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Effluent, nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China

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ABSTRACT

Global aquaculture has grown at a rate of 8.7% per year since 1970. Particularly along the coasts of tropical Asia, aquaculture ponds have expanded rapidly at the expense of natural wetlands. The objectives of this study were (i) to characterize the extent and production process of brackish-water pond aquaculture at the NE coast of Hainan, tropical China, (ii) to quantify effluent and organic carbon, nitrogen and phosphorus export from shrimp and fish ponds and (iii) to trace their effect on the water quality in adjacent estuarine and nearshore coastal waters harboring seagrass meadows and coral reefs. During two expeditions in 2008 and 2009, we determined dissolved inorganic nutrients, dissolved organic carbon (DOC) and dissolved organic nitrogen (DON), chlorophyll a (chl *a*) and particulate organic matter (POM) in aquaculture ponds, drainage channels and coastal waters in three areas varying in extent of aquaculture ponds. From the analysis of satellite images we calculated a total of 39.6 km^2 covered by shrimp and fish ponds in the study area. According to pond owners, there is no standardized production pattern for feeding management and water exchange. Nutrient and suspended matter concentrations were high in aquaculture ponds and drainage channels, but varied considerably. The calculated annual export of total dissolved nitrogen (TDN) and particulate nitrogen (PN) from pond aquaculture into coastal waters was 612 and 680 t yr^{-1}, respectively. High concentrations of dissolved inorganic nitrogen (DIN), phosphate and chl *a* at the majority of the coastal stations point at eutrophication of coastal waters, especially close to shore. Coastal eutrophication driven by the introduction of untreated aquaculture effluents may be especially harmful in back-reef areas, where estuarine retention and mixing with open ocean water is restricted thus threatening seagrasses and corals.

1. Introduction

Aquaculture is with an average annual increase of 8.7% over the past 40 years the fastest-growing food-producing sector and set to overtake capture fisheries as a source of food fish. The per capita supply of food fish from aquaculture has already increased from 0.7 kg in 1970 to 7.8 kg in 2008 (FAO, 2010). Decreasing fish stocks in the oceans and rapid growth of human population will most probably lead to a further increasing reliance on farmed seafood as source of protein (Naylor et al., 2000). China is by far the largest producer of aquaculture goods (32.7 million tonnes in 2008) accounting for 62% of global production in terms of quantity and 51% of global value (FAO, 2010). In the Asia-Pacific region, where 89% of the global aquaculture production takes place, culture in earthen ponds is the most important farming method for finfish and crustaceans in fresh and brackish water (FAO, 2010). Brackish-water culture, which represented 7.7% of world production in 2008, accounted for 13.3% of total value, reflecting the prominence of relatively high-valued crustaceans and finfishes cultured in brackish water (FAO, 2010). Despite generating profits and income for local communities, aquaculture production bears a suite of adverse environmental consequences.

Between 1980 and 2005, when aquaculture experienced the greatest increase, 20% of the world's mangrove area was lost (FAO, 2007) and pond construction is regarded as one of the major causes for this decline (Alongi, 2002; Chua et al., 1989; Páez-Osuna, 2001a). Conversion of mangrove area into pond area reduces the mangrove's valuable ecosystem services (e.g. fish habitat, coastal protection, sediment trapping) thereby affecting biodiversity and causing coastal erosion. Other impacts resulting from pond aquaculture are water pollution by excessive

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application of herbicides, pesticides and antibiotics, salinization, acidification, reduction of wild fish supplies through introduction of non-indigenous organisms, wild seed stock collection and catch of wild fish for aquaculture feed, as well as socio-economic consequences, such as marginalization of coastal communities and changes in traditional livelihoods (Dierberg and Kiattisimkul, 1996; Flaherty and Karnjanakesorn, 1995; Naylor et al., 2000; Páez-Osuna, 2001b; Phillips 1998; Primavera, 1997, 1998; Senarath and Visvanathan, 2001; Thongrak et al., 1997). One of the key environmental concerns about aquaculture is water degradation, due to discharge of effluents with high levels of nutrients and suspended solids into adjacent waters causing eutrophication, oxygen depletion and siltation (e.g. Burford et al., 2003). To guarantee adequate water quality for the animals raised, pond water is usually exchanged several times during the production cycle and nutrient-rich effluents are released into adjacent natural water bodies mostly without prior treatment. High concentrations of suspended organic solids, carbon, nitrogen and phosphorus in aquaculture effluents mainly originate from excess feeds or from excretion from the farmed animals (Burford and Williams, 2001). High stocking rates, low-grade food quality and low feed conversion rates promote high remineralisation within ponds. In the early stage of crop production, N–P–K fertilizers are often added to pond waters, in order to trigger growth of algae serving as feed for the young animals.

Tropical shallow coasts are often fringed by coral reefs and seagrass meadows, which are usually adapted to oligotrophic water conditions. They provide valuable ecosystem services, such as water filtration, coastal protection and nursery and feeding habitat for fish and other marine resources (Beck et al., 2001; Hemminga and Duarte, 2000). Worldwide degradation of those habitats is mainly related to high nutrient inputs promoting vast growth of benthic algae, which may outcompete seagrass and corals (e.g. Hauxwell et al., 2001; Hughes, 1994; Silberstein et al., 1986). Little is known about the effects of pond aquaculture on the health of those habitats.

The majority of studies on pond aquaculture focus on water quality assessments in the ponds themselves or the quantification of effluent fluxes from intensively, semi-intensively and extensively managed shrimp and fish ponds (e.g. Alongi et al., 1999, 2000; Briggs and Funge-Smith, 1994; De Silva et al., 2010; Islam et al., 2004; Jackson et al., 2003; Páez-Osuna et al., 1997; Rivera-Monroy et al., 1999; Wahab et al., 2003). It has been shown that high loads of nitrogen, phosphorus and suspended solids are released from shrimp and fish ponds. Impacts of aquaculture effluents on water quality in coastal creeks have been addressed by a few studies, e.g. Biao et al. (2004), Burford et al. (2003), Costanzo et al. (2004) and Wolanski et al. (2000), who found elevated concentrations especially of dissolved nitrogen and chl *a* in outlet channels. However, only little is known on the effects of effluents from pond aquaculture on nutrient and chl *a* dynamics of the coastal seas.

To our knowledge, there are no quantitative reports on the effect of pond aquaculture on coastal waters existing from China, one of the worldwide leading shrimp and fish producers. The first comprehensive study about general operating characteristics of shrimp farming in China was presented by Biao and Kaijin (2007); Theodore (2007) studied ecological and socioeconomic characteristics of integrated aquaculture practices specific to north Hainan. However, cultivation practices and related effluent fluxes may vary between regions, e.g. due to climatic conditions, and therefore need to be evaluated locally.

Aim of this study was to determine the amount and composition of dissolved and particulate matter released from fish and shrimp ponds in NE Hainan, tropical China, and to assess the impact on water quality of the receiving estuarine and nearshore coastal waters. Effluent, nutrient and particulate matter export from shrimp and fish farms were calculated from areal extent of ponds, operating characteristics and water quality parameters in pond effluents. We also determined dissolved constituents and chl *a* in three coastal areas varying in size of aquaculture cultivation area in their hinterland. This study is to our knowledge the first one that combines data on effluent fluxes from brackish-water pond culture with related effects on water quality in adjacent coastal waters harboring coral reefs and seagrass meadows.

2. Materials and Methods

2.1. Study area

The study area is located at the NE coast of the island Hainan, South China, in the marginal tropics (Fig. 1a) and comprises a coastline of ~45 km. Coral reefs fringe parts of the coast in 0.5–4 km distance from the shore, and seagrass meadows occur in the back-reef areas (Fig. 1b). The area is subject to mixed semidiurnal microtides with a tidal range of about 0.5 and 1.5 m at neap and spring tide, respectively. The region is characterized by a tropical monsoon climate with a dry season from November to April and a rainy season from May to October. The total annual precipitation is 1,500–2,000 mm, of which 35–60% are related to typhoon-induced rainfall occurring mainly from July to September (Huang, 2003; Wang et al., 2008). Average air temperatures range between 14.6–20.8 °C in January and 25.2–33.1 °C in July.

