	6.4	0.1	0.6	0
	FRA	42	Dark brown clayey silts	0.5	83	17.7	15.3	2.3	1.3	1.4
	MIS	43	Olive brown sandy clayey silts	5.8	96	15.7	14.4	1.3	1.7	1.9
	CAY	45	Black sandy silts	0.5	67	9.8	9.7	0.1	1.0	0.1
	YAL	18	Dark yellowish brown clayey silts	11	78	9.0	1.7	7.4	1.1	0
	COBA	61	Olive gray silty sands	0.5	63	14.9	6.7	8.2	0.4	0
Belizean lowlands	ALM	8	Dark yellowish brown sandy clayey silts	1.5	75	8.0	8.0	<0.1	–	–
	CRO	9	Olive gray, highly organic	3	75	8.7	6.1	2.7	–	–
	HON	10	Pale yellowish brown clayey silts	7.5	86	21.4	15.9	5.5	–	–
Min				0.5	52	1.7	0.3	0.1	0	0
Max				165	97	44.5	44.4	10.3	2.7	1.9

The ID-Nr. corresponds to the sampling sites in Fig. 1

Table 6 Description and geochemistry of surface sediments of additional studied aquatic environments

Aquatic environment	Code	ID-Nr.	Sediment description	Sample water depth (m)	Water content (%)	TC (%)	TOC (%)	TIC (%)	N (%)	S (%)
Cenotes	XLA	50	Brown sandy clayey silts	0.5	73	23.1	16.3	6.7	1.2	0.5
	MON	52	Dark brown, highly organic	0.5	78	25.9	19.3	6.6	1.1	0.7
	IGN	55	Light grayish brown sands with gravels	0.5	46	11.7	0.5	11.2	0	0
	CHE	56	Grayish brown clayish sands with gravels	0.5	56	13.4	2.6	10.8	0.4	0
	TIM	57	Dark brown clayey silts with gravels	0.5	80	21.8	16.6	5.2	2.3	0.2
	YOK	58	Grayish brown clayey silts with gravels	0.5	55	14.7	4.8	9.9	0.5	0
	JUA	60	Brown clayey silts with gravels	0.5	34	13.9	2.8	11.1	0.3	0
	YAA	63	Gray clayey sands with gravels	0.5	25	12.1	1.0	11.1	0.4	0
	KAN	54	Dark brown sandy clays with gravels	0.5	48	19.8	11.1	8.7	0.6	0
	TEK	62	Brown clayey sands with gravels	0.5	56	12.4	5.4	7.0	0.5	0
Coastal water bodies	PRO	35	Light grayish sandy clayey silts	3.2	82	13.5	3.8	9.7	0.5	0
	CEN	11	Olive gray sandy clayey silts	9	77	17.3	9.1	8.2	–	–
	ROSA	49	Light brown clayey sands with gravels	0.5	42	12.2	2.0	10.2	0.3	0
	CEL	51	Light brown clayey sands	0.5	71	15.1	6.3	8.8	0.6	0.3
Rivers	SUB	31	–	–	–	–	–	–	–	–
	IXL	27	Grayish brown clayey silts	0.5	54	12.8	9.3	3.5	0.1	0
	DUL	24	Brown sandy clayey silts	4	44	3.6	2.5	1.2	0.2	0
	CUB	44	–							
	CAN	46	Light grayish brown clayey silts	0.5	56	13.5	6.4	7.1	0.4	0.4
	GUE	47	Dark brown clayey silts	0.5	58	8.7	6.0	2.7	0.6	0.3
Wetland	JAM	48	Dark brown clayey sandy silts	0.5	65	7.4	6.2	1.2	0.6	0.1
Ponds	TÜM	53	–	–	–	–	–	–	–	–
	LOC	59	Dark brown clayey silts	0.5	78	17.7	11.9	5.8	1.1	0.1
	SIL	40	Reddish dark brown, highly organic	2.5	97	37.3	37.2	0.1	4.4	0
	BZ1	6	Light olive gray clayey silts with gravels	0.5	46	0.3	0.2	0.1		
	BZ2	7	Dark yellowish brown clayey silts with gravels	0.5	15	11.4	0.3	11.1	–	–
Min				0.5	15	0.29	0.2	0.1	0	0
Max				9	97	37.3	37.2	11.2	4.4	0.7

