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Water quality of inlets' water bodies in a growing touristic barrier reef Island "Isla Holbox" at the Yucatan Peninsula

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ABSTRACT

Holbox Island faces issues related to the availability of freshwater and living space given the increasing coastal migration and tourism development in the region. We report the water quality of 12 tidal inlets (which are geomorphological features of barrier islands), which neighbor hotels. Because no previous studies of tidal inlets exist on Holbox, we used reference published values of water quality and unpublished water values collected at 43 sampling sites throughout the Yalahau Lagoon. Analyses of water quality variables and the trophic index (TRIX) were measured. Inlets sites salinity values ranged from 11 to 36 psu. Average values for nitrates (0.83 μmol l^{-1}), and nitrites (0.14 μmol l^{-1}), at inlets, had lower values in the fronts season. Soluble reactive phosphate (48.8μmol l^{-1}), and silicate (78.6 μmol l^{-1}) were higher at inlets during rains and chlorophyll-α (29.7 mg/m^3) was more top at inlets during fronts. TRIX values for inlets ranged between 2 and 6, indicating low water quality in most inlets associated with hotel sites. Seasonal changes in soluble reactive phosphate and chlorophyll-α at inlets suggests these could be receiving sewage water discharges from human activities. Besides inlet's higher water residence time and slower water interchange rate can favor the accumulation of pollutants. Results demonstrate that water quality issues exist on Holbox and need management actions to prevent the decay of coastal ecosystem services. These are necessary for positive feedback between local communities' wellbeing and successful tourism development in the region.

1. Introduction

Water quality of barrier islands and their nearshore environments (*e.g.* watersheds, shores, estuaries, coastal lagoons, coral reefs, mangroves) is being affected globally by the increasing economic development related to human activities such as tourism, fisheries, aquaculture, and agriculture. The actions are proven to cause changes in the ecological structure, functions, and dynamics, of barrier islands and nearshore environments worldwide (Rivera-Monroy et al., 2004; UNESCO, 2010; Michalak, 2016). The ecological functions of nearshore environments at barrier islands in the state of Quintana Roo (QR) in the Yucatan Peninsula (YP), provide an array of ecosystem services such as: fisheries, carbon sequestration, storm protection, and recreation, to thousands of coastal settlers and millions of tourists who visit the region yearly (Hernández-Terrones et al., 2015; SEDETUR, 2015; Salas et al., 2011; Herrera-Silveira et al., 2013) (Fig. 1).

Over the past 35 years the increasing tourism-based economic development at QR has initiated multiple socio-environmental issues related to the availability of freshwater for human use, living space, environmental degradation, organic pollution, and overexploitation of coastal resources (Herrera-Silveira et al., 2004a, b; Carte et al., 2010; Leatherman et al., 2010; Rubio-Maldonado et al., 2010; Leal-Bautista et al., 2013; Hernández-Terrones et al., 2011, 2015; López Santillán, 2010, 2015). Cancun's barrier island transformation over the last 36 years is an example of how the natural landscape turned into roads, marinas, shopping centers, and hotels which harbor over 30,608 rooms (Wiese, 2000; Vargas Martínez et al., 2013; SEDETUR, 2015). Consequently, mangrove forests, shores, reefs, and coastal lagoons, among other ecosystems are facing threats to their ecological functions which limits the successful delivery of ecosystem services these environments provide to humans. For example, the severe erosion problems at Cancun beaches which have caused ecological and economic losses during the hurricane season (Silva et al., 2014).

The high tourism demand for Cancun allowed for several decades the slowdown of the detrimental effects of economic

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Abbreviations: YP, Yucatán Peninsula; QR, Quintana Roo; NO_2^-, Nitrite; NO_3^-, Nitrate; NH_4^+, Ammonium; SRP, Soluble reactive phosphate; SRSi, Soluble reactive silicate; Chl-*a*, Chlorophyll-*a*

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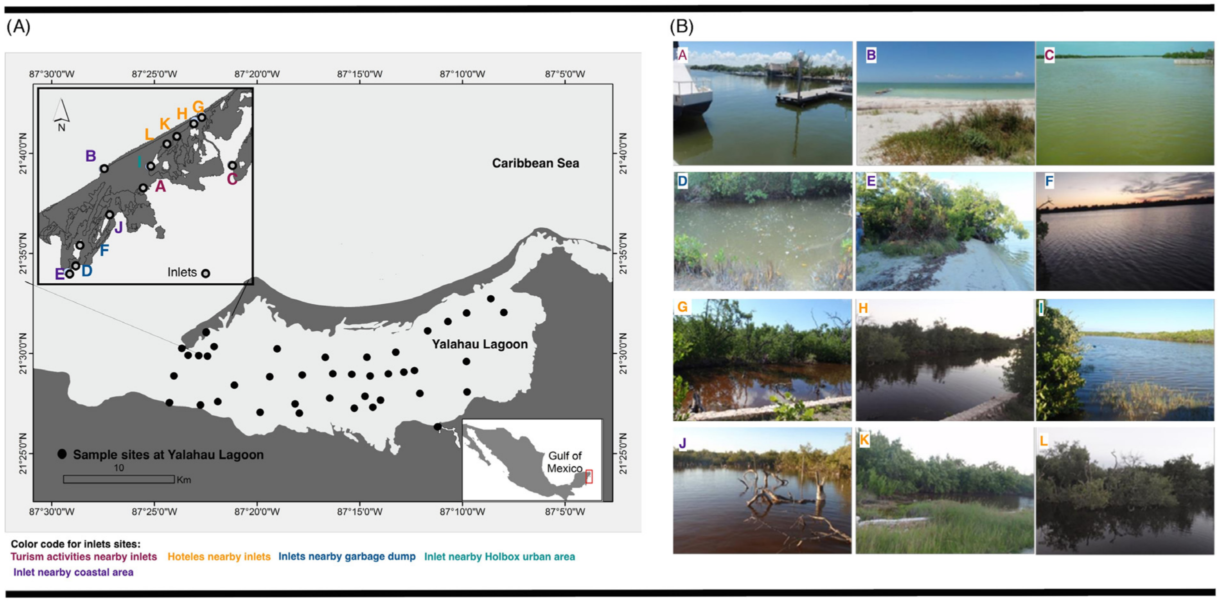

Fig. 2. (A) Inlets sites, gray circles. Black circles show sample sites at Yalahau. (B) Inlets sites with color-coded letter associated with human activities that occur near inlets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

development at QR northern coast where coastal communities subsisted mainly from fisheries and agriculture. Our study took place on Holbox Barrier Island (hereafter Holbox) and the adjacent Yalahau Lagoon (hereafter Yalahau) (Fig. 2). In the past 15 years, Holbox community has faced a rapid and unorganized urban and tourist development that raises concern about the health of the Island's water quality (Tran et al., 2002a, b, 2005; Restrepo, 2014; López Santillán, 2010, 2015; Fig. 3). Though protection of the natural environment on Holbox exist through the Yum Balam Natural Protected Area (NPA) since 1994, however, the area's management plan is still in preparation (Diario Oficial de la Federacion, 1994; Vázquez, 2015).

Overall, the preservation of water quality throughout QR is necessary to prevent human health issues, eutrophication of nearshore environments, harmful algal blooms, fish kills, seagrass loss, coral reef destruction, and marine fauna mortality. These factors threaten the imminent loss of valuable ecosystem services needed for local and regional economic development (Herrera-Silveira et al., 2004b; Rivera-Monroy et al., 2004; Merino-Virgilio et al., 2014; Hernández-Terrones et al., 2015; Calderón, 2016).

Earlier studies remark on the importance of generating information on water quality at different spatiotemporal scales, these can provide key water features for tailored management actions in water preservation of coastal environments (Tran et al., 2002a, b, 2005; Herrera-Silveira et al., 2004a, b; Tran, 2006; Herrera-Silveira and Morales-Ojeda, 2009; Xiao et al., 2016). As such, the water quality of Yalahau and offshore environments near Holbox is described (see Tran et al., 2002a, b, 2005; Cárdenas-Palomo et al., 2010; Aguilar Trujillo, 2010). However, no description of water quality of tidal inlets (which are geomorphological features of barrier islands) on Holbox exists. Currently, the ecological health of some of these inlets is at risk by the water discharges of hotels; constructions built nearby inlets, and increasing trash throughout the island (*e.g.* plastics, trash that is thrown into the mangroves) (Alonzo and Hernández, 2014; Figs. 2 and 3; Table 1). Additionally, human health issues related to Holbox's poor water quality and the lack of a proper sewage system exist in the local news (García, 2016).