2.2. Study sites and sampling time

This study focused on the three main sites of pond aquaculture production at the NE coast of Hainan (Fig. 1), the Wenchang/Wenjiao Estuary and adjacent coastal zone (WWE), as well as the areas of Changqi and Qingge including their back-reef areas. The **Wenchang/Wenjiao Estuary (WWE**; 19°35.9′ N, 110°49.0′ E) is fed by two lowland rivers (Wenchang and Wenjiao) that drain agriculture areas of the coastal plain. They discharge into a shallow (mean depth: 3 m), kidney-shaped lagoon (Bamen Bay), which is connected to the sea via a narrow channel (max. depth = 10 m). In total, the estuary comprises an area of ~40 km^2. Since the 1960s, 73% of the fringing mangrove along the estuary has been lost at the expense of aquaculture ponds with approximately 7.5 km^2 residual mangrove area in 2009 (Krumme et al., submitted for publication). In addition to ponds, approximately 0.05 km^2 are covered by floating net cages for fish cultivation (Krumme et al., submitted for publication). In the outer estuary, fringing coral reefs and seagrass meadows occur in south-eastern direction to the outlet of the estuarine lagoon. **Changqi** (19°27.2′ N, 110°47.8′ E) is the second largest aquaculture production area in NE Hainan. Ponds are mainly located around a tidal channel reaching ~6 km inland parallel to the coastline. Though, there are also ponds situated along the coastline, which release their effluents directly into the sea via artificial drainage channels. Shrimp and fish ponds cover major parts of the former mangrove area, of which approximately 85% had been lost since the 1960s with about 1.8 km^2 residual mangrove area in 2009 (Krumme and Herbeck, unpublished data) mainly near the outlet of the tidal channel. The reef crest is located ~3 km from the shoreline and the back-reef area comprises ~23.2 km^2. Seagrass meadows dominated by *Thalassia hemprichii* and *Enhalus acoroides* occur in the back-reef area. **Qingge** (19°19.7′ N, 110°41.3′ E) situated in the south of the study area represents another important aquaculture production area, which now replaces former agricultural fields. Mangroves have not formerly

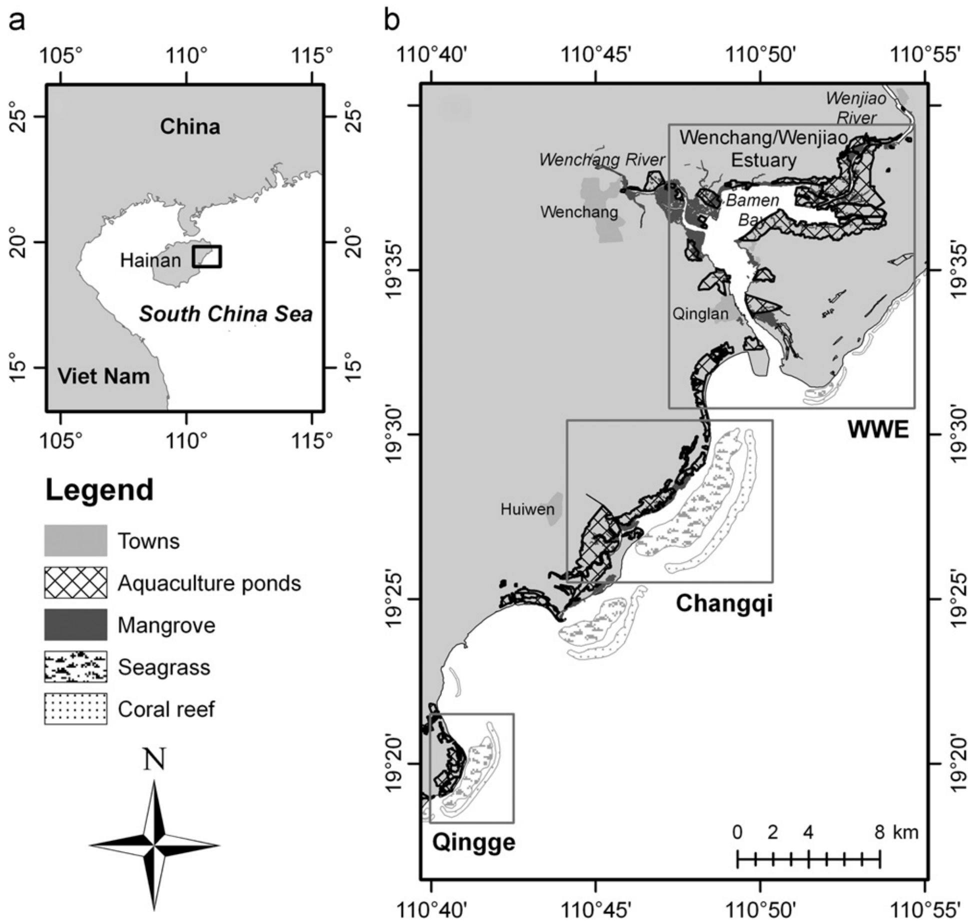

Fig. 1. Location of the study area at the NE-coast of Hainan, China (a) and overview on the study area (b) with location of the three study sites WWE, Changqi and Qingge including extent of coastal habitats and aquaculture ponds.

occurred in this area. The pond area is drained into the sea by a multitude of artificial channels. The reef crest is located ~1 km offshore and the back-reef area comprises ~8.4 km^2. Seagrass meadows dominated by *T. hemprichii* and *E. acoroides* occur in the back-reef area.

Sampling took place in July/August 2008 (rainy season) and March/April 2009 (end of dry season). During both sampling campaigns major precipitation events occurred (Unger et al., this issue).

2.3. Sampling and analysis

2.3.1. Spatial extent of shrimp and fish farms

The spatial extent of aquaculture ponds in the study area and specifically at the three study sites was determined from satellite images from 2009 (Geo Eye^{TM}, 2009), on which pond complexes were clearly visible (Fig. 2). Images were geo-referenced and groundtruthed with appropriate waypoints taken over the study area with a GPS, and digitized using ESRI ArcGIS 9.

2.3.2. Operating characteristics of fish and shrimp farms

In order to collect information on operating characteristics of fish and shrimp farms in the selected areas, 18 and 41 interviews with randomly selected pond owners were carried out in 2008 and 2009. In total, there was a minimum of 15 interviews taken in each of the three study sites. Interviews were based on a semi-structured questionnaire with minutes translated and transcribed from memory. The questionnaire mainly focused on parameters

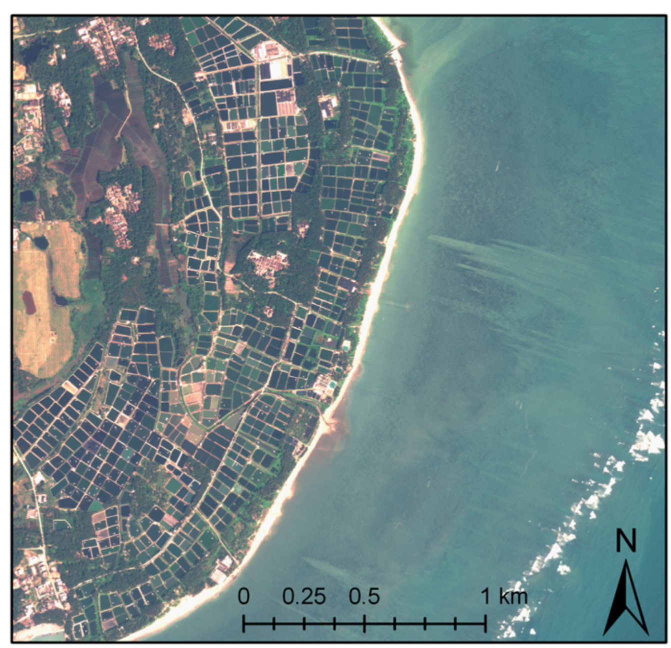

Fig. 2. Satellite image (Geo Eye^{TM}, 2009) showing aquaculture ponds at Qingge. White line at the bottom right site of the picture indicates waves breaking at the reef crest.

needed to estimate the annual effluent export (e.g. number of crops per year, rate and quantity of water exchanged, pond depth), but also contained general questions related to stocking densities, feeding management, etc. In addition, specific information about ponds that were sampled for water (see below) were obtained regarding e.g. age of animals raised and days since last water exchange.