The ID-Nr. corresponds to the sampling sites in Fig. 1

needed. Highland lakes showed a greater temperature difference between surface and bottom waters than lowland lakes. Previously studied Lakes Atitlán and Petén Itzá, Guatemala, had the deepest thermoclines (20- to 40-m-water depth). Basterrechea (1988b) also reported that Lake Petén Itzá's thermocline started below a depth of ~20 m. He described the lake as warm monomictic, stratified from February to November, with brief mixing during winter (December–January). Other warm monomictic lakes in Guatemala include highland Lakes Atitlán and Amatitlán (Juday, 1915; Deevey, 1955). Lake Atitlán lies in the Guatemalan highlands, whereas Lake Petén Itzá is located in the Guatemalan lowlands. Water transparency in both lakes was high, 6.6 and 7.5 m, respectively. Their respective surface areas, 126 and 100 km^2, are also similar. We visited and sampled each lake on only one occasion, and thus missed temporal variability in physical and chemical measures that are detected by frequent or seasonal sampling (Deevey, 1957; Basterrechea, 1988b). Detection of short-term, i.e., diurnal, fluctuations in such variables as temperature and oxygen requires intensive sampling, at times throughout the day. For instance,

Table 7 Major and trace element concentrations in surface sediments retrieved from lakes in the study area

Area	Code	ID-Nr.	As (ppm)	Br (ppm)	Cu (ppm)	Fe (%)	Ni (ppm)	Pb (ppm)	Rb (ppm)	Se (ppm)	Sr (ppm)	Y (ppm)	Zn (ppm)	Zr (ppm)
Guatemalan Highlands	AMA	19	201	69	49	4	0	16	25	0	257	8	113	89
	ATI	20	16	12	44	5	0	7	11	0	526	8	85	104
	AYA	23	–	–	–	–	–	–	–	–	–	–	–	–
	GÜI	21	29	6	52	6	0	37	100	0	103	23	178	174
	ATE	22	12	0	76	6	0	17	37	0	94	19	98	161
Guatemalan Lowlands	OQU	25	10	32	60	2	59	23	30	0	17	24	106	197
	SAL	26	0	38	31	1	0	13	24	0	1,407	2	35	0
	ITZ	2	13	42	46	2	12	30	28	0	203	14	78	121
	SAC	28	16	93	40	3	0	19	22	0	43	14	77	133
	GLO	29	16	47	60	4	49	26	25	0	24	28	86	193
	DIE	30	21	177	67	3	47	27	22	0	26	23	83	143
	POZ	32	33	81	49	3	40	23	14	0	28	24	90	122
	PET	33	0	16	43	2	58	0	18	0	353	7	38	101
	ROS	34	00	57	25	1	20	0	17	3	482	0	26	0
	JOS	36	9	59	22	1	0	18	22	0	98	18	58	76
	SAB	37	–	–	–	–	–	–	–	–	–	–	–	–
	BAT	38	5	29	25	1	22	17	22	0	59	13	106	74
	LAR	39	16	47	81	5	57	41	46	0	27	31	209	253
	JOB	41	11	7	52	4	104	29	131	0	23	35	105	212
	FRA	42	11	32	44	2	105	22	6	0	145	26	135	200
	MIS	43	11	102	47	3	170	34	24	0	420	23	72	190
	CAY	45	12	9	73	3	447	24	17	0	94	53	117	251
	YAL	18	13	65	19	1	0	5	21	0	1,914	0.5	23	0
	COBA	61	8	27	0	0.5	0	11	0	0	1,710	0	0	0
Min			0	0	0	0.5	0	0	0	0	17	0	0	0
Max			201	177	81	6	447	41	131	3	1,914	53	209	253

The ID-Nr. corresponds to the sampling sites in Fig. 1

Caballero et al. (2006) studied the daily variability of oxygen and temperature profiles in Lago Verde, Mexico.