Coastal ecosystems of the YP experience three well-defined seasons: dry (March to May), rainy (June to October), and northern winds (November to February), which is dominated by cold fronts (Herrera-Silveira et al., 1998). For this study, water samples for Holbox's inlets were collected throughout the rainy and the northern winds (hereafter fronts) seasons to describe inlets' water quality variables. We complement our description of the water quality of inlets on Holbox with unpublished and published reference values for water quality at Yalahau and other coastal lagoons in the YP. Our results can contribute to shortening the gap of knowledge related to water quality on this rapidly changing barrier reef island. Besides these can also shed insights for understanding the health of nearshore environments on Holbox. The later is essential for the continuation of the provision of ecosystem services to humans that live and visit the island. Our working hypothesis is that knowledge on the water quality of inlets and coastal lagoons can help coastal managers understand the environmental degradation of coastal ecosystems in rapidly growing tourism destinations of tropical latitudes.

2. Materials and methods

2.1. Study area

Holbox is a 42 km long and 2 km wide barrier island that is intermittently connected to the mainland in the northern coast of the YP in QR (Appendini et al., 2012; Fig. 2). This island complex forms the Yalahau Lagoon (275 km^2) this is the primary connection between land and sea for submarine groundwater discharges (SGD) (Herrera-Silveira and Morales-Ojeda, 2009; Fig. 4). Besides SGD fluxes, occasional overland flows occur along a channel that goes from Lake Coba to the coast through the Island's fracture zone (Tulaczyk et al., 1994). Holbox's bottom also has breaks and water channels, which allow the water to flow from the sea to the lagoon.

Mangroves surround the lagoon, and an extensive cover of seagrasses and macroalgae dominates the benthos where water transparency is high. Currents from the Gulf of Mexico and the Caribbean Sea influence Holbox's lagoonal, nearshore, and offshore waters. These bring nutrients from upwelling events at the north-eastern shelf of the YP (Reyes-Mendoza et al., 2016). The aforementioned has historically allowed the development of diverse aquatic fauna in nearshore and offshore waters of Holbox. Examples are the large aggregations of whale sharks *Rhincodon typus* (Reyes-Mendoza, 2015; Cárdenas-Palomo et al., 2015). Holbox is part of

Table 1
Names and descriptions of Holbox's inlets.

Site label in Fig. 2	Site name	Site description	Latitude	Longitude
A	Cove	Site affected by the port infrastructure of Holbox Island. Here is the boarding station of the ferry that goes from Chiquila to Holbox Island.	21°31′09.9″	087°22′32.3″
B	Beach	Beach located in the north end of the Island, it borders with the Gulf of Mexico.	21°31′23.1″	087°22′59.4″
C	Cocodrilo Cay	A cay used for ecotourism activities located ∼5 km east of the Cove.	21°31′25.72″	87°21′33.79″
D	Siricote Lagoon	Lagoon located southwest of Holbox, it receives water flow from a larger lagoon located behind the Island's garbage dump.	21°30′17.1″	087°23′17.7″
E	Point Siricote	Site where Siricote Lagoon opens into the Yalahau Lagoon.	21°30′12.5″	087°23′23.1″
F	Inlet nearby the garbage dump	Inlet located behind the Island's garbage dump.	21°30′30.5″	087°23′14.7″
G	Hotel las Nubes	Inlet located behind the Hotel Las Nubes.	21°31′59.8″	087°21′53.8″
H	Hotel Flamingos	Inlet behind Flamingos Hotel.	21°31′55.9″	087°21′58.4″
I	Salt flats	Inlet located on the east side of the urbanized area of Holbox Island. Construction of houses is happening near the area.	21°31′24.7″	087°22′28.7″
J	Cárcamo	Lagoon located by the Island's sump pump.	21°30′52″	087°22′54.9″
K	Hotel Delfines	Inlet behind Hotel Delfines.	21°31′45.1″	087°22′10.6″
L	Paraíso Lagoon	Inlet behind the Flamingos and Delfines hotels.	21°31′40.3″	087°22′17″

Table 2
Criteria for water quality variables used for this study according to salinity. Values were obtained from published literature (Herrera-Silveira et al., 1998, 2004a, b; Herrera-Silveira and Morales-Ojeda, 2009; Aguilar Trujillo, 2010; Morales-Ojeda et al., 2010).

Water type	NO_3	NO_2	NH_4^+	SRP	SRSi	Chl-*a*	TRIX
Oligohaline							
Good	<11.76	<1.32	<11.69	<0.36	<234	<5.74	<5.53
Fair	11.76–12.79	1.32–1.9	11.69–16.6	0.36–0.8	234–312	5.74–10.4	5.53–7.49
Poor	>12.76	>1.9	>16.6	>0.8	>312	>10.4	>7.49
Bad							
Estuarine							
Good	1.64–7.14	0.2–0.4	1-7.03	0.14–0.34	48.90–150.03	2.66–4.50	1.07–2.62
Fair	7.14–12.7	0.4–0.83	7.04–15	0.34–0.58	150.04–206.56	4.51–5.26	2.63–3.23
Poor	>12.78	>1.43	15.10–40.07	0.59–0.80	206.57–274.10	5.63–6.25	>3.23
Bad			>40.07	>0.80	>274.10	>6.25	
Euhaline							
Good	1.14–1.26	0.12–0.33	0.52–5.56	0.15–0.23	8.90–31.96	0.28–3.23	0.86–1.52
Fair	2.6–4.48	0.34–0.91	5.57–8.50	0.24–0.49	31.97–70.70	3.24–5.89	1.53–2.38
Poor	4.49–7.87	0.92–1.47	8.51–19.88	0.50–0.69	70.71–246.70	5.90–6.92	2.39–3.75
Bad	>7.88	>1.47	>19.88	>0.69	>246.70	>6.92	>3.75
Hyperhaline							
Good	<0.51–0.92	0.11–0.37	1–4.30	0.15–0.26	<21	0.37–4.02	0.91–2.02
Fair	0.93–1.77	0.38–1.01	4.31–8.03	0.27–0.57	21–43.37	4.03–6.50	2.03–2.77
Poor	1.78–7.39	1.02–1.53	8.04–39.10	0.57–1.29	43.38–66.85	6.51–26.91	>2.77
Bad	>7.40	>1.53	>39.14	>1.29	>66.85	>26.91	

the Yum Balam NPA which aims to protect the nearshore and freshwater environments (*e.g.* lakes and streams throughout the tropical forest); together with the high biodiversity in the region.

2.2. Water samples

Collection of water samples on Holbox's inlets

Twelve sample sites of small tidal inlets on Holbox were selected for water collection (Fig. 2; Table 1). Water samples were collected throughout the rainy (September) and fronts (February) seasons of 2013 and 2014, respectively. Measurements of water quality parameters (temperature, dissolved oxygen, and salinity) were conducted *in situ* using a YSI Professional Plus handheld multiparameter probe. Sample processing involved collecting one liter of surface water with dark polyethylene bottles. Of this 500 ml were stored in a freezer immediately after filtration for analyses of dissolved nutrients (NO_2^-; NO_3^-; NH_4^+; SRP; and SRSi) according to the method reported by Strickland and Parsons (1972) and Parsons et al. (1984). Chl-*a* was determined by filtering 250 ml of water through a Millipore membrane filter (0.45 mm). Pigments were extracted with 90% acetone and calculated using the equations of Jeffrey and Humphrey (1975) using a spectrophotometer wavelength scale.

Use of reference values from water samples collected at Yalahau Lagoon

We used published water quality reference values (see: Herrera-Silveira et al., 1998, 2004a, b; Herrera-Silveira and Morales-Ojeda, 2009; Cárdenas-Palomo et al., 2010; Aguilar Trujillo, 2010; Morales-Ojeda et al., 2010; Table 2), that were used to classify our water quality results in: good, fair, poor, and bad according to Herrera-Silveira and Morales-Ojeda (2009) (Table 2). We also used reference values from forty sample sites for water collection at Yalahau (see Tran et al., 2002a, b, 2005, for site descriptions). Water samples ($n = 341$) were obtained during the rainy and fronts seasons (Fig. 2). A multi-parameter probe YSI 85 provided *in situ* measurement of temperature, dissolved oxygen, and salinity. Water samples were collected at surface levels and used for analyses of dissolved nutrients (nitrite NO_2^-; nitrate NO_3^-; ammonium NH_4^+; soluble reactive phosphate SRP; and soluble reactive silicate SRSi) following standard methods (Strickland and Parsons, 1972; Parsons et al., 1984).