2.3.3. Water sampling and analysis

Water samples were collected from fish and shrimp ponds, drainage channels, estuaries/tidal inlets and coastal sites during several dates of the study period. Water from shrimp ponds ($n=31$), fish ponds ($n=24$) and drainage channels ($n=59$) was collected by submersing a bottle from the pond/channel edge. Drainage channels were sampled 1–5 m before their discharge into the sea. Coastal waters were sampled randomly by boat along a land-sea gradient.

Water samples for nutrient analysis were filtered immediately after sampling through single use Sartorius Minisart ® membrane filters (0.45 μm pore size) into PE bottles, which were rinsed three times with the filtered sampling water beforehand. Samples were preserved with a mercury chloride solution (50 μl of a 20 g L^{-1} $HgCl_2$-solution added to 100 ml sample) and stored cool until analysis. For dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) analysis, 10 ml of water was filtered through single use membrane filters into precombusted (5 h, 450 °C) glass ampoules. Samples were acidified to pH 2 with phosphoric acid, sealed and stored frozen until analysis. Water samples for chlorophyll *a* (chl *a*) and particulate matter determination, which were only collected from ponds and drainage channels, were stored cool and dark in PE tanks. Salinity (± 0.1) and pH (± 0.1) were measured with a WTW MultiLine F/Set3 multi-parameter probe before the water was filtered under constant pressure onto GF/F filters on the same day. Filters for particulate matter determination were dried at 40 °C, whereas filters for chl *a* determination were stored frozen until analysis.

Dissolved nutrients were analyzed using a continuous flow injection analyzing system (Skalar SAN++System). Nitrate + nitrite (NO_x^-), nitrite (NO_2^-), phosphate (PO_4^{3-}) and silicate ($Si(OH)_4$) were detected spectrophotometrically and ammonium (NH_4^+) fluorometrically as a colored complex (Grasshoff et al., 1999). Determination limits were 0.08 μM, 0.03 μM, 0.06 μM, 0.07 μM and 0.19 μM for NO_x^-, NO_2^-, NH_4^+, PO_4^{3-} and $Si(OH)_4$, respectively. The coefficient of variation of the procedure was < 3.4%. Nitrate (NO_3^-) was calculated as $NO_x^- - NO_2^-$. Concentration of dissolved inorganic nitrogen (DIN) is the sum of NO_3^-, NO_2^-, and NH_4^+. DOC and TDN were measured simultaneously by the high temperature catalytic oxidation (HTCO) method using a Teledyne Tekmar Apollo 9000 Combustion TOC Analyzer at 680 °C (for samples collected in 2008) and a Shimadzu TOC-V_{CPH} Total Organic Carbon Analyzer with a TNM-1 Total Nitrogen Measuring Unit combusting at 720 °C (for samples collected in 2009). No significant differences were found between measurements at both devices (M. Birkicht, pers. comm.). The relative deviation of the method was < 2%. Dissolved organic nitrogen (DON) was calculated as TDN–DIN.

Concentrations of total suspended matter (TSM) were determined by weighing the dried filter, subtracting the original weight of the empty filter and dividing it by the respective volume of water filtered. Values given are the average of 2–3 filters. TSM on GF/F-filters was analyzed for total carbon (TC) and particulate nitrogen (PN) by high-temperature combustion in a Carlo Erba NA 2100 elemental analyzer (Verardo et al., 1990). Particulate organic carbon (POC) was determined the same way after removal of carbonate by acidification with 1 N HCl and subsequent drying at 40 °C. Measurements had a precision of 0.06% for POC and 0.02% for PN, based on repeated measurements of a standard (LECO 1012). Chl *a* concentrations were determined as follows: pigments were extracted from the filters in 10 ml of 90% acetone at 4 °C in the dark for approximately 24 hours, and extracts were subsequently centrifuged at 60 rpm for three minutes. Chl *a* in the supernatant of samples collected in 2008 was determined with a Lovibond PC Spectro 1.0 photometer and calculated after Lorenzen (1967). Chl *a* in samples collected in 2009 was determined with a TURNER 10-AU field fluorometer after Arar and Collins (1997). Significant differences between standards measured with both devices could not be detected.

2.3.4. Data analysis

Outliers were removed from the datasets of concentrations of nutrients, DOC, DON and particulate matter in ponds and drainage channels based on statistical analysis provided by box plots. Very high concentrations may have been derived from factors such as high sulfide concentration, which are likely to occur in drainage channels as a consequence of high organic matter degradation rates, and can disturb the photometric/fluorometric detection of dissolved nutrients (Grasshoff et al., 1999). Thus, calculated average concentrations for shrimp and fish ponds and especially in drainage channels represent conservative numbers.

The average annual export of effluents from shrimp and fish ponds was calculated for the different areas using the following equations:

$$E_S = c_S P\, a_S/100d + i_S c_S z_S/100 P a_S/100d$$
$$E_F = c_F P\, a_F/100d + i_F c_F z_F/100 P a_F/100d$$
$$E_T = E_S + E_F$$

E_S is the effluent export from shrimp ponds [$m^3\ yr^{-1}$]; E_F is the effluent export from fish ponds [$m^3\ yr^{-1}$]; E_T is the total effluent export from aquaculture ponds [$m^3\ yr^{-1}$]; c_S is the number of shrimp crops per year; c_F is the number of fish crops per year; P is the pond area [m^2]; a_S is the portion of shrimp ponds in area [%]; a_F is the portion of fish ponds in area [%]; d is the average pond depth [m]; i_S is the events of partial water exchange in shrimp ponds during each crop; i_F is the events of partial water exchange in fish ponds during each crop; z_S is the portion of shrimp pond water exchanged [%]; z_F is the portion of fish pond water exchanged [%].

The related annual export of dissolved and particulate matter was calculated for each area as the sum of average effluent export from shrimp ponds (E_s) and fish ponds (E_F) multiplied by average concentrations of dissolved and particulate matter in drainage channels.

The statistic tool of SIGMAPLOT 11.0 was used to perform the statistical analyses. The data were tested for normal distribution before choosing parametric or non-parametric statistical methods. The Pearson Product Moment Correlation analysis or Spearman Rank Order Correlation analysis was performed to test for significant correlations. Linear regression analysis was also performed. Kruskal-Wallis One Way Analysis of Variance on Ranks followed by Pairwise Multiple Comparison Procedure (Dunn's method) was used to determine significant differences in water quality parameters between shrimp ponds, fish ponds and drainage channels. The Mann-Whitney t-test by Rank Sum was applied to detect significant differences between water quality parameters in the coastal zone between the rainy season 2008 and the dry season 2009.

3. Results

3.1. Spatial extent and operating characteristics of shrimp and fish farms in NE Hainan

In total, 39.6 km^2 are used for pond aquaculture in our study area (Table 1). The main production area is located in the lagoon of the Wenchang/Wenjiao Estuary (WWE) and covers 21.6 km^2. Coastal fish and shrimp ponds that are situated directly along the

Table 1
Spatial extent, contribution of fish and shrimp culture and average annual export of effluents and dissolved and particulate matter from pond aquaculture at the different study sites in NE Hainan (Coastal pond aquaculture refers to all ponds that drain their effluents directly into coastal waters, and includes the study sites Changqi and Qingge amongst others).

	WWE	Changqi	Qingge	Coastal pond aquaculture	Total pond aquaculture
Pond area (km^2)	21.6	8.7	2.4	18.0	39.6
Fish culture (%)	10	80	70	55	40
Shrimp culture (%)	90	20	30	45	60
Average export of aquaculture effluents ($10^6\ m^3\ yr^{-1}$)	210	88	24	180	391
Average annual export loads from pond aquaculture ($t\ yr^{-1}$)					
TP*	**27**	**11**	**3**	**23**	**51**
DIN	184	77	21	158	344
DON	144	60	16	123	268
PN	364	153	41	312	680
TN	**692**	**290**	**78**	**593**	**1292**
DOC	1189	498	134	1019	2220
POC	2106	882	238	1805	3931
TOC	**3295**	**1380**	**372**	**2824**	**6151**

* refers to PO_4^{3-}-phosphorus only.

shoreline make up 18.0 km^2, of which 8.7 km^2 are found in Changqi and 2.4 km^2 in Qingge (Table 1).