We did not measure temperature and oxygen profiles in cenotes. Only surface waters were analyzed. Hydrochemical characteristics of cenotes in southeast Mexico were studied by Comín et al. (1996) and Herrera-Silveira et al. (1998). Cervantes-Martínez et al. (2002) studied eight cenotes during the dry season. Perry et al. (1995, 2002, 2003) focused on the hydrogeology and hydrogeochemistry of the karst aquifer system of the northern Yucatán Peninsula. The biota and the physical and chemical characteristics of cenotes were studied by Schmitter-Soto et al. (2002), and the stable isotope systematics of two cenotes were studied by Socki et al. (2002).

Waterbodies in the peninsula display local geochemical variations that are related to groundwater influence (Perry et al., 2002, 2009).

Multivariate analysis, using water variables of all sampled aquatic environments, showed that conductivity is the dominant factor to characterize the waters, reflecting the steep NW–S precipitation gradient and saltwater intrusion at coastal sites. Talling & Talling (1965) and Kilham (1990) suggested that conductivity and total ionic composition of lake waters can be used as indicators of water type. The pH and dissolved oxygen explained 19% of the variance in the water

Table 8 Major and trace element concentrations in surface sediment retrieved from the additional aquatic environments in the study area

Aquatic environment	Code	ID-Nr.	As (ppm)	Br (ppm)	Cu (ppm)	Fe (%)	Ni (ppm)	Pb (ppm)	Rb (ppm)	Se (ppm)	Sr (ppm)	Y (ppm)	Zn (ppm)	Zr (ppm)
Cenotes	XLA	50	9	59	25	1	25	34	17	0	495	2	48	64
	MON	52	23	206	31	0.5	30	0	19	21	1,464	1	10	0
	IGN	55	0	13	23	1	0	0	13	0	298	2	42	49
	CHE	56	0	66	0	0.4	0	0	0	0	1,615	0	0	0
	TIM	57	15	32	58	1	0	9	22	0	978	3	229	0
	YOK	58	0	54	23	0.5	0	0	14	0	634	1	25	0
	JUA	60	7	26	0	0.5	1	9	15	0	1,210	0	67	0
	YAA	63	7	7	0	1	0	14	14	0	388	3	19	50
	KAN	54	0	26	0	0.5	0	0	16	0	1,229	0	37	0
	TEK	62	22	22	29	2	0	25	44	0	214	20	174	116
Coastal water bodies	PRO	35	12	69	0	1	0	8	18	0	1,245	1	11	65
	ROSA	49	0	72	0	0	0	0	17	0	2,436	0	0	0
	CEL	51	0	229	20	0	0	0	16	0	2,365	0	0	0
Rivers	SUB	31	26	4	60	8	39	36	64	0	21	66	128	324
	IXL	27	9	15	33	1	0	18	25	0	307	10	53	113
	DUL	24	11	7	47	7	1,095	17	54	0	149	15	109	128
	CUB	44	14	9	0	2	63	24	0	0	645	41	48	176
	CAN	46	8	12	27	1	38	14	0	0	1,144	5	50	101
	GUE	47	9	86	38	3	105	18	74	0	599	12	55	170
Wetland	JAM	48	9	9	38	3	31	36	62	0	44	33	109	204
Ponds	TÜM	53	–	–	–	–	–	–	–	–	–	–	–	–
	LOC	59	10	135	0	1	0	14	49	0	502	18	42	102
	SIL	40	–	–	–	–	–	–	–	–	–	–	–	–
Min			0	4	0	0	0	0	0	0	21	0	0	0
Max			26	229	60	8	1,095	36	74	21	2,436	66	229	324

The ID-Nr. corresponds to the sampling sites in Fig. 1

chemistry data set, providing evidence of eutrophication in some waterbodies (i.e., Amatitlán and Timul). PCA was used by Alcocer & Bernal-Brooks (2002) to identify variables that explain spatial and temporal differences within Lake Pátzcuaro, Mexico. Variables that explained most of the variance included conductivity and total residue. Conductivity in our study systems ranged from 127 µS cm^{-1} to 55.3 mS cm^{-1}. Highest conductivities were measured in the north and lower values were recorded in the south, reflecting the latitudinal precipitation–evaporation gradient and higher marine influence in the northern Yucatán Peninsula. Coastal lakes affected by saltwater intrusion and/or sea spray display high conductivities. Such waters were neutral to alkaline and characterized by HCO_3, SO_4, and Cl, Ca, Mg, and Na.