2.3. Water quality condition

Water quality can be evaluated based on three criteria: (*i*) One is the use of physical and chemical parameters of water; (*ii*) the detection of biological indicators such as bacteria (*e.g.* the presence

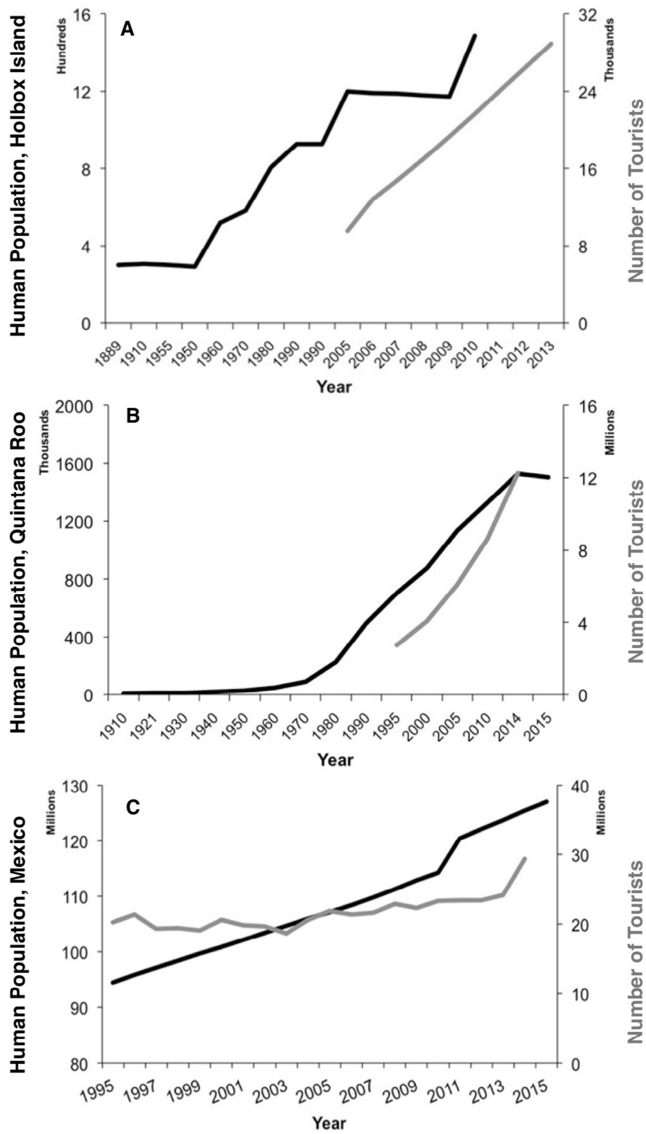

Fig. 1. Population and tourists numbers, (A) state of Quintana Roo; (B) Holbox; (C) Mexico.

of total fecal coliforms in water samples Hernández-Terrones et al., 2015); and (iii) trophic indices as TRIX index. Dissolved inorganic nutrients (NO_2^-; NO_3^-; NH_4^+; SRP; and SRSi), are indicators of water eutrophication (EPA, 2001; Crouzet et al., 1999), whereas Chl-*a* can help assess deviations in marine water health status (*e.g.* Assessment of Estuarine Trophic Status-ASSETS by Bricker et al., 2003). Previous water quality assessments for the YP demonstrate that for coastal systems of this region, particular emphasis should be given to SRP and SRSi. The latter is because in, the karstic areas such as the YP, SRP could be a limiting nutrient due to its precipitation in the presence of calcium carbonate to form apatite (Coelho et al., 2004; Slomp and Van Cappellen, 2004); while SRSi on the other hand, may be used as a tracer of groundwater discharges (Smith et al., 1999).

A water quality index can assess complex water quality data and facilitate the understanding of results to a general audience. The composite trophic status index (TRIX) provides useful metrics for the assessment of the trophic status of coastal waters. It was initially developed for Italian coastal waters and then in other European coastal areas (Adriatic, Tyrrhenian, Baltic, Black and Northern seas). The TRIX index by Vollenweider et al. (1998) was calculated by early studies in the YP that evaluated the trophic condition of coastal waters (*e.g.* Herrera-Silveira, 2006, Morales-Ojeda, 2007, Herrera-Silveira and Morales-Ojeda, 2009, Morales-Ojeda et al., 2010). We followed a similar approach and calculated the index for our water samples.

The TRIX index is a linear combination of four state variables related to primary production (Chl-*a* and oxygen) and nutritional condition (dissolved inorganic nitrogen, inorganic phosphorus) (Melaku-Canu et al., 2003). This index was calculated as follows:

$$TRIX = \frac{[\log(Chl - a * |\%DO| * DIN * P + k)]}{m}$$

where P is the mineral or inorganic phosphorus (P-PO_4 µl mol l), DIN is the mineral nitrogen: dissolved inorganic nitrogen (µmol l^1), Chl-*a* is the chlorophyll-*a* concentration, as µlg l^1, %DO is the absolute value of the oxygen saturation deviation from the oxygen calculated as |100 −%DO|. Parameters $k = 1.5$ and $m = 1.2$ are scale coefficients which were included to fix the lower limit value of the index and the length of the related trophic scale from two to eight. The meaning of each index value is shown in Table 2.

2.4. Statistics, and geographic information system GIS tools for the qualitative description of results

For each season and water quality variable shown in Table 2, a 95% confidence interval was estimated using the Bootstrap re-sampling method by Efron and Tibshirani (1986). This analysis was run for water samples at inlets and the lagoon. We used GIS tools to spatially describe the water quality values obtained for each variable (Fig. 5).

3. Results and discussion

3.1. Description of inlets and lagoonal waters between seasons

Temperature values of inlets and lagoonal waters were lower during the fronts and higher for the rains. This temperature pattern is common in other coastal lagoons of the YP (*e.g.* Celestún, Sisal, Punta Nizuc and Punta Cancun, Table 3). Since fronts occur in winter when the atmospheric temperature is lower, winds promote the mixing of the water column, which results in lower water temperatures (May-Kú et al., 2016). Water temperature at Yalahau during fronts M = 25.51 °C, 95%CI [25.34, 25.66]; was lower than at inlets M = 29.6 °C, 95% CI [28.19, 30.98]. Lagoonal waters have lower residence times and higher mixing rates due to wind forcing when compared to inlets. These environments are shallow (M = 0.6 m) and enclosed which favors that the solar radiation generates heat fluxes across the shallow water column. Besides the reduced wind forcing can also favor longer water residence times that can also influence higher water temperatures of inlets during fronts.

Salinity values at inlets were higher during fronts M = 26.26, 95% CI [17.75, 33.39] than for rains M = 18.98 kg/g, 95% CI [11.24, 27.08]. Reference salinity values at Yalahau were overall higher than the values for inlets. However at Yalahua slightly lower salinity values were reported during fronts M = 35.22, 95% CI [33.98, 35.97] than for rains M = 36.92 psu, 95% CI [35.03, 38.12]. During fronts, winds in the YP move from north to south which advects water to the shore and the average sea level increases this can allow that Yalahau's salinity values for fronts be similar to marine water. During rains (summer months) higher salinity values at Yalahau can be influenced by greater evaporation rates when compared to the freshwater input. Overall salinity differences between Yalahau and Holbox's inlets were of at least 10 psu, suggesting a flow of fresh water into inlets possibly either via runoff or SGD (Fig. 4). This pattern can exacerbate during rains when (1) the aquifers at the YP

Table 3
Estimated water quality values for other coastal lagoons in the YP and elsewhere.