Aquaculture development in NE Hainan started in the 1980s and is still increasing. The main shrimp species cultured are *Litopenaeus vannamei* (white shrimp), *Penaeus chinensis* (chinese shrimp) and *Penaeus monodon* (black tiger shrimp) and the main cultured fish species are *Epinephelus awoar* (banded grouper) and *Epinephelus lanceolatus* (gentiana grouper). In 2009, the majority of ponds were used for shrimp cultivation (~60% on average), while fish cultivation (~40% on average) was less important. The respective share of each, however, varied regionally (Table 1) and temporally depending on market prices. Three to four crops of shrimp are cultured per year, which have an average culture time of 70–80 days in summer and 90–120 days in winter. Some farms intermit their production during winter time (Dec–Feb). For fish culture, one crop is raised each year (culture time ~360 days). The ponds have an average size of 0.25 ha (ranging from 0.07–1.33 ha) and an average depth (d) of 1.7 m (ranging from 1.2 to 2.0 m). 82% of the fish and shrimp farmers interviewed own up to three ponds, but bigger farms with up to 18 ponds also exist ($n=33$).

The interviews revealed that the majority of farms appear to be intensively managed, though cultivation practices varied considerably from pond to pond. Most ponds were equipped with paddle-wheel aerators, which either work all day or during the night with a few hours in the day depending on the weather. The bottom of some ponds, especially those located above sea level, was covered by plastic sheets, in order to avoid seepage and to facilitate removal of accumulated organic matter after each production cycle. Larvae were mainly obtained from larvae-culturing factories in the area. Pond owners quoted that stocking densities of shrimp were between 49 and 300 individuals per m^2 (mean ± SD = 135 ± 66, $n=10$) and stocking densities of fish were between 300 and 750 individuals per m^2 ($n=5$). Four different kinds of artificial feed pellets varying in size are used for the different age classes of shrimp and are often complemented by fish, fish eggs and other homemade feed. Artificial feed pellets are also fed to fishes < 8 cm and captured fish is used, when they are older. Shrimps are fed 2–4 times a day depending on age, whereas fish are usually fed between twice a day and once every two days depending on age. Farm owners reported to produce between 563 and 22,500 kg shrimp per ha per cycle ($n=10$). This represents extremely high mean annual yields of 5.3 kg shrimp per m^2 ranging from 0.2 to 7.9 $kg\ m^{-2}\ yr^{-1}$ with an average survival rate of ~50% ($n=10$). Survival rates of fish are also 50% on average (10–70%). Though, survival rates can vary considerably from crop to crop and have been reported to be decreasing during the past years, especially for shrimp. Antibiotics, disinfectors and water conditioners are widely used in most farms. Nevertheless, almost all farmers bewail increasing occurrence of diseases.

The frequency of water exchange varied according to production stage and instantaneous water quality. Pond water exchange is usually minimal during the first month of crop production and increases with maturity of the animals raised. On average, 25% (z_S) of the shrimp pond water is exchanged 2.5 times (i_S) during each production cycle, whereas the same portion of fish pond water (z_F) is exchanged 20 times (i_F) during the production cycle. In addition, the ponds are drained completely during harvest procedure 3.5 times a year (c_S) in shrimp ponds and once a year (c_F) in fish ponds. Pond effluents are released into natural creeks or artificial drainage channels or pumped directly into estuarine or coastal waters without prior treatment. New water for the ponds is taken in from estuarine/coastal waters using pumping systems. Water intake only takes place during high tide, while effluents are released any time. Overall, the interviews revealed that there is no consistent pattern in operating practices.

3.2. Water quality in shrimp ponds, fish ponds and drainage channels

An average pH around 8.3 and average salinities of 12.8 in shrimp ponds and 20.3 in fish ponds (Table 2) confirm brackish water pond culture to be the common cultivation practice in the area. The lower pH and salinity in drainage channels (7.8 and 17.2 on average, respectively) indicate that these carried a mixture of pond effluents and freshwater from the upper watershed.

High average concentrations of nutrients and dissolved organic matter (DOM = DOC and DON) were found in shrimp and fish ponds and drainage channels (Table 2). Especially average ammonium concentrations were high, ranging from 36.2 μM in fish ponds to 46.4 μM in shrimp ponds, and accounted for 60–85% of the DIN (Fig. 3). DIN concentrations in shrimp and fish ponds correlated significantly with age (in days) of the shrimps ($p < 0.05$; r = 0.55) and fishes ($p < 0.05$; r = 54) cultured. DON in shrimp ponds accounted for ~60% of the TDN and was significantly higher than in fish ponds and drainage channels ($p < 0.05$). Average DOC concentrations in shrimp and fish ponds of ~800 μM were almost twice as high as in drainage channels. Average phosphate concentrations in ponds and drainage channels ranged between 3.0 and 8.1 μM. Silicate concentrations in drainage channels of 52.9 μM were significantly higher than in shrimp and fish ponds ($p < 0.05$).

In drainage channels, average concentrations of TSM (193 $mg\ L^{-1}$), POC (10 $mg\ L^{-1}$) and PN (1.7 $mg\ L^{-1}$) were higher than in fish and shrimp ponds. PN and POC concentrations were

Table 2
Water quality in shrimp ponds, fish ponds and drainage channels.

	Salinity	pH	PO_4^{3-} (μM)	$Si(OH)_4$ (μM)	NO_3^- (μM)	NO_2^- (μM)	NH_4^+ (μM)	DIN (μM)	DON (μM)	DOC (μM)	TSM (mg L^{-1})	PN (mg L^{-1})	POC (mg L^{-1})	Chl a (μg L^{-1})
Shrimp ponds														
Mean	12.8	8.2	3.0	17.9	9.2	6.1	46.4	54.1	128.7	880.6	109.1	1.4	8.8	71.3
SD	6.6	0.6	1.4	15.1	18.3	12.1	83.8	72.5	256.3	477.4	91.4	1.4	8.1	61.0
Range n=16–31	2.0–23.1	7.6–9.5	1.2–7.3	0.2–90	0–90	0.0–36.8	0.8–429	0.8–247	23.8–1,110	502–2,399	16.5–321	0.1–5.9	0.6–34.9	2.7–195
Fish ponds														
Mean	20.3	8.3	8.1	29.9	13.3	2.1	36.2	56.5	27.2	800.8	154.1	1.5	9.6	51.9
SD	7.0	0.6	7.7	27.6	16	1.9	34.3	49.8	28.8	785	107.3	1.2	6.5	58.5
Range n=17–24	3.3–30.2	7.5–10.0	1.1–28.1	0–101	0–52	0.1–5.8	3.0–99	6.4–149	2.2–94	164–2,228	42.9–439	0.3–5.0	2.3–27.3	1.2–191.2
Drainage channels														
Mean	17.2	7.8	4.2	52.9	14.8	3.1	41.8	62.7	48.9	472.2	193.1	1.7	10.0	50.1
SD	10.7	0.4	3.8	36	16.6	3.4	33.2	50	30.1	262.0	246.8	2.1	11.1	75.0
Range n=25–56	0.1–32.7	6.9–8.5	0.8–19.6	3.7–114	0–69	0.2–15.9	0.1–168	0.5–284	15.6–145	178.5–1,033	15.1–1,007	0.01–10.4	0.1–48.4	0.2–270