The pH of Lake Amatitlán waters was considerably lower in 1969 (7.7, Brezonik & Fox, 1974) than in 2008 (9.3). One explanation for this difference may be the cultural eutrophication of the lake that occurred over the last few decades. Today, dense algal blooms in surface waters rapidly consume dissolved CO_2 during photosynthesis, driving pH higher as the rate of CO_2 uptake for photosynthesis exceeds the rate of metabolic CO_2 production. Time of day may also influence the water-column pH, with higher values expected during the period of maximum primary production in the afternoon. Seasonal differences in precipitation may also play a role. Basterrechea (1986) studied Lake Amatitlán from March to November 1985. pH values were lower during the dry season (7.5) than during the rainy season in 1985 (8.5).

Seasonal precipitation differences also affect conductivity. The conductivity we measured at the end of the rainy season in 2008 (630 μS cm^{-1}) was lower than values determined in summer 1969 by Brezonik & Fox (830 μS cm^{-1}).

Lake Amatitlán displayed the highest chloride concentration among the Guatemalan lakes (163 mg l^{-1}). This is probably related to the volcanic terrain and high-chloride content of water and gas entering the lake (Deevey, 1955).

Comparisons between electrical conductivities measured in Petén lakes in 1969 and during our study show a slight increase over the past four decades: Lago Petén Itzá (1969, 483 μS cm^{-1}; 2008, 533 μS cm^{-1}), Lake Macanché (1969, 700 μS cm^{-1}; 2008, 850 μS cm^{-1}), and Lake Salpetén (1969, 4,100 μS cm^{-1}; 2008, 4,300 μS cm^{-1}). This may, in part, be explained by a different reference temperature used in measurements (i.e., 20 vs. 25°C). Highland Lake Atitlán also showed a slight increase in conductivity through time (1969, 420 μS cm^{-1}; 2008, 465 μS cm^{-1}). Seiler et al. (1994) reported a value of 2,000 μS cm^{-1} for Lake Atitlán, which they related to high lake evaporation. Nevertheless, $\delta^{18}O$ values for lake waters (−1.6‰) are consistent with those reported by Seiler et al. (1994), suggesting factors besides evaporation are responsible for the temporal change in conductivity. We determined higher concentrations of cations and anions, except for Mg, in Lago Petén Itzá than did Brezonik & Fox (1974). This may be associated with reduced groundwater outflow (Basterrechea, 1988b; Pérez et al., 2010). Waterbodies in the Petén Lake District are located close to one another (Fig. 1). They all have a tectonic/solution origin and lack overland outflows, but they differ significantly in water chemistry and conductivity. Sulfate-rich Lake Salpetén (Nr. 26, Fig. 1) has the highest conductivity (4,300 μS cm^{-1}) among the sampled lakes, while Lakes Yaxhá, Sacpuy, Perdida, Gloria, and San Diego (Nr. 5, 28, 3, 29, 30, Fig. 1) are relatively fresh (≤285 μS cm^{-1}). High conductivity in Lake Salpetén may indicate that the lake receives hydrologic input from a salt spring or groundwater that flows through gypsum deposits. The $\delta^{18}O$ value of waters (+4.6‰) and the Sr concentration (1,407 ppm) in sediments from Lake Salpetén were the highest values measured in Petén lakes and indicate high evaporation. Our water chemistry results are consistent with results published by Basterrechea (1988a) for Lakes Salpetén, Yaxhá, Atescatempa, and Ayarza. The water chemistry of Lake Izabal showed similar composition in 2005 and in 1969 (Brezonik & Fox, 1974).

Classification of aquatic ecosystems across a climatic gradient

Classification of the aquatic environments in the study area by chemical composition is difficult because many factors affect water chemistry. Accurate limnological classification requires that geographic, geologic, and climatic characteristics be considered. We conducted a cluster analysis on 13 physical and chemical variables, and distinguished three groups of aquatic environments located in two regions.