Site	Site Description	Season			Variables									Source
		Rains	Fronts	None	Temp °C	Salinity	DO mg l^{1}	NO_3^- μmo l^{-1}	NO_2^- μmo l^{-1}	NH_4^+ μmo l^{-1}	SRP μmo l^{-1}	SRSi μmo l^{-1}	Cla mg m^{-3}	
Cabo Catoche, Mx	S	✓			27.8	35.8		1.47	0.1	4.68	0.21	13.25	1.53	1
Cabo Catoche, Mx	S		✓		24.9	36.4		1.37	0.11	3.33	0.29	13.28	0.83	
Holbox, Mx	S	✓			26.2	33	6.5	3	0.18	3	0.9	1.6	1	2
Holbox, Mx	S		✓		25.1	36	6.8	0.2	0.3	6.1	0.65	0.2	1.95	
Dzilam, Mx	S	✓			29.9	37	4.5	6.1	0.75	5	0.81	12.2	1.5	3
Dzilam, Mx	S		✓		24.3	33.9	71	11.8	0.75	5.5	0.61	7.2	2	
Progreso, Mx	S	✓			28.3	37.6	5	0.5	0.25	3.1	0.3	4	4	
Progreso, Mx	S		✓		24.1	37.8	7	4.5	0.6	4.5	0.44	6.8	3	
Sisal, Mx	S	✓			28.3	36.5	5.5	8	1.4	11.2	0.4	12.8	10.2	
Sisal, Mx	S		✓		24.2	35.7	6.6	10	1.7	4.6	0.82	13.5	11.5	
Celestun, Mx	S	✓			28.9	38	7	2.1	0.3	5	0.42	6	13	
Celestun, Mx	S		✓		23.8	37.5	6.5	2	0.8	8	0.6	3	6.8	
Holbox, Mx	CL	✓			31.3	39.2	3.5	1.2	0.3	3.7	0.2	49.3		4
Isla Mujeres, Mx	S	✓			30.9	33.5	7.2	1.4	0.5	1.9	0.05	1.7	0.35	5
Isla Mujeres, Mx	S		✓		25.5	34.5	5.6	2	0.35	3.5	0.08	6	0.5	
Punta Cancún, Mx	S	✓			32.5	33.6	6.1	1.4	0.11	3	0.02	5.5	0.36	
Punta Cancún, Mx	S		✓		26	35.1	6	1.8	0.4	2.5	0.04	3.7	0.4	
Punta Nizuc, Mx	S	✓			29.5	33.8	5.7	16.2	0.1	2.2	0.08	10.5	0.26	
Punta Nizuc, Mx	S		✓		25.2	34.1	5.8	4.3	0.32	3	0.12	3.8	0.49	
Laguna Macapule, Sinaloa, Mx	CL	✓			24.9	38.7	6.05				1.4	25.3	2.43	6
Laguna Macapule, Sinaloa, Mx	CL		✓		21	36.6	6.92				1.32	25.5	1.92	
Chesapeake Bay, USA	E	✓			24.1	10		3	1	4	0.8	17	10	7
Delaware Bay, USA	E		✓		12.5	27.9		7	1	5	1.7	6	16	
Hudson River, USA	E	✓			14	19.8		3	1	6	1.2	5	5	
Celestún, Mx	CL			✓	27.8	21.1	3.6	4.04	0.69	11.84	1.09	143.1	3.93	8
Chelem, Mx	CL			✓	26.7	35.4	5.6	3.23	0.21	9.46	0.52	51.8	2.17	
Dzilam, Mx	CL			✓	31	26.5	5	4.76	0.25	2.43	0.21	77.4	3.91	
Rio, Lagartos, Mx	CL			✓	27.3	57.6	5.8	2.65	0.84	5.13	1.38	33.3	4.7	
Holbox, Mx	CL			✓	28.1	38.8	4.2	0.72	0.35	4.65	0.57	33.2	1.99	
Chacmocchuck, Mx	CL			✓	31.5	34.4	5.1	0.47	0.82	5.09	0.63	31.2	3.22	
Nichupte, Mx	CL			✓	28.6	30.2	5.8	8.56	0.96	8.64	0.43	38.1	1.57	
Bojorquez, Mx	CL			✓	28.9	30.2	5.1	8.96	0.88	6.23	0.57	20	1.36	
Ascención, Mx	CL			✓	29.5	30.7	7.1	0.98	0.4	1.75	0.24	20.8	0.41	
Chetumal, Mx	CL			✓	29.2	13.2	6.2	2.49	1.16	12.72	0.46	187.3	1.04	
Yucatán, Mx	S			✓	28.61	36.61		1.25	0.22	1.23	0.25	9.7	3.11	9
Dzilam, Mx	CL			✓	27.2	36.1	5.38	4.94	0.69	4.42	0.62	8.57	1.14	10
Progreso, Mx	CL			✓	26.3	38.4	5.29	1.23	0.31	4.14	0.47	4.32	1.7	
Sisal, Mx	CL			✓	26.4	37.7	5.87	4.62	0.86	4.04	0.47	6.62	3.08	
Celestun, Mx	CL			✓	26.6	37.6	5.76	1.75	0.49	5.21	0.47	7.6	2.51	
Tampa Bay, Florida	B			✓	27.8	41.4	7.32	0.59	0.13	1.89	0.03		1.05	11
Great Barrier Reef lagoon, Aus	RL			✓				0.2		0.18	0.15		0.75	12
Venice Lagoon, It	L			✓	29.5			0.8	0.4	1.85	1.2		9.5	13

Site description: S = sea, CL = coastal lagoon, E = estuary, B = bay, R = reef lagoon, L = lagoon. Mx = México, Aus = Australia, It = Italy. (1) Cárdenas-Palomo (2007); (2) Aguilar Trujillo (2010); (3) Álvarez Góngora and Herrera-Silveira (2006); (4) Tran et al. (2002a, b); (5) Cortés Balán (2006); (6) Magaña Álvarez (2004); (7) Fisher et al. (1988); (8) Herrera-Silveira and Morales-Ojeda (2010); (9) Morales-Ojeda et al. (2010); (10) Aranda-Cicerol et al. (2006); (11) Fourqurean et al. (1993); (12) Schaffelke et al. (2012); (13) Sfriso et al. (1987).

and the Holbox Fracture Zone are recharged and (2) surface runoff increases on Holbox town. Perry et al. (2011) report a groundwater flow which leads to SGD towards the Gulf of México from the Holbox Fracture Zone. Water from these sources can be either freshwater or recirculated brackish water (Langevin et al., 2007). Diffuse discharges produce weak SGDs on the order of centimeters per day (Cable and Martin, 2008; Paulsen et al., 2004; Fig. 4).

Besides changes in salinity by SGD, we suggest Holbox's inlets hydrology may also be susceptible to adverse changes in the water quality of SGD. For example, if a point source of pollution for SGD exists miles away off the Holbox Fracture Zone (*e.g.* agricultural or anthropogenic wastes), this may reach Holbox's inlets, but further studies are needed. Avelar et al. (2013) documented non-point source pollution of heavy metals in Yalahau. The authors recorded high iron >400 μg/g; cadmium >4 μg/g; and chromium ≈1 μg/g in the tissues of roots and leaves of *Thalassia testudinum* seagrass beds for central sites of Yalahau which have the highest SGD inputs. Avelar et al. (2013) suggest pollution of heavy metals at Yalahau can arrive through the aquifer from Cancun city. Lastly, surface runoff can also contribute to the inlets hydrology beyond salinity changes. However, further research is needed to understand for example how human development is modifying the water quality and the flow patterns of surface runoff on the island.

Dissolved oxygen (DO) values were lower during fronts at both systems (inlets $M = 5.57$ mg l^{-1}, 95% CI [3.8, 7.17], lagoon $M = 6.34$ mg l^{-1}, 95% CI [6.01, 6.62]) when compared to DO values during rains (inlets $M = 8.47$ mg 1^{-1}, 95% CI [8.18, 8.76]; lagoon $M = 7.08$ mg 1^{-1}, 95% CI [6.56, 7.6]). The latter is related to large amounts of organic matter that wash off from adjacent mangroves on the barrier island and the continent during rains. Organic matter can also reach Yalahau by overland channels that have landward–seaward surface flows and can extend up to 3 km inland. These flows are part of the Holbox Fracture Zone, which is surrounded by a vast extension of mangroves and wetlands (Fedick et al., 2000).

Higher amounts of organic matter at inlets and Yalahau during rains and early fronts season can require higher oxygen consumption for its degradation. The previous can explain the higher DO values in our results during rains. However, the oxygen saturation

Table 4
Estimated reference values for water quality variables on Holbox's inlets (n = 48).

Season	Water quality parameter	Estimate	E.E.	95% CI		Unit
Rains	DO	8.47	0.15	8.18	8.76	mg 1^{1}
	Salinity	18.98	4.01	11.24	27.08	psu
	Temp	32.23	0.32	31.63	32.82	°C
	NO_3^-	2.76	0.52	1.73	3.8	μmo l^{-1}
	NO_2^-	0.27	0.03	0.22	0.32	μmo l^{-1}
	NH_4^+	1.86	0.21	1.44	2.25	μmo l^{-1}
	DIN	4.89	0.58	3.67	5.98	μmo l^{-1}
	SRP	48.86	14.11	22.96	77.71	μmo l^{-1}
	SRSi	78.68	12.5	54.5	103.57	μmo l^{-1}
	Cla	17.67	4.4	10.02	27.49	mg m^{-3}
	Trix	4.27	0.92	2.41	5.96	
	Satox	264.8	7.23	251.25	278.02	%
	N:P	2.62	1.19	0.64	5.13	
Fronts Northern winds	DO	5.57	0.89	3.8	7.17	mg 1^{1}
	Salinity	26.26	3.95	17.75	33.39	psu
	Temp	29.6	0.72	28.19	30.98	°C
	NO_3^-	0.83	0.14	0.58	1.11	μmo l^{-1}
	NO_2^-	0.14	0.03	0.09	0.2	μmo l^{-1}
	NH_4^+	1.88	0.53	1.11	3.12	μmo l^{-1}
	DIN	2.87	0.63	1.92	4.31	μmo l^{-1}
	SRP	0.28	0.06	0.17	0.41	μmo l^{-1}
	SRSi	16.61	4.37	8.64	25.73	μmo l^{-1}
	Cla	29.79	9.52	13.82	50.46	mg m^{-3}
	Trix	2.88	0.6	1.8	4.11	
	Satox	180.62	29.76	119.62	235.28	%
	N:P	15.42	3.32	12	9.14	22.2