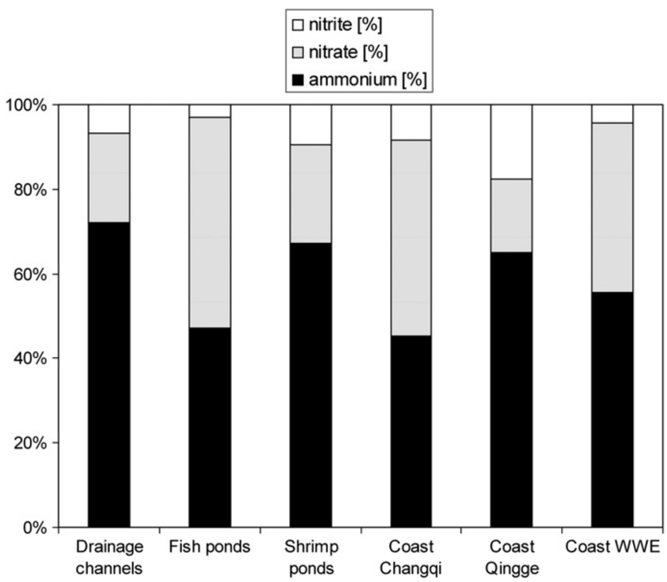

Fig. 3. Average composition of DIN in shrimp and fish ponds, drainage channels and nearshore coastal waters at the three study sites.

similar in fish and shrimp ponds, whereas TSM concentrations were higher in fish ponds (154 mg L^{-1}) than in shrimp ponds (109 mg L^{-1}). Average chl *a* concentrations ranged from 50 to 71 μg L^{-1} and were highest in shrimp ponds (Table 2). Average molar C/N ratios of particulate matter (POC/PN) were significantly higher ($p<0.05$) in drainage channels (10.2) than in fish ponds (7.8) and shrimp ponds (7.5), whereas average C/N ratios of DOM (DOC/DON) were lower in drainage channels (10.4) than in fish ponds (17.0) and shrimp ponds (16.0). Average inorganic N/P-ratios (DIN/PO_4^{3-}) were higher in drainage channels (20.3) than in fish ponds (14.6) and shrimp ponds (16.1).

Concentrations of all parameters measured in the respective fish and shrimp ponds and in drainage channels varied considerably, as indicated by the large range and standard deviation (Table 2). Due to the high variability within the three groups, only few significant differences between fish ponds, shrimp ponds and drainage channels could be detected.

3.3. Export of effluents and dissolved and particulate matter from shrimp and fish ponds

Based on the presented data, we calculated that a total of 391×10^6 m^3 effluents are released without any prior treatment from shrimp and fish ponds in the study area every year (Table 1). 54% of these effluents are initially drained into the Wenchang/Wenjiao Estuary, whereas the remaining 46% are directly exported to coastal waters via small drainage channels. Effluent export from the study sites Changqi and Qingge accounted for 49% and 13% of the direct export to coastal waters, respectively. In total, 6,151 t yr^{-1} total organic carbon (TOC), 1,292 t yr^{-1} total nitrogen (TN) and 51 t yr^{-1} dissolved phosphate are exported from pond aquaculture (Table 1). Particulate matter contributed 53% to TN and 64% to TOC.

3.4. Water quality in receiving estuarine and nearshore coastal waters

In estuarine waters of the WWE and Changqi, nutrient concentrations and phytoplankton biomass were mostly high with concentrations >10 μM DIN, >1 μM PO_4^{3-} and >3 μg L^{-1} chl *a* (Fig. 4). Nutrient dynamics of the WWE are described in detail in Liu et al. (2011). Water quality parameters in nearshore coastal waters were comparable at all three study sites (Figs. 4 and 5). Lowest salinities and highest concentrations of dissolved nutrients and organic matter were found within 100 m distance from the shore and there was a general trend of rising salinity and decreasing concentrations of dissolved nutrients, organic matter and chl *a* in offshore direction (Fig. 5). There was a linear relationship of salinity with silicate (r^2=0.77, $p<0.001$) and nitrate (r^2=0.68, $p<0.001$), but not with phosphate and ammonium (Fig. 6). Temporal variability was visible on a seasonal scale (rainy season 2008 vs. end of dry season 2009; Figs. 4 and 5), as well as on a day-to-day scale.

Due to enhanced estuarine mixing, the range of salinity variability in the coastal waters of WWE and Changqi (8–34 and 13–33, respectively) was higher than in Qingge (19–34; Figs. 4a and 6). Salinity values <15 were recorded during the rainy season in 2008 and were associated with a typhoon event (Herbeck et al., 2011). Elevated silicate concentrations were observed in WWE and Changqi (up to 76 μM) during individual sampling events of the rainy season (Fig. 6a).

At all coastal sites, phosphate concentrations (Figs. 4b, 5a, and 6b) were significantly higher ($p<0.05$) during the dry season in March/April 2009 (0.8–3.7 μM) than during the rainy season in July/August 2008 (0–1.8 μM). In WWE and Qingge, phosphate concentrations declined in offshore direction, whereas values stayed on a relatively constant level in Changqi (Fig. 5a). High phosphate concentrations also occurred at high salinities (Fig. 6b). DIN concentrations (Figs. 4c and 5b) were high close to the shore at some sampling events (up to 31 μM) and decreased in offshore direction ($p<0.05$ except for Changqi in 2008). DIN was

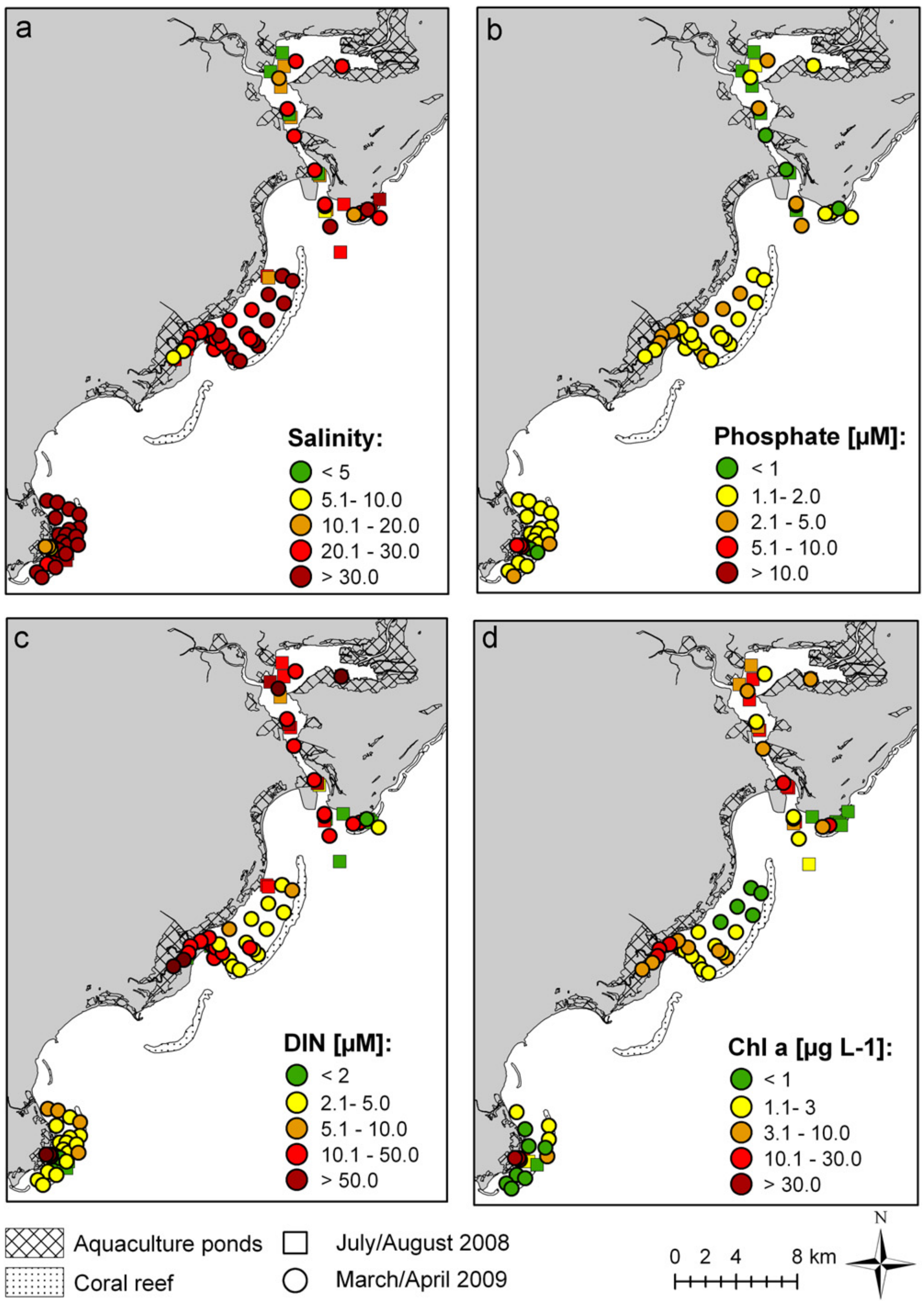

Fig. 4. Salinity (a), and concentration of PO_4^{3-} (b), DIN (c) and chl *a* (d) in estuarine and nearshore coastal waters in July/August 2008 and March/April 2009.

dominated by ammonium making up 45–65% of the DIN pool (Fig. 3). While nitrate+nitrite concentrations tended to decline with increasing salinity, this was not the case for ammonium (Fig. 6c and d). Also, DON concentrations (Fig. 5c) were high, especially in Qingge and Changqi (> 150 μM) and did neither correlate with distance nor with salinity ($p > 0.05$).