Lowlands

The lowlands are characterized by lakes, cenotes, rivers, small ponds, wetlands, and coastal waterbodies. Rivers and large waterbodies are missing in the northern part of the Yucatán Peninsula due to rapid infiltration of rainfall. All lowland waterbodies had slightly negative or slightly positive water column $\delta^{18}O$ values. Values of $\delta^{18}O$ are controlled mostly by evaporation/precipitation ratio, the mean oxygen isotopic composition of the catchment precipitation, groundwater exchange, and seasonal stratification and mixing of the lake. Physical processes such as evaporation and water circulation govern the isotopic composition of lake waters. Evaporation from lakes is related to relative humidity, temperature, and wind stress, and the impact on the oxygen stable isotope signature is further controlled by surface area/volume ratio and water residence time (Covich & Stuiver, 1974; Gat, 1995, 1996; Griffiths et al., 2002; Schwalb, 2003). For instance, Leng & Anderson (2003) observed that water column $\delta^{18}O$ values depend on lake size in western Greenland. It is possible that our $\delta^{18}O$ measurements were affected by large rainfall inputs associated with the 2005 hurricanes that shifted values more negative. The $\delta^{18}O$ of water in closed-basin lakes, i.e., lakes lacking major surficial inflows or outflows, is controlled largely by the ratio of evaporation to precipitation (Talbot, 1990; Curtis et al., 1996). Lakes such as Salpetén, Macanché, Yaxhá, Lago Petén Itzá, Sacpuy, La Gloria, Honey Camp, and Chichancanab display δ^{18}O values greater than those of regional precipitation, illustrating evaporative enrichment (Brenner et al., 2003). Lakes Yalahau and Chichancanab (Nr. 18, 16, Fig. 1) are located farther north, where precipitation is lower. This may explain their relatively higher water δ^{18}O values. A relatively low δ^{18}O value (~ -4.0‰) was determined at Cenote "La Normal," which is a sinkhole connected to Lake Bacalar (Nr. 13, Fig. 1). It receives a large amount of groundwater as part of its hydrologic budget, thus accounting for the negative δ^{18}O value. Groundwater δ^{18}O values on the karst Yucatán Peninsula are similar to those for weighted mean rainfall, because rapid infiltration precludes evaporative fractionation (Brenner et al., 2003). Lakes in the south displayed low δ^{18}O values, typical of areas with high-effective moisture (i.e., low evaporation/precipitation). Lake Izabal is located in the wetter SE lowlands of Guatemala with annual precipitation approaching 2,900 mm year^{-1}, and lake waters thus showed relatively low δ^{18}O values (-3.8‰) compared to other lowland lakes located farther north. In addition, Lake Izabal receives ^{18}O-depleted input waters via the Río Polochic, which originates in the Guatemalan highlands. Lake Izabal, despite being in the lowlands, plotted in the dendrogram with the lakes in the highlands, where precipitation is high.

Inland waters were mainly dominated by Ca, HCO_3, and SO_4. Waterbodies in the karstic Petén Lake District were rich in carbonate and their sediments contained abundant ostracodes and gastropods. Waterbodies close to the coast were dominated by Cl and Na, and foraminifera were found in many cases. Seawater intrusion reaches as far as the central part of the Yucatán Peninsula ($\sim$100 km), and is driven mainly by tidal motion (Perry et al., 1995; Alcocer & Escobar, 1996). Perry et al. (2002) divides the carbonate platform of the Yucatán Peninsula into six hydrogeochemical/physiographic regions (Fig. 1). They are characterized by tectonics, rock type, sedimentation patterns, erosion, and rainfall/evaporation. Lakes Milagros, Bacalar, and Chichancanab (Nr. 12, 13, 16, Fig. 1) are located in the evaporative hydrogeochemical region. In our study, Milagros and Chichancanab did not group with the other lowland lakes (Fig. 5), reflecting higher conductivity ($\geq$2,060 µS cm^{-1}), and greater δ^{18}O values ($\geq$+1.1‰).