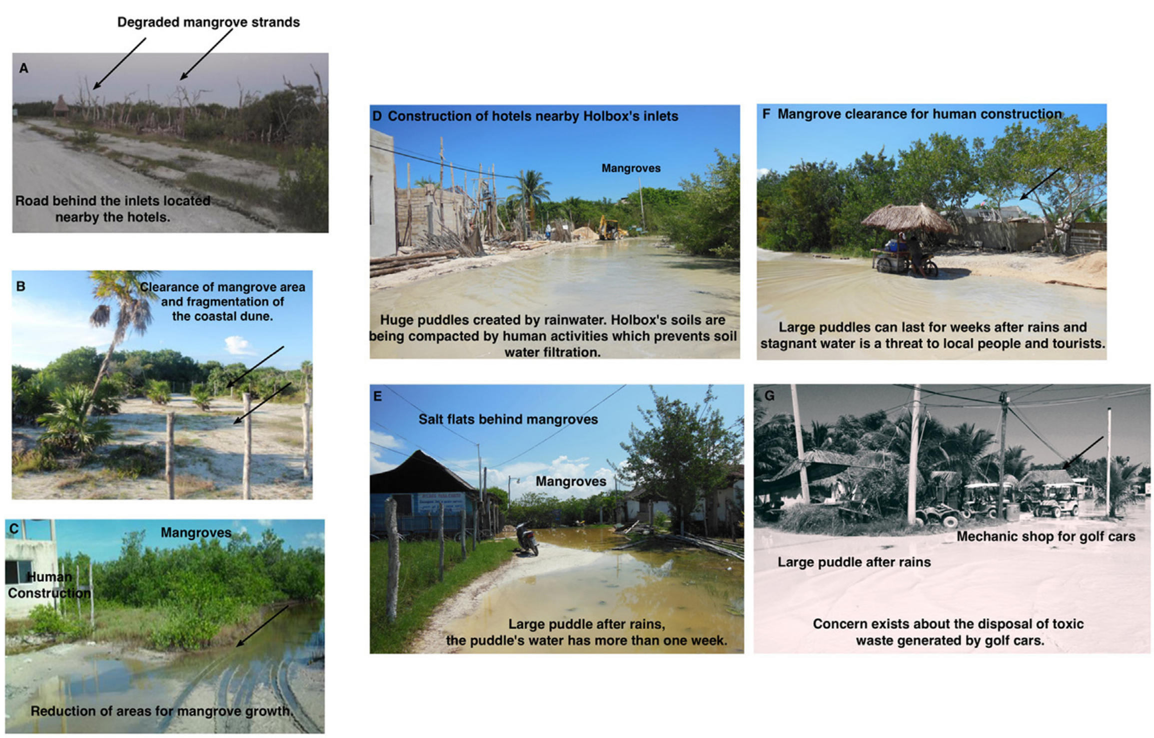

Fig. 3. (A–C) Examples of habitat fragmentation in sites near inlets. (D–G) Examples of Holbox's puddles during rains.

values are high (<80%; Tables 4 and 5) at both study sites. For inlets, their shallowness can generate proper oxygenation which can favor oxygen diffusion between atmosphere and water leading to higher DO concentrations. As well inlets' shallowness together with their closeness contributes to both higher water temperature and water residence time. The previous can increase the organic matter at inlets' shallow water column, especially in the early fronts season, leading also to high DO concentrations. Similar processes are recorded in Florida Bay and the Northwestern YP, where shallowness favors sediment resuspension and turbidity during windy events (Boyer et al., 1999; Morales-Ojeda et al., 2010).

Challenges exist for water quality analysis when trying to understand the contribution of each nutrient source to nearshore or lagoonal waters. Since a diversity of nutrient sources exists for these systems (*e.g.* upwelling, SGD inputs, sea). Differences in nitrogen compounds between rains and fronts seasons are reported for the YP coastal lagoons and nearshore areas (Table 3). The latter is influenced by diverse sources including the geographic location

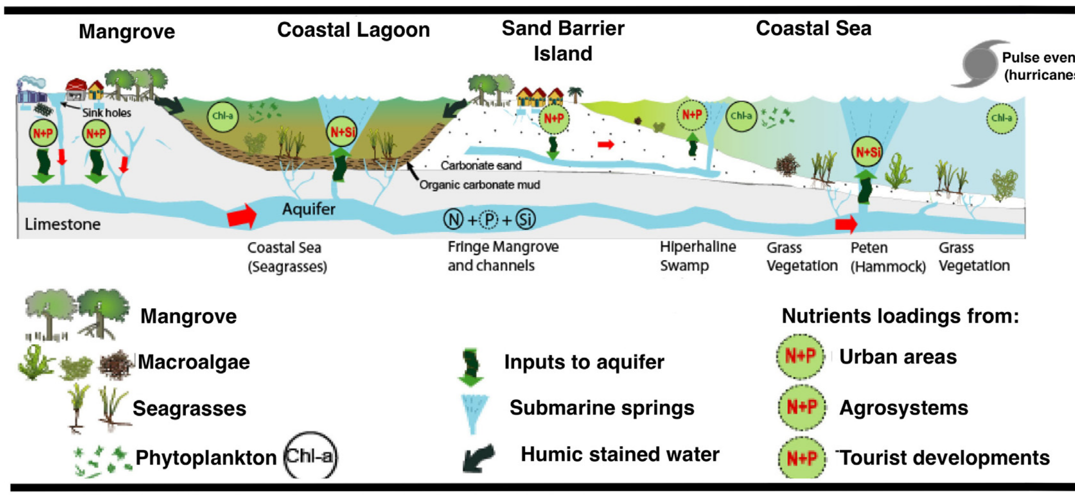

Fig. 4. Diagram of a transversal section of the YP, modified from Herrera-Silveira et al. (2013).

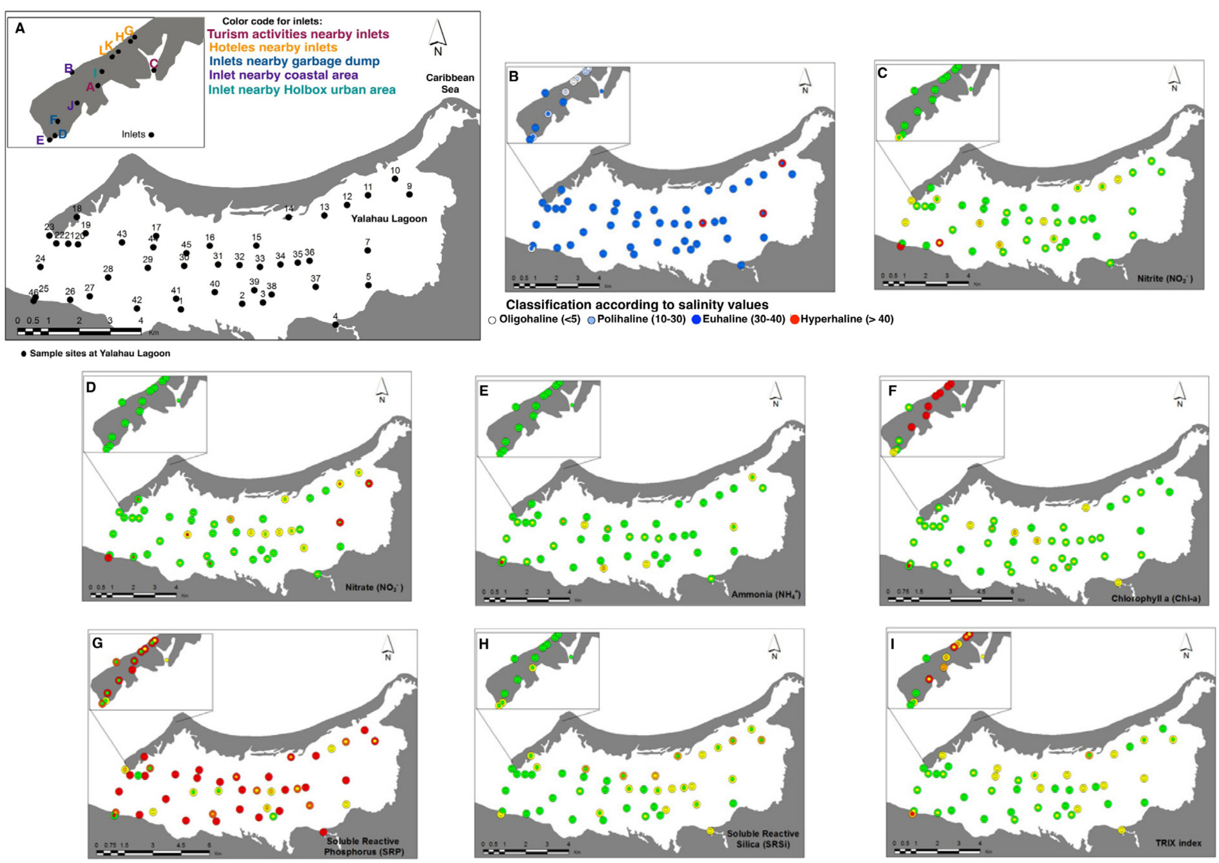

Fig. 5. The Status of water quality variables found at inlets and Yalahau lagoon. Water quality: good (green), fair (yellow), poor (orange), and bad (red). Inner circles represent water quality for fronts, and outer circles show water quality for rains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and population numbers near each site. For example, ammonium and dissolved inorganic nutrients (*e.g.* NO_2^-, NO_3^- and NH_4^+), which come from, waste, sewage, sediment re-suspension, and recycling processes can vary throughout lagoons (Álvarez Góngora and Herrera-Silveira, 2006; Troccoli-Ghinaglia et al., 2010).