Concentrations of DOC (Fig. 5d) were significantly higher ($p < 0.05$) at all coastal sites during the dry season in March/April 2009 (156–1,718 μM) compared to the rainy season in July/August 2008 (42–1,077 μM). Chl *a* concentrations were up to 38 $\mu g\,L^{-1}$ directly adjacent to the shore, but decreased in offshore direction and were $< 3\,\mu g\,L^{-1}$ at most stations (Figs. 4d, 5e). Chl *a* concentrations correlated positively with salinity, DIN, ammonium, nitrate and silicate in WWE and Changqi ($p < 0.05$). In Qingge, significant correlations of chl *a* were only found with salinity and nitrate (2009) and TDN and DOC (2008).

4. Discussion

4.1. Water quality in shrimp ponds, fish ponds and drainage channels

The water quality in drainage channels was comparable to that in fish and shrimp ponds, which confirms pond effluents to be their primary source of water. Very high average concentrations of nutrients and dissolved and particulate organic matter in shrimp ponds, fish ponds and drainage channels reflect high

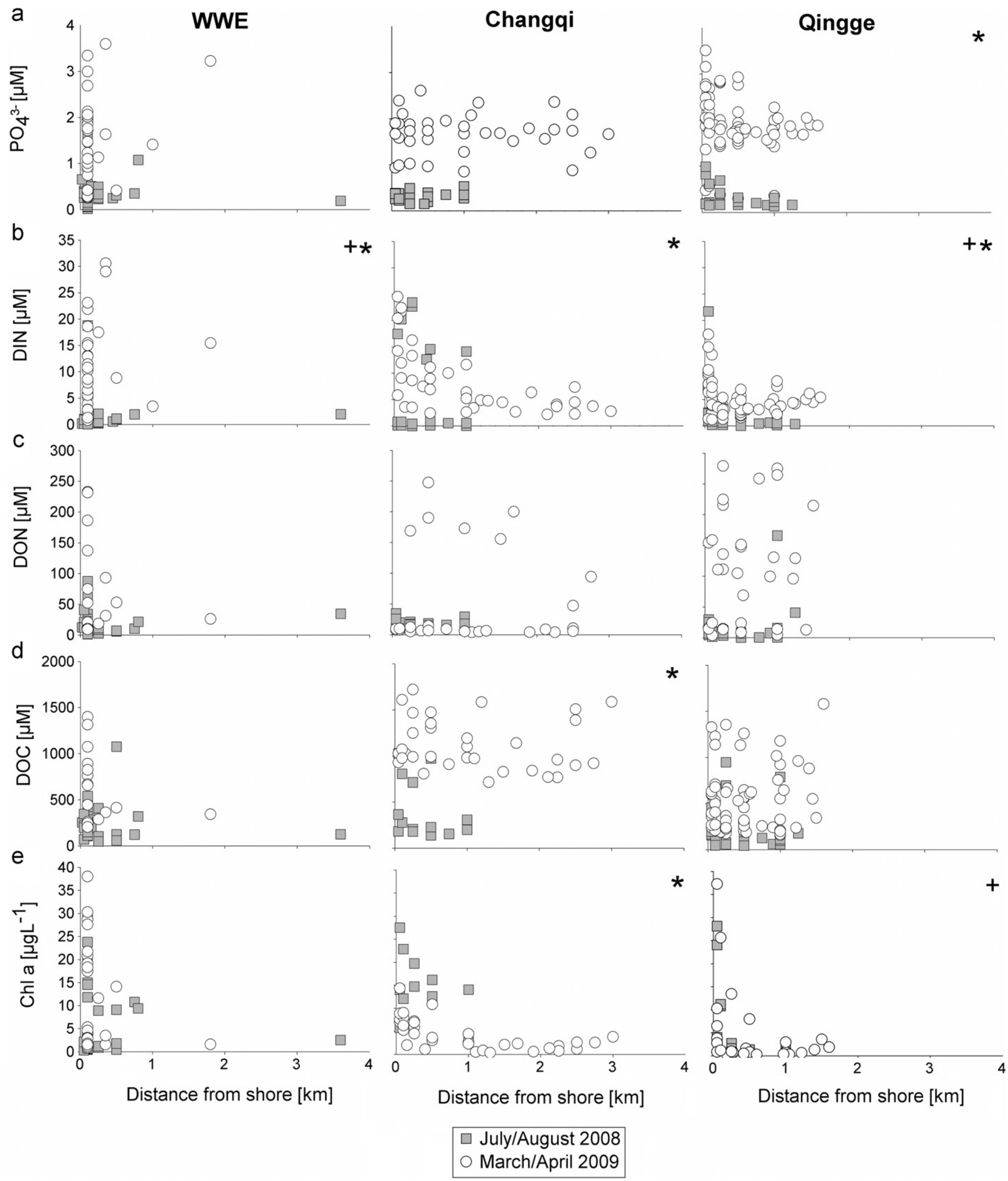

Fig. 5. Concentrations of PO_4^{3-} (a), DIN (b), DON (c), DOC (d), and chl *a* (e) over a distance gradient from the shore in nearshore coastal waters at the three study sites in July/August 2008 and March/April 2009. Significant Spearman Rank Order Correlations are indicated with + for 2008 and * for 2009.

inputs and intensive remineralisation. Ammonification appears to be especially high resulting in the high ammonium concentrations in ponds and drainage channels. Lower nitrate concentrations in ponds were probably related to a low abundance of nitrifying bacteria in pond sediments, which may have been inhibited by pond conditions (Hargreaves, 1998; Burford and Longmore, 2001). In contrast to earlier findings that ammonium is the dominant N species (Lorenzen et al., 1997), we found DON