Lake waters were dominated by SO_4 ($\leq$2,410 mg l^{-1}), while Cl concentrations were much lower ($\leq$235.4 mg l^{-1}), indicating groundwater flow into lakes. Groundwater in this region is characterized by high sulfate concentrations and relatively low chloride concentrations. Our results are consistent with measurements made by Perry et al. (2002) in this area in 1995 and 1996. Their study identified a southwest flow of sulfate-rich groundwater in this region that may even extend into Belize and Guatemala. The SO_4/Cl ratio in inland waters was compared to that for seawater to assess the contribution of seawater to aquatic habitats. Seawater chlorinity is about 19,370 mg l^{-1} and sulfate concentration is $\sim$2,780 g l^{-1}, yielding a SO_4/Cl ratio of $\sim$0.143. Although Lake Bacalar is close to the coast, the Cl concentration was low (83 mg l^{-1}) relative to seawater and the SO_4 concentration in the lake (1,374.4 mg l^{-1}) yielded a high SO_4/Cl ratio (16.56), indicating that any contribution from seawater is overwhelmed by sulfate-rich groundwater input.

Cenotes and rivers were grouped together. This can be explained by the distinctive oxygen isotopic composition of their waters. δ^{18}O values were all negative (~ -4.0‰), with the exception of Cenotes Timul, and Kaná (Nr. 57, 54, Fig. 1), where higher values suggest the strong influence of evaporation ($\delta^{18}O = \leq +3.8$‰). These two cenotes displayed the highest $\delta^{13}C_{DIC}$ values (up to +13.6‰), indicating that they are highly productive (McKenzie, 1985). Most of the sampled cenotes (Xlacah, Ignacio Chocholá, Chenhá, San Francisco Kaná, and Timul) are located in the Chicxulub Sedimentary Basin (Perry et al., 2002), in the NW lowlands of the Yucatán Peninsula (Fig. 1). The region is characterized by low permeability, and groundwater chemistry reflects mixing with saline waters (Perry et al., 2002). Na contents were relatively high in surface waters, up to 381 mg l^{-1}. Sediments collected in the cenotes had high concentrations of TIC, typical of waterbodies that are formed by limestone dissolution. Cenote waters had the highest HCO_3 concentrations of all aquatic environments.

Highlands

Cluster analysis showed that lakes in the Guatemalan highlands have similar physical and chemical characteristics. Most of the highland lakes are of volcanic origin, and are large and deep. Although lake waters displayed somewhat variable δ^{18}O values, all were negative to slightly positive (≤+1.2‰). The most negative value was measured in Lake Güija (−5.1‰). Lake Güija has three main inflow rivers, Ostúa, Angue, and Cusmapa, which probably supply relatively ^{18}O-depleted waters. The altitude effect (Clark & Fritz, 1997) may also account for the relatively low oxygen isotope values in the highland lakes. In contrast to the lowland lakes, where Ca dominated, Na dominated the waters of the highland lakes. Although volcanic areas sometimes display acid waters (Brezonik & Fox, 1974), the highland lake waters were characterized by high pH values and bicarbonate concentrations. Laguna de Atescatempa (Nr. 22, Fig. 1), because of its shallow depth (2 m) and small size (~1.1 km^2), differs from the rest of the highland lakes in the region (≥14 km^2). Furthermore, this lake has experienced a pronounced reduction in volume and surface area in the last few decades due to agriculture expansion. In 1988, the lake was larger and deeper (5.6 m) than it is today (Basterrechea, 1988a). Lake Amatitlán also differs from the rest of the highland lakes. Lakewater and sediment variables indicate that the lake has become hypereutrophic.

Trophic state and pollution

The trophic status of each aquatic environment was assessed using nutrient and chlorophyll *a* concentrations in the waters. In this study, we used water transparency (Secchi depth) and $\delta^{13}C_{DIC}$ values as indicators of primary production. Heavy metal concentrations in lake sediments provided preliminary information on the degree of pollution in the aquatic ecosystems. We analyzed a few surface sediment samples from each waterbody, which we considered sufficient for preliminary descriptive purposes. Better pollution assessments will require more intensive sampling and comparison of results to global reference values (Turekian & Wedepohl, 1961).