Overall the dissolved inorganic nitrogen compounds NO_2^-, NO_3^- and NH_4^+ had low values at inlets, but NO_2^- and NO_3^- had higher values during rains (Tables 4 and 5). For NH_4^+ values were similar between seasons. Reference NO_2^- values at Yalahau were higher in fronts. This seasonal pattern is present in other coastal lagoons in the YP: Progreso (0.6 µmol l^{-1}fronts, 0.25 µmol l^{-1}rains) and Celestún. (0.8 µmol l^{-1}fronts, 0.3 µmol l^{-1}rains). NO_3^- had lower values at Yalahau for the fronts, a similar seasonal pattern occurs for NO_3^- values at Progreso (4.5 µmol l^{-1} frons to 0.5 µmol l^{-1}rains) and Celestún (0.8 µmol l^{-1} fronts to 0.3 µmol l^{-1} rains). A similar pattern seen for NO_2^- is presented for NH_4^+ values, which were higher at Yalahau and inlets for the fronts season. This pattern was also documented at Progreso (4.5 µmol l^{-1} fronts, 3.1 µmol l^{-1}

Table 5
Estimated reference values for water quality variables at Yalahau Lagoon (n = 341).

Season	Water quality parameter	Estimate	E.E.	95% CI		Unit
Rains	DO	7.08	0.28	6.56	7.6	mg 1^1
	Salinity	36.92	0.85	35.03	38.12	psu
	Temp	30.63	0.19	30.25	31	°C
	NO_3^-	4.95	2.9	1.72	11	µmo l^{-1}
	NO_2^-	0.38	0.07	0.26	0.54	µmo l^{-1}
	NH_4^+	3.66	0.23	3.22	4.09	µmo l^{-1}
	DIN	9.1	2.98	5.66	15.39	µmo l^{-1}
	SRP	0.86	0.06	0.73	0.98	µmo l^{-1}
	SRSi	41.79	5.11	32.46	52.48	µmo l^{-1}
	Cla	2.35	0.12	2.12	2.58	mg m^{-3}
	Trix	1.4	0.09	1.23	1.59	
	Satox	239.12	10.08	218.95	257.75	%
	N:P	134.54	102.47	19.53	345.61	
Fronts Northern winds	DO	6.34	0.16	6.01	6.62	mg 1^1
	Salinity	35.22	0.52	33.98	35.97	psu
	Temp	25.51	0.08	25.34	25.66	°C
	NO_3^-	3.88	0.89	2.42	5.88	µmo l^{-1}
	NO_2^-	0.67	0.29	0.34	1.29	µmo l^{-1}
	NH_4^+	7.72	2.92	4.37	14.15	µmo l^{-1}
	DIN	12.81	4.25	7.47	23.79	µmo l^{-1}
	SRP	0.96	0.1	0.78	1.16	µmo l^{-1}
	SRSi	25.84	1.1	23.77	28.14	µmo l^{-1}
	Cla	4.52	0.36	3.96	5.32	mg m^{-3}
	Trix	1.63	0.14	1.42	1.95	
	Satox	193.36	5.52	182.89	203.7	%
	N:P	25.71	3.44	19.04	32.8	

Table 6
Modified from Tran et al. (2002a). The table shows the percent of interviewed people (n = 69) by Tran et al. (2002a) that reported environmental changes were happening in Holbox (see Fig. 6 for zones information). * Describes if the documented changes by Tran et al. (2002a) have continued on Holbox. Data for this table is based on field observations on Holbox Island and fishers' responses to surveys about their perspectives on changes in the environment (Rubio-Cisneros et al., in review). ** Represents a qualitative description based on field information and interdisciplinary literature research.

	Zone 19			Zone 12			Zone 21			Zone 30			Zone 8			Zone 28		
	Percent of interviews reporting a change¢	Have changes continued *	Intensity of change**	Percent of interviews reporting a change¢	Have changes continued*	Intensity of change**	Percent of interviews reporting a change¢	Have changes continued *	Intensity of change**	Percent of interviews reporting a change¢	Have changes continued*	Intensity of change**	Percent of interviews reporting a change¢	Have changes continued *	Intensity of change**	Percent of interviews reporting a change¢	Have changes continued*	Intensity of change**
Changes in form and size of the beach (erosion, accretion, breakwaters, groynes)	6	✓	H	5.7	✓	H												
Increase of urban development	5.3	✓	H	1.4	✓	H												
Reduction of land vegetation	4.2	✓	H	2.2	✓	H	2.4	?										
Population increase	3	✓	H															
Coastal water contamination	3.6	✓	H?													4.4	✓	M?
Quantity of solid wastes	3	✓	H	2.2	✓	H												
Reduction in fish catches	2.4	✓	H	3.6	✓	H	3.2	✓	H	6.1	✓	H	3	✓	H			
Soil compaction	1.8	✓	H															
Changes in sea bottom (topography, canals, mud)	1.8	✓	M?															
Reduction of submerged vegetation	1.2	?		2.2	?													
Reduction of birds							3.2	?										
Increase number of tourists	1.2	✓	H															
Blocking of the river													3	✗	L			

rainy) and Celestún (8 µmol l^{-1} fronts, 5 µmol l^{-1} rainy) (Álvarez Góngora and Herrera-Silveira, 2006; Table 3).

Soluble Reactive Phosphate (SRP), values were higher at inlets during the rainy season $M = 48.86$ µmol l^{-1}, 95% CI [22.96, 77.71] when compared to reference values of Yalahau $M = 0.86$ µmol l^{-1}, 95% CI [0.73, 0.98]. For Yalahau SRP values during rains are similar to average SRP values of 0.1 µmol l^{-1} reported by Tran et al. (2002a, b) and by May-Kú et al. (2016) for this lagoon. SRP values on Holbox's inlets were higher than values reported for other karstic regions where high alkalinity favors the precipitation and low concentrations of SRP (Cravo et al., 2003; Jones et al., 2003). Examples from the nearshore waters of the western YP report an average SRP value of 0.25 µmol l^{-1} (Morales-Ojeda et al., 2010) and the lagoons of Dzilam, and, Sisal report SRP concentrations of 0.62 µmol l^{-1} and 0.51 µmol l^{-1}, respectively (Herrera-Silveira et al., 2004a, b). However most importantly SRP values on Holbox's inlets during rains were also much higher than SRP concentrations recorded for coastal areas with high population densities in the YP such as Progreso, Celestún, and Laguna de Términos. For these sites, high SRP concentrations of 2 to 4 μmol l^{-1} are attributed to runoff, harbors, septic tank effluents that discharge into the aquifer, and wastewater from the shrimp farms (Álvarez Góngora and Herrera-Silveira, 2006; Aranda-Cicerol et al., 2006). High SRP concentrations of 6.44 μmol l^{-1} are also reported during harmful algal blooms events (Yentsch et al., 2008). For Holbox's inlets, high SRP concentrations can associate to anthropogenic inputs from wastewaters of hotels nearby inlets together with the degradation of suspended organic matter (*e.g.* decomposition of seagrass) at inlets' shallow water columns.

For the fronts Yalahau's SRP values were higher $M = 0.96$ μmol l^{-1}, 95% CI [0.78, 1.16] when compared to inlets' SRP values $M = 0.28$ μmol l^{-1}, 95% CI [0.17, 0.41]. Higher SRP values during fronts at Yalahau can be related to (1) new upwelled waters of Cabo Catoche upwelling system which peak from March to September (Reyes-Mendoza et al., 2015); and (2) to nutrient-rich runoff waters from the mainland that reach Yalahau and interact with large areas of seagrass beds which are the main bottom substrate at Yalahau. The latter can promote remineralization processes by decomposition of roots and leaves of seagrasses, which can favor higher SRP concentrations. Overall Yalahau's SRP values for fronts are similar to values reported for other coastal lagoons in the YP (Dzilam 0.61 μmol l^{-1}; Sisal 0.82 μmol l^{-1}; Celestún 0.6 μmol l^{-1}; Álvarez Góngora and Herrera-Silveira, 2006; Table 3).