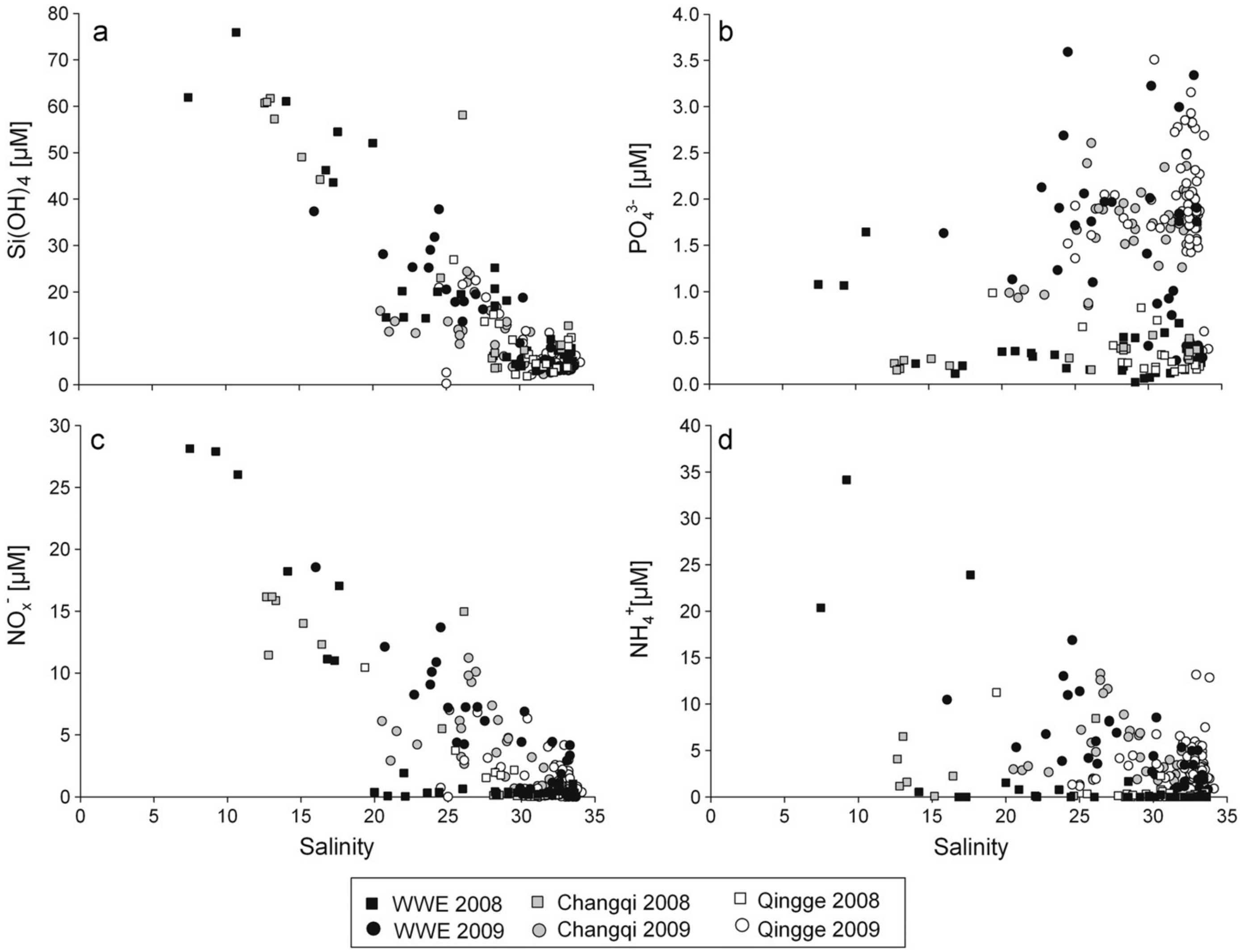

Fig. 6. Concentrations of $Si(OH)_4$ (a), PO_4^{3-} (b), NO_x^- (c), and NH_4^+ (d) versus salinity in nearshore coastal waters of the three study sites in July/August 2008 and March/April 2009.

to be the dominant dissolved N component in shrimp ponds, as also observed by Jackson et al. (2003); Burford and Williams (2001) found that most of the dissolved nitrogen leaching from the feed and shrimp feces was in organic rather than in inorganic forms. Higher concentrations of DON and DOC in shrimp ponds than in fish ponds indicate dissolution of greater amounts of feed in the water of shrimp ponds. Reasons for that may be the addition of homemade feed, such as low quality local fish and eggs, to shrimp ponds, which are frequently used in Chinese farms and are often instable in water getting rather remineralized than consumed (Biao and Kaijin, 2007). More frequent feeding of shrimp compared to fish may have also caused larger amounts of feed to remain in excess resulting in enhanced leaching of DOM from food particles in shrimp ponds. Since DON is only slowly utilized by bacteria in shrimp pond water, it can accumulate over the crop cycle (Burford and Williams, 2001). High chl *a* concentrations together with a C/N ratio of particulate matter close to the Redfield ratio (6.6) indicate phytoplankton as the primary suspended matter source in shrimp and fish ponds, as was also inferred by Jackson et al. (2003). Enhanced concentrations of POC and PN with an elevated C/N ratio compared to shrimp and fish ponds indicate additional contribution of OM-rich pond sediments in drainage channels. Those are resuspended in the water during pond drainage at harvest. Since drainage channels receive effluents from several ponds, the variability in their water quality parameters is a composite of different production stages and farm management of neighboring ponds of an area. The high variability in the water quality parameters between individual shrimp and fish ponds is concordant with results of other studies and is largely due to the different production states of the ponds (e.g. Burford et al., 2003; Jackson et al., 2003). The observed increase of nutrient concentrations in shrimp and fish ponds with animal age is consistent with results of other studies (e.g. Biao et al., 2004; Burford et al., 2003; Hopkins et al., 1993). It can be related to enhanced ammonia excretion by larger animals and to increased remineralisation resulting from higher food application towards the end of the cultivation period. Despite the high variability, nutrient concentrations (especially NH_4^+ and DON) in 95% of the drainage channels sampled exceeded the maximum allowed concentrations (DIN: 7.1 µM; PO_4^{3-}: 0.48 µM) for inlet and outlet rivers in China (State Environmental Protection Administration of China (SEPA), 1997).

4.2. *Export of effluents and dissolved and particulate matter from shrimp and fish ponds*

The major part of the exported carbon and nitrogen occured in solid form with POC and PN accounting for 64% and 53% of the

TOC and TN, respectively. Total phosphorus (TP) was not measured, but according to other studies dissolved phosphate accounts for less than 15% of the TP in shrimp pond effluents (e.g. Funge-Smith and Briggs, 1998; Islam et al., 2004). This supports the assumption that exported matter from aquaculture ponds mainly consists of phytoplankton and organic matter-rich particles, which are further recycled in the receiving natural waters. But also the flux of dissolved matter with aquaculture effluents was very high (Table 1).

There are few data available about export rates from other pond aquaculture areas. Biao and Kaijin (2007) reported that 658 t of nitrogen and 307 t of phosphorus were released with shrimp sewage in 1998 in Fujian Province, which has a coastline of 2,120 km. Our estimates from a much smaller area in NE Hainan (coastline ~45 km) exceed those loads by far, which indicates that NE Hainan is a globally significant area of aquaculture production. De Silva et al. (2010) estimated an export of 31,602 t of nitrogen and 9,893 t of phosphorus to be discharged from a 70 km^2 pond-based striped catfish production in the Mekong Delta in 2007. These estimates are substantially higher than ours. However, they were calculated from nutrient models based on nutrients added as feed and removed by fish harvest, which did not take into account other quantitatively important loss terms, such as uptake by phytoplankton and other biota, denitrification and volatilization of ammonia within the ponds and drainage channels. Thus, they do not represent the actual net N and P loads released, as calculated in our approach.

Export yields of TN from aquaculture ponds in NE Hainan was in between those of other intensive shrimp ponds and similar or higher than export rates from ponds of semi-intensive and extensive shrimp production reported by other studies worldwide (Table 3). Assuming that dissolved inorganic phosphate accounts for 15% of the TP, we arrive at an extrapolated TP export rate of about 8 t km^{-2} yr^{-1}, which corresponds to those reported in the literature (Table 3). Annual export of N and P in Hainan is higher than in other regions due to the fact that there are up to four crops of shrimp raised, while in many regions of the world only two crops are harvested each year (e.g. Briggs and Funge-Smith, 1994; Islam et al., 2004; Páez-Osuna et al., 1997). It is likely that the major part of the nutrients and organic matter is released into the environment at the time of harvest due to the high concentration at the late production stage, the fact that the ponds are completely emptied during harvest, and the additional export of suspended organic matter-rich pond sediments.

Uncertainties in the calculation of fluxes and yields may introduce large errors to any total budget. The variety of methods used to calculate export yields impairs comparison between studies and areas. Our calculations of annual effluent export can be regarded as conservative, because extremely high nutrient and organic matter concentrations were identified as outliers and were excluded from the calculations. Furthermore, our calculations consider minimal water exchange from ponds and do not include additional water exchange related to e.g. excessive rain water flushing.

Nonetheless, our calculations indicate a substantial supply of organic carbon, nitrogen and phosphorus to a relatively small coastal area of NE Hainan. This is of particular importance, since aquaculture ponds predominantly replaced former mangrove areas turning the region from a net nutrient sink or small source into a very large net nutrient source. Therefore, the additional inputs of N and P from aquaculture production represent a considerable human intervention in a tropical coastal zone.