Waterbodies in the region display a broad range of trophic states. Only a few oligotrophic lakes were identified. Water transparency in some highland lakes was high (≥6.6 m). For instance, Lake Atitlán was sampled in February 2008, when there was high-water transparency. Brezonik & Fox (1974) classified the lake as pristine and oligotrophic in July 1969. In October and November 2009, however, the lake supported a dense cyanobacteria bloom. *Lyngbya hieronymusii* (Lemmermann, 1905) spread rapidly, covering up to 75% of the lake surface. This toxic cyanobacterium is a potential danger to human and animal health, and created a need for the Guatemalan Government to develop strategies to improve lake water quality (Persson, 2009).

Lake Amatitlán (Nr. 19, Fig. 1) showed the lowest water transparency (≤0.8 m) among the lakes. Secchi depth in February 2008, at 1400 h was only 0.1 m, but increased to 0.8 m by 1600 h. This rapid shift in water transparency may be explained by vertical plankton migration, but may also reflect settling of plankton through the water column when winds subside in the late afternoon. Eutrophic conditions in this lake were reported as early as the 1950s (Deevey, 1955), but were probably established even earlier. Deevey (1955) reported total phosphorus concentrations in the water column of ~75 μg l^{-1} and he collected abundant *Chironomus* sp. from the lake bottom, a dipteran taxon indicative of mesotrophic to eutrophic conditions (Massaferro et al., 2004). Green waters are indicative of high algae concentrations in the lake. The lake has one main input river, the Río Villalobos and one outflow, the Río Michatoya. Drainage waters of the Río Michatoya are used for hydroelectric power generation. The main source of contaminants to the lake is the Río Villalobos, which carries wastewater from the capital, Guatemala City, 20 km away (Basterrechea, 1986). There is only rudimentary wastewater treatment, and consequently, nutrients, industrial wastes, and biological contaminants make their way to the lake. Mountains surrounding the lake are deforested, promoting rapid soil erosion, and watershed agriculture employs large amounts of fertilizer. Surface sediments are relatively high in organic components (8.9% TOC), and have relatively high concentrations of Br (69 ppm) and As (201 ppm). According to Müller (1979), such a high concentration of As indicates that lake sediments are strongly polluted. Other highland lakes had lower TOC, Br and As concentrations. Wells that supply the city of Amatitlán with drinking water derive their water from the Río Michatoya. High As levels have also been reported in drinking water from the city of Amatitlán (Portillo Guzmán, 2009).

High $\delta^{13}C_{DIC}$ values are characteristic of lakes with highly productive waters (McKenzie, 1985). For example, Laguna Perdida and El Rosario (Nr. 3, 34, Fig. 1), in the lowlands of Petén, Guatemala displayed the highest values, up to +7.4‰. Cenote Timul (Nr. 57, Fig. 1) in the northern Yucatán Peninsula had even higher values (+13.6‰). At the time of water sampling, the lake was very green, due to a dense algae bloom. The carbon isotope composition of the dissolved inorganic carbon (DIC) in lacustrine waters is largely controlled by the photosynthesis–respiration cycle (McKenzie, 1985). In eutrophic lakes, phytoplankton preferentially assimilate ^{12}C during photosynthesis, which enriches the DIC pool with ^{13}C (Herczeg & Fairbanks, 1987). Therefore, the ^{13}C value in lacustrine carbonates can be used as a proxy for biological productivity (Aravena et al., 1992). This would lead one to suspect that the $\delta^{13}C_{DIC}$ of eutrophic Lake Amatitlán waters should be relatively high. The $\delta^{13}C_{DIC}$ values of Lake Amatitlán surface waters, were, however, quite negative (−14.7‰), as were those of Lake Güija (−20.8‰). Variations in the $\delta^{13}C_{DIC}$ values of lake waters are largely explained by exchange with atmospheric CO_2. The ^{13}C content of the inflowing groundwater (dissolved carbonates) and CO_2 produced during the decomposition of organic matter may contribute to variations as well. The low $\delta^{13}C_{DIC}$ values in these two waterbodies may reflect a CO_2 contribution from degradation of organic matter (∼−25‰) and/or rapid rate of CO_2 input from geologic sources in volcanic terrains (Fritz & Poplawski, 1974; Peterson & Fry, 1987; Leng & Anderson, 2003; Myrbo & Shapley, 2006).