SRSi values were higher during rains for both study sites, but at inlets $M = 78.68$ μmol l^{-1}, 95% CI [54.5, 103.57] values were higher compared to lagoonal values in rains $M = 41.79$ μmol l^{-1}, 95% CI [32.46, 52.84]. SRSi is associated with freshwater runoff (Burton and Liss, 1973) and groundwater percolation, which dissolves silica under reductive conditions (Asano et al., 2003), and promotes high rock mineralization rates in tropical climates (White and Blum, 1995; Stonestrom et al., 1998). Throughout the rainy season, the underwater aquifers of the Peninsula recharge and there is an increase in SGD rich in silicates that can reach both the lagoonal and inlets (Herrera-Silveira et al., 2004a). Results of SRSi values for inlets during rains were even higher than suggested high SRSi values reported for Sisal (13.5 μmol l^{-1}), which were associated with shrimp-farms discharges and nutrient exports from Sisal harbor (Álvarez Góngora and Herrera-Silveira, 2006; Table 3).

SRSi plays an essential role in the structure of phytoplankton communities since it can be a limiting nutrient for diatom growth. A deficiency in SRSi can replace diatoms by dinoflagellates communities, or high inputs of SRSi can increase the growth of diatoms and also modify phytoplankton communities (Fogg, 2002). For example, phytoplankton blooms dominated by diatoms are documented within 1 to 5 km off the coast in areas of the YP that have experienced high silicate inputs from SGD (Merino-Virgilio et al., 2014). Phytoplankton blooms can be an issue of further study and consideration on Holbox's inlets given the high SRSi values documented during rains. Inlets have a geomorphological and ecological significance for the barrier island and modifications in their phytoplankton communities can lead to adverse outcomes in the delivery of water ecosystem services that inlets provide to humans and the associated fauna and flora that inhabits these systems.

For the fronts season Yalahau SRSi values were higher $M = 25.84$ μmol l^{-1}, 95% CI [23.77, 28.14] when compared to inlets' values $M = 16.61$ μmol l^{-1}, 95% CI [8.64, 25.73]. But, overall SRSi values reported at Yalahau were in the range of previously documented SRSi values for this lagoon by Tran et al. (2002a, b) (3.8 to 128.7, mean 37.2).

In the Northern YP seasonal variations of Chl-*a* occur, and generally higher values are reported for the rainy and fronts seasons when compared to Chl-*a* values during the Peninsula's dry season (Herrera-Silveira et al., 2004a, b). Chl-*a* values at inlets were higher (rains $M = 17.67$ mg/m^3, 95% CI [10.02, 27.49]; fronts seasons $M = 29.79$ mg/m^3, 95% CI [13.82, 50.46]) when compared to Yalahau (rains $M = 2.35$ mg/m^3, 95% CI [2.12, 2.58], fronts $M = 4.52$ mg/m^3, 95% CI [3.96, 5.32]). But, overall Chl-*a* values were higher in fronts. The later may be related to the gradual nutrient increases that can occur from SGD and surface runoff towards the end of the rainy season and to the sediment resuspension from turbulence during the fronts season. In shallow areas of the YP benthic diatoms that are epibionts from aquatic vegetation may be found in higher numbers in the water column during the fronts season (Álvarez Góngora and Herrera-Silveira, 2006). Phytoplankton diversity was not an objective of our study but is worthy of consideration for future studies that focus on the management of Holbox's water quality. Because benthic phytoplankton can lead to algal blooms if the right concentrations of nutrients and silicates exist in the system.

Phytoplankton biomass and productivity can fluctuate with human events related to coastal disturbance (Hambright and Zohary, 2000; Álvarez Góngora and Herrera-Silveira, 2006). Overall Chl-*a* values for Holbox's inlets were considerably higher when compared to values for other lagoons of the YP that are under fair ecosystem health or in early stages of eutrophication associated to human activities (*e.g.* Dzilam 1.0–7 mg/m^3, Nichupte 0.1–4 mg/m^3, Bojorquez 0.2–4 mg/m^3). For example, Álvarez Góngora and Herrera-Silveira (2006) report high concentrations of Chl- *a* occurred during fronts at Celestún (6.8 mg/m^3) and Sisal (11.5 mg/m^3). At Celestún trawl fishing in shallow lagoonal areas during rains and strong winds during fronts can enhance Chl-*a* values and at Sisal high Chl-*a* values are from nutrients inputs generated by the shrimp farm and the harbor.

The higher Chl-*a* values at inlets can suggest seasonal eutrophication which can lead to algal blooms. High seasonal concentrations of Chl-*a* have been documented in Progreso for the rainy season (4 mg/m^3), as a consequence of nutrient input from SGD as seepages that increase in rains and enhance phytoplankton growth. Besides this season is coupled with a human population increase from 50,000 to 200,000 people that visit Progreso in summer and boost wastewater input to the aquifer via septic tanks. Similarly, on Holbox's inlets SGD inputs increase in rains together with surface runoff waters that may come from stagnant, contaminated water that prevails in large puddles throughout Holbox town during the rainy season. Besides wastewaters generated by hotels and restaurants during summer (high tourism season) can also reach the inlets. The previous factors may all enhance phytoplankton growth at inlets.

Inlets' N:P values at fronts $M = 15.42$, 95% CI [9.14, 22.2] indicates nutrients are not limiting phytoplankton growth. On the other hand, inlets' N:P values at rains $M = 2.62$, 95% CI [0.64, 5.13] indicate that nitrogen is a limiting factor for phytoplankton growth, which suggests the inlets' environments might be experiencing additional input sources of phosphorus which shows probable contamination by detergents for human use which have phosphates. Yalahau's N:P values in rains $M = 134.54$, 95% CI [19.53, 345.61] and the fronts seasons $M = 25.71$, 95% CI [19.04, 32.8] indicate the limiting nutrient is phosphorus. This condition of a limiting phosphorus environment is common in YP because of the water alkalinity and its concentration of calcium carbonate. The phosphorus absorbs this and forms apatite that precipitates to the sediments and prevents the availability of phosphorus to the environment making it a limiting nutrient.

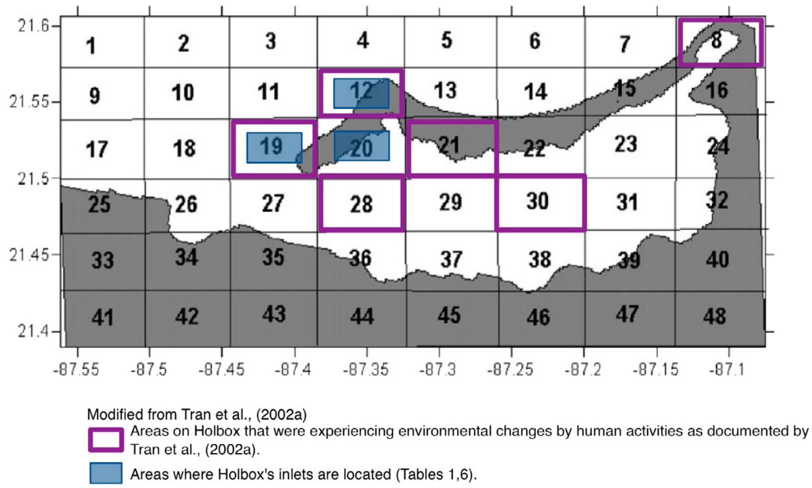

Fig. 6. Modified from Tran et al. (2002a). Areas on Holbox that were experiencing anthropogenic changes, as documented by Tran et al. (2002a), purple squares. Blue squares show areas where inlets are located, see Table 6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Health condition using water quality indicators

Holbox's inlets

Since reduced information exists about Holbox's water quality, we used Tran et al. (2002a) work as a reference for our water quality results at inlets. We believe this information is relevant given that Tran et al. (2002a) sampled coastal areas nearby inlets and also documented local population surveys about their perceptions on Holbox's environmental changes (Fig. 6, Table 6). Inlets had good water condition for NO_3^- and NH^{4+} throughout both seasons (Fig. 5D and E). Similarly, the NO_2^- condition was good except at Point Siricote (site E see Table 1; Fig. 5C) which had fair water condition during rains. Tran et al. (2002a) reported Point Siricote as an area where urban development and tourism activities were leading to ecosystem degradation (area 19, Fig. 6).