4.3. Effects on water quality and trophic status of receiving coastal waters

High concentrations of nutrients, DOM and chl *a* close to the shore (Figs. 4 and 5) reflect considerable input from land. Concentrations of nutrients and DOM tended to decrease in offshore direction as a result of dilution with oceanic water and uptake by primary producers. A similar composition of DIN species in coastal waters and pond waters and drainage channels (Fig. 3) indicates nitrogen to mainly originate from aquaculture effluents. While silicate and nitrate+nitrite concentrations, which are typically not enhanced in aquaculture effluents, were low at high salinities, concentrations of ammonium and phosphate could be very high in high salinity coastal waters (Fig. 6) reflecting direct injection of phosphate- and ammonium-laden water from aquaculture drainage channels into high salinity coastal waters. Chl *a* concentrations were high close to the shore due to introduction of phytoplankton-rich aquaculture effluents and nutrient-stimulated in situ productivity, but decreased in offshore direction with decreasing nutrient availability.

The spatial and temporal variability in nutrient, DOM and chl *a* concentrations in coastal waters, especially close to the shore (Fig. 5)

Table 3
Comparison of nitrogen and phosphorus export from aquaculture ponds in NE Hainan to that of ponds for intensive, semi-intensive, and extensive shrimp production worldwide. Yields are based on total nitrogen and total phosphorus if not stated else.

	Net nitrogen export (t km^{-2} yr^{-1})	Net phosphorus export (t km^{-2} yr^{-1})	Reference
Intensive shrimp production			
NE Hainan, China	31.9	1.3[a]	this study
Thailand	60.2	6.1	Briggs & Funge-Smith (1994)
Thailand	143.4	42.4	Phillips (1994) cited by Beveridge et al. (1997)
Thailand	19.9	3.9	Robertson and Phillips (1995)
Australia	36.2	–	Jackson et al. (2003)
USA	119.8	8.1[a]	Hopkins et al. (1993)
Semi-intensive shrimp production			
Mexico	10.4	1.7	Páez-Osuna et al. (1997)
Honduras	35.6	4.8	Teichert-Coddington et al. (2000)
Columbia	6.4[b]	–	Rivera-Monroy et al. (1999)
Venezuela	9.1[b]	–	Clifford (1994) cited by Rivera-Monroy et al. (1999)
Vietnam	12.8	4.0	Robertson and Phillips (1995)
Bangladesh	34.4	11.5	Islam et al. (2004)
Thailand	2.9	2.7	Phillips (1994) cited by Beveridge et al. (1997)
Extensive shrimp production			
Bangladesh	1.6	0.6	Wahab et al. (2003)

[a] refers to PO_4^{3-}-phosphate only.
[b] refers to DIN-nitrogen only.

was mainly driven by temporally and spatially varying export of aquaculture effluents to coastal waters via drainage channels. The release of effluents from only a single pond may cause an enormous local increase of nutrient concentrations in the receiving water body. Also, tidal dynamics may influence nutrient and suspended matter concentrations, which is most evident at sites with strong land-derived inputs. Krumme et al. (submitted for publication) observed a tidally driven variability of nutrient concentrations at a station ~1.5 km offshore the outlet of the WWE with nitrate+nitrite ranging from 0.1–1.8 μM, ammonium from 0.3–5.3 μM, phosphate from 0.3–1.0 μM and silicate from 3.1–6.0 μM. This reveals that even in a micro tidal area, tidal currents have a great effect on nutrient concentrations and dispersal.

Furthermore, rain events can cause nutrient inputs because drainage channels additionally may carry nutrient-rich floodwater derived from the hinterland. Strong rainfalls, especially those associated with typhoon Kammuri in August 2008, were responsible for low salinities in back-reef areas between 2 and 5, where salinities are usually >20 (Figs. 4a and 6). High concentrations of silicate and nitrate+nitrite, but not of ammonium and phosphate, at low salinities (Fig. 6) in coastal waters indicate that rain events are mainly responsible for the release of nitrate and silicate into coastal waters with floodwater. Nitrate probably originates from atmospheric inputs from rain and leaching of fertilizers from agricultural fields, while silicate inputs can be attributed to increased export during rainfalls (Herbeck et al., 2011).

Concentrations of most parameters displayed little seasonal variation, which is most probably related to the fact that there were significant rain events during both sampling seasons. Average phosphate, DOC and DON concentrations were higher in March/April 2009 than in July/August 2008. This is likely due to the fact that rainfalls were the first after the dry season probably leaching significant amounts of nutrients from the hinterland that have accumulated over the dry season. This 'first-flush' effect was also observed in other areas with the onset of the rainy season (e.g. Eyre and Twigg, 1997; Eyre and Balls, 1999; Boonphakdee and Fujiwara, 2008).

According to trophic status categories established for coastal waters of the Baltic (DIN >2.1 μM; Håkanson, 1994) and of the eastern Mediterranean Sea (DIN >0.4 μM; Karydis, 1996), DIN concentrations ranked almost all the stations in the category of eutrophic or hypertrophic waters. The same was true for phosphate concentrations, which were higher than the threshold value of 1.1 μM TP for eutrophic waters (Smith et al., 1999) at the majority of stations. Concentrations of <2 μM DIN and <0.5 μM phosphate are reported for the majority of other tropical back-reef and seagrass areas (e.g. Szmant, 2002). Chl *a* concentrations were at most stations between 1 and 3 μg L^{-1}, which refers to mesotrophic waters according to the classification by Håkanson (1994) for the Baltic Sea. In coral reef areas worldwide, however, chl *a* concentrations are usually <1 μg L^{-1}, while values around 1 μg L^{-1} are found in sewage contaminated reef areas (e.g. Furnas et al., 1990; Liston et al. 1992; Otero and Carbery, 2005; Van Duyl et al., 2002). Accordingly, our values indicate strong eutrophication effects in coastal waters of NE Hainan.

Although aquaculture area and amounts of effluents released were highest in WWE, nutrient concentrations in adjacent coastal waters were not elevated compared to coastal sites of Qingge and Changqi. This is attributed to the fact that effluents from WWE are first released into the estuarine lagoon, which functions as a filter reducing nutrient export under dry weather conditions or moderate rain (Herbeck et al. 2011). In contrast, aquaculture effluents are released directly to coastal waters at Qingge and Changqi. Furthermore, the barrier like structure of the fringing reef hampers water exchange of back-reef waters with the coastal ocean, especially off Qingge and Changqi. It increases the residence time of nutrient-rich effluents in back-reef areas and hence exposure of seagrass and corals to high nutrient and organic matter concentrations. This may even amplify eutrophication effects causing enhanced productivity not only of phytoplankton, but also of macroalgae and epiphytic algae, which shade seagrasses and corals and deteriorate their health (e.g. Hauxwell et al., 2001; Hughes, 1994; Silberstein et al., 1986). We observed thick epiphytic mats on seagrass leaves and corals, which reflect the nutrient enrichment in coastal waters. Herbeck (2012) also showed that seagrasses exposed to pond effluents in NE Hainan had a lower performance in terms of shoot density, species abundance and biomass compared to less affected sites. Therefore, the placement of ponds in Qingge and Changqi appears especially harmful, since the enclosed character of the back-reef areas worsens negative effects of aquaculture related eutrophication.

5. Summary and conclusions

High amounts of aquaculture effluents rich in dissolved inorganic and organic matter are released from aquaculture ponds at the NE coast of Hainan agglomerated in a relatively small geographical area. These inputs cause eutrophic conditions in the adjacent coastal waters. Concentrations decreased in offshore direction but exceeded threshold values for good water quality even at most remote stations. Aquaculture effluents initially released into waters of the estuarine lagoon in WWE have less effects on the water quality of coastal waters than effluents from ponds in direct vicinity to the shore in Changqi and Qingge, as in WWE parts of the nutrients are retained in the estuarine coastal waters at least under dry season conditions. Aquaculture production in direct adjacency to back-reef areas, such as in Qingge and Changqi, may be especially harmful to seagrass meadows and coral reefs, because limited water exchange in reef-fringed coastal waters reinforces eutrophication and, subsequently, shading and competition pressure on these valuable habitats from an increased algae biomass. In order to conserve the natural services provided by the coastal habitats, effluents should be treated before release into natural water bodies and pond aquaculture next to back-reef areas should generally be relinquished.

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