Lake Atescatempa (Nr. 22, Fig. 1), in the eastern highlands of Guatemala, displayed evidence of moderate pollution. The lake has been largely drained for agriculture (Basterrechea, 1988a). The use of chemical fertilizers and pesticides led to higher concentrations of Cu, Zn, and Fe in the lake sediments. The Río Subín (Nr. 31, Fig. 1), in Petén, Guatemala, was the most polluted of all the studied rivers. Sediments displayed high concentrations of As, Cu, Fe, Pb, Rb, Y, Zn, and Zr, suggesting moderate pollution. The river is a popular attraction for local inhabitants and serves as an important water source although it flows through several agricultural land holdings that employ fertilizers.

The highest Ni concentrations (1,095 ppm) were determined in sediments of Río Dulce (Nr. 24, Fig. 1), the outlet from Lake Izabal. This indicates that Río Dulce is strongly polluted. A mine and a smelter were established at El Estor, on the shore of Lake Izabal, in the 1960s to exploit a rich Ni deposit (Brinson et al., 1974). Laguna Cayucón (Nr. 45, Fig. 1) also displayed relatively high concentrations of Ni (447 ppm) and lake sediments were classified as moderately to strongly polluted. Trace amounts of Ni are required by organisms, but when Ni uptake is high, it can endanger their health. Br is generally bound to organic matter and Lake San Diego (Nr. 30, Fig. 1) had both the highest Br and organic carbon concentrations among sediments from the sampled lakes.

Intensive sampling is needed in the study area. Future regional studies should include limnological, meteorological, geological, physiographical, and vegetation data. A joint effort among scientists from several disciplines will be needed. This will allow better characterization of waterbodies and interpretation of limnological data from the Yucatán Peninsula, Belize, and Guatemala.

It is our hope that the data presented here will also contribute to the formulation of strategies for aquatic ecosystem conservation and management in the region. Guatemala, Mexico, and Belize are rich in aquatic resources, however, insufficient support for study and management of these ecosystems places them at risk. Short-term, “snapshot” studies are still the norm, with little attention paid to routine monitoring and evaluation of water quality over time. Lake dynamics are best studied using intensive sampling strategies (i.e., monthly and at various times throughout the day). We encourage collaborations between local and foreign universities, government agencies, and NGOs to achieve better management of aquatic environments in developing countries.

Conclusions

This study highlights the diversity of aquatic ecosystems on the Yucatán Peninsula (Mexico), Belize, and Guatemala. PCA using physical and chemical variables of surface waters of 61 waterbodies indicated that conductivity explains 29% of the variability in the water chemistry data set. This reflects the steep NW–S precipitation gradient and marine water influence in aquatic habitats close to the coast. The pH, dissolved oxygen and related variables explained 19% of the variance, reflecting eutrophication in lakes Amatitlán and Timul. Aquatic ecosystems in the highlands and lowlands can be classified into three groups: (1) lowland lakes, ponds, wetlands, and coastal waterbodies, (2) highland lakes, and (3) sinkholes and rivers. Water ionic composition was determined largely by the lake's mode of origin. Highland volcanic lakes display waters dominated by Na, HCO_3, and Cl, whereas Ca, HCO_3, and SO_4 dominate the waters of lowland lakes of karst origin. Waterbodies close to the coast are dominated by Na and Cl. Local hydrogeochemistry of aquatic ecosystems is related to groundwater influence. Cenotes on the NW Yucatán Peninsula display negative $\delta^{18}O$ values (−4.0‰), with the exception of Timul and Kaná ($\leq$+3.8‰). Highland lakes of Guatemala display the greatest water transparency ($\geq$6.6 m), with the exception of Lake Amatitlán, which suffers from cultural eutrophication. Other waterbodies (Laguna Rosario, Perdida, and Cenote Timul) show evidence of highly productive waters ($\delta^{13}C = \leq +13.6$‰) as well. Heavy metal concentrations in aquatic sediments provided information on the degree of pollution. High concentrations of Ni in sediments of Río Dulce suggest severe pollution. Lake Atescatempa and the Subín River were identified as moderately polluted waterbodies.

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