For inlets, Chl-*a* indicates a bad water condition for both seasons for all hotel sites, the Cove, Salt flats, and Cárcamo and Paraiso Lagoons (Table 1; Fig. 5F). Similarly, inlets' SRP condition was mostly bad in rains (Fig. 5F). Remarkably the inlet nearby Holbox garbage dump (site F see Table 1, Fig. 5G) only had bad SRP conditions in rains. On the other hand, inlets' SRP condition during fronts was good (n = 7 stations) to fair (n = 3 stations). The Cove (site A see Table 1) had bad SRP conditions for both seasons. SRSi water condition for inlets was good (n = 9 stations out of 12 sampled). Fair SRSi water quality values during rains were reported at the Cove and at Point and Laguna Siricote (sites A, E, D, see Table 1). Overall these sites are located in areas where Tran et al. (2002a) documented adverse environmental changes related to increasing urban development, and reduction in land vegetation, among others (Table 6; Fig. 6). Our results of inlets' water quality show signs of human activities that can generate negative impacts on inlets' biological and physical processes. Herrera-Silveira et al. (1998, 2004a, b) and Herrera-Silveira and Morales-Ojeda (2009) reported this pattern for other areas in the YP.

Nowadays thousands of tourists visit Holbox from May to September to swim with whale sharks (Ziegler et al., 2012). By 2013 Holbox had a population of about 1143 people but a floating population of ∼10,000 people can coexist in high season (SEDETUR, 2015; Fig. 1). Since late 1990s whale shark tourism on the Island is the primary driver for the construction of rooms, small hotels, shops, and restaurants. Many of these constructions are close to inlets. Overall Holbox developments are happening in areas that inhabitants already considered vulnerable to anthropogenic changes since 2002. Regrettably, urban development continues on Holbox with mild enforcement from government authorities (Tran et al., 2002a; Restrepo, 2014; Vázquez, 2015; Fig. 6; Table 6).

Statistics show Holbox has 589 hotel rooms but little information exists about the Island's urban changes (SEDETUR, 2015). Growing urbanization and tourism boosted water usage (*e.g.* laundry services) together with trash production. Of particular concern for water management on Holbox are solid and liquid toxic wastes (*e.g.* motor oil from boats and golf cars) disposed into the ground or sea, for which no documentation exists (personal communication obtained at the field from fishers). However, estimates show 1007.82 kg of trash were generated per day on Holbox in the high season of 2008 (Alonzo and Hernández, 2014). These values are conservative given that urban infrastructure and people continue to increase on the Island.

TRIX results at the Cove (site A, Table 1) show a poor water condition for both seasons (fronts TRIX 3.56; rains TRIX 2.57). Here anthropogenic activities such as boating, water tourism, and picnicking have increased mainly in the past two decades. A primary activity at the Cove are the daily ferry trips that transport people to Holbox from Chiquilá port, but no documentation exists about water contamination by ferries in the region.

Other inlets had a bad TRIX condition during rains: Paraiso Lagoon (site L; TRIX 8.42), Hotel las Nubes (site G; TRIX 7.99), Hotel Flamingos (site H; TRIX 6.11), and Cárcamo site (site J; TRIX 5.30) the latter located near Holbox sump pump. TRIX values are related to the high Chl-α and SRP values which are part of the index calculation. Bad TRIX values suggest hotels nearby may be discharging wastewaters. Besides Holbox soil is compacting, even though roads are still unpaved, the increasing traffic of golf cars, motorcycles, and small trucks have compacted Holbox soft sandy paths. The previous limits soil water filtration during rains leading to massive floods where puddles are created (Fig. 3D–G). Puddles develop nearby inlets, and its stagnant water can have a residence time of weeks. This water will end up at inlets. Stagnant water during rains is a threat to human health (García, 2016) and has negative implications for the Island's provision of water ecosystem services.

Hotel Delfines had a fair (site K; TRIX 6.83) condition in rains. Lastly, the inlet near the garbage dumpsite had a good condition (site F; TRIX rains 0.15, TRIX fronts 1.31) for both seasons together with inlets at Point Siricote (site E; TRIX rains 0.79, TRIX fronts 1.37) and the beach (site B; TRIX rains 0.22, TRIX fronts 0.1). These last two sites have a more open environment. The beach site was used as a control and in general, has a good water condition except for SRP values during rains (Fig. 5E)

Yalahau Lagoon

Values for NO_2^- at Yalahau stations had overall good condition for rains (n = 32 stations out of 44 stations sampled); and fair (n = 22 stations) to good (n = 19 stations) condition for fronts (Fig. 5C). Tran et al. (2002b) together with Herrera-Silveira and Morales-Ojeda (2010), and May-Kú et al. (2016), report similar results which suggest Yalahau's water condition is good. However, lagoonal stations 29 and 41 had poor water condition for NO_2^- in fronts, and station 27 had bad water condition for NO_2^-. The water spring, station 46, had bad water condition for both seasons. These stations are in areas that Tran et al. (2002b) suggest as areas with nitrate-rich freshwater.

Values for NO_3^- at Yalahau had good condition for rains (n = 31 stations out of 44) and fronts (n = 24 stations). Exceptions were stations 7 and 9 on the east side of Yalahau and station 46 (water spring) which had a bad water condition in rains. Stations 7 and 9 can receive freshwater inputs from the wetland which can enhance NO_3^- values (Fig. 5D). During fronts, Yalahau stations 1, 11, 18, 26, 29, and 46, had bad NO_3^- water condition. Station 1 is near Chiquilá port, here increasing anthropogenic activities such as picnicking, boating, and ferry trips occur daily. Stations 26, 29, and 46 (water spring) are near the entrance of the lagoon and stations 26 and 29 are nearby area 28 which is defined by Tran et al. (2002a) as a maritime zone subject to anthropogenic changes as documented by Holbox inhabitants. Station 28 is in the ferry's track that crosses from Chiquilá to Holbox. In recent field interviews, fishers reported that lagoonal waters are turning turbid (Fig. 6). Elder fishers recall that the ferry's track used to have clear water and abundant fish.

Values for NH_4^+ at Yalahau had a good condition for rains (n = 39 stations out of 44) and fronts (n = 27 stations). During fronts' stations 1, 43, and 45 had poor NH_4^+ values, and a bad water condition occurred at station 46 (water spring) (Fig. 5E). Chl-α values at Yalahau were overall good (n = 32 stations out of 44) in rains and fair (n = 32 stations) in fronts. Stations 3, 29, 31, 45 had poor Chl-α conditions in fronts, and the water spring had bad water condition for both seasons (Fig. 5F). SRP values for Yalahau were overall bad for rains (n = 26 stations out of 44) and fronts (n = 24 stations). Exceptions were stations 3 and 46 (water spring) which had good water condition during rains. Station 21 (near Holbox town) had good SRP water condition for both seasons and stations 29, and 30 (center of the lagoon) had good water condition only for fronts (Fig. 5G). Bad SRP conditions during rains at Yalahau do occur in stations 21 and 30. These are located in areas that Tran et al. (2002a) described anthropogenic changes were happening. Nowadays boat transit in station 21 has increased as more tourists arrive on Holbox and visit Isla Pajaros for birdwatching tours. Besides, station 21 is around Isla Pájaros where a diversity of birds have their nests. Higher SRP values can be associated with the abundance of birds' feces (Adame et al., 2015). Yalahau's SRSi values were overall good during fronts and good to fair in rains. Stations 9 and 11 (east of Yalahau) and 14 to 17 (behind the Ensenada) had a poor SRSi condition in fronts. Yalahau had good (n = 28 stations out of 44) to fair (n = 14 stations) TRIX values in rains, but at fronts values shifted to a fair condition (n = 23 out of 44 stations). The water spring was the only site with a bad TRIX 6.8 condition in fronts and a poor TRIX 3.3 condition in rains.

4. Conclusion

Holbox's inlets are punctually influenced by the surface runoff coming from the insular area which provides naturally derived nutrients entering from the overwash of soil and vegetation. Inlets also receive anthropogenic fluxes from the transformation of wastewaters, or decomposition of solid wastes that occur on Holbox. For example, the wastewater supply of N and P at inlets. Understanding and preserving inlets' water dynamics matters because these systems are geomorphological structures characteristic of Holbox barrier island and play a role in accomplishing ecological processes related to water fluxes. These are vital for aquatic flora and fauna and the generation of ecosystem services (*e.g.* water for drinking and household use, healthy nurseries for fishes, water filtration, biodiversity). The availability of reference water values can allow conservation managers to monitor the performance of water resources in the region and can enable detecting early stages of eutrophication (Tables 4 and 5). The later can help reduce the risk of human (*e.g.* algal blooms, water pollution) and environmental health problems such as the degradation of seagrasses and coral reefs. Lastly, continuing water quality monitoring is necessary for the preservation and continuation of coastal ecosystem services in the region such as tourism and fisheries services from which local people sustain their livelihoods.

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