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Physico-chemical characteristics of the improved extensive shrimp farming system in the Mekong Delta of Vietnam

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Abstract

Consecutive failure of the improved extensive shrimp farming system has deterred the economy of some coastal areas in Vietnam. To investigate pond physico-chemical characteristics, a monitoring scheme was performed in the Cai Nuoc district of Southern Vietnam. Results show that the system was not optimal for shrimps. While ponds were not contaminated by organic loadings or major nutrients (N, P) and salinity and pH were most optimal for shrimp, more than 37% of dissolved oxygen (DO) measurements were lower than recommended. In the early morning hours, DO measurements were even much lower (0.84–2.20 mg L^{-1}). Sulphate (SO_4^{2-}) concentrations were most within the acceptable range. Total suspended solids (TSS) were above the acceptable limit (<50 mg L^{-1}). Iron, alkalinity and hydrogen sulphide were also higher than recommended. Pond sediment was anaerobic (redox potential -422 to -105 mV) and contained high amounts of organic matter (9.84–21.96%). Lethal DO levels, high TSS and anoxic sediment are the drawbacks in this system. Suggested measures to improve pond conditions are (1) allowing sedimentation before filling culture ponds, (2) covering dikes, (3) including no-culture breaks between shrimp crops, (4) drying pond bottom, (5) removing sediment and (6) controlling pond's vegetation.

Keywords: improved extensive shrimp farming, Mekong Delta, physico-chemical characteristics, sediment characteristics, water quality

Introduction

Shrimp farming is one of the fastest growing economic activities in the Asia–Pacific region (Wolanski, Spagnol, Thomas, Moore, Alongi, Trott & Davidson 2000; Raux & Bailly 2002; EJF 2004) and experienced spectacular growth over recent decades (Thornton, Shanahan & Williams 2003; EJF 2004). In Vietnam, extensive farming of shrimp started about 100 years ago (Nhuong, Luu, Tu, Tam & Nguyet 2002) and was characterized by low shrimp yields (100–400 kg ha^{-1} year^{-1}) (Binh & Lin 1995). In the Mekong Delta of Vietnam, extensive shrimp farming systems started soon after the end of the Vietnam war (ADB/MoFi 1996). Modern shrimp farming, however, started only after the 1980s when the country launched the economic reform and the government encouraged shrimp farming (Nhuong *et al.* 2002). In 2000, the government released the resolution 09/NQ-CP, which allowed conversion of saline and low productivity rice fields into shrimp farms. As a result, shrimp farming boomed in the area (Vuong & Lin 2001; Nhuong *et al.* 2002; Binh, Vromant, Hung, Hens & Boon 2005).

The improved extensive shrimp farming system is the most predominant in the Mekong Delta of Vietnam (Nhuong *et al.* 2002; Binh *et al.* 2005). Currently, black tiger shrimp (*Penaeus monodon*) is widely farmed in the area. Although the criteria for shrimp farming system classifications may differ (Rönnbäck 2001; EJF 2003), shrimp farming in the area can be categorized as 'extensive', 'improved extensive' and 'intensive' systems. In the first system, shrimps are usually cultured in mangrove forests, relying mostly on natural seedstocks, sometimes with supplementary stocking (1–1.5 postlarvae m^{-2}). The improved extensive shrimp farming system can be characterized by (1) shrimp reared in a monoculture system in earthen ponds, (2) stocking of 1–7 ind m^{-2}, (3) sediment dredging and subsequent pond liming and (4) low survival rate (3–20%). The intensive shrimp farming system witnesses the highest level of intensification (mechanical pond preparation, stocking density of 15–45 postlarvae m^{-2}, use of industrial feed and chemicals) (Phuong, Minh & Tuan 2004). Despite great innovations in shrimp farming, farmers have operated their farms based on their own experiences and the knowledge transferred by their neighbours (Vuong & Lin 2001; Sels 2004). This system is subject to low and unstable shrimp yields (Hens, Vromant, Tho & Hung 2009). While other shrimp farming systems in the Mekong Delta are well documented (Alongi, Tirendi & Trott 1999; Vuong & Lin 2001; Brennan, Preston, Clayton & Be 2002; Clough, Johnston, Xuan, Phillips, Pednekar, Thien, Dan & Thong 2002; Preston & Clayton 2003), little is known about the improved extensive shrimp farming system. While the physico-chemical condition of the cultured ponds plays a vital role in the growth of shrimps (Haws & Boyd 2001; Hena Abu, Sharifuzzaman, Hishamuddin, Misri & Abdullah 2008), whether pond water and sediment in this system is optimal for shrimps remains unanswered. An overall assessment of the ponds' physico-chemical characteristics is not available.

The survival and growth of black tiger shrimp are affected by a wide variety of physico-chemical parameters. Salinities between 5 and 35 $g\,L^{-1}$ are most suitable for shrimp (Haws & Boyd 2001) and low salinities are linked to shrimp diseases (Joseph & Philip 2007). Water temperatures above 32 °C for prolonged periods can stress shrimp and reduce growth as it affects shrimp metabolism and feeding rates (Lazur 2007). Dissolved oxygen (DO) should be higher than 4 $mg\,L^{-1}$ (Chien 1992; Lazur 2007) as lower values can affect shrimp respiration and reduce shrimp resistance to diseases. Total suspended solid (TSS), which can deter the penetration of solar radiation into the water column and reduce primary production, is recommended from 2 to 14 $mg\,L^{-1}$ for black tiger shrimp (Jayasinghe, Corea & Wijegunawardana 1994) or <50 $mg\,L^{-1}$ for aquaculture in general (Vietnamese Standard 5943-1995). Recommended range for alkalinity, a measure of carbonate bases and which can affect primary production, is from 50 to 100 $mg\,L^{-1}$. Extremely low pH can stress shrimp and cause soft shell and poor survival. High shrimp mortality is observed at pH below 6 (Chien 1992). Nitrate (NO_3-N) is generally not toxic in pond environment (Lazur 2007). At high pH values, total ammonium nitrogen (TAN) can have an impact on shrimp, as the toxic gas NH_3 increases relative to NH_4-N (Haws & Boyd 2001). NH_3 can damage gills and reduce growth or cause mortality of shrimp, even at low concentrations (Lazur 2007). Nitrite (NO_2-N), an intermediate product of nitrification and nitrate reduction, is less toxic to shrimp (Chien 1992). At high concentrations, nitrite combines with haemocyanin in shrimp blood and reduces the ability of the blood to transport oxygen (Haws & Boyd 2001). Toxicity levels of hydrogen sulphide (H_2S) to shrimp is controversial, ranging from non-detectable to <0.25 $mg\,L^{-1}$ (Jayasinghe *et al.* 1994; Haws & Boyd 2001; Lazur 2007). Biochemical oxygen demand (BOD) – an indicator of organic pollution – is allowed in shrimp ponds at concentrations of <10 $mg\,L^{-1}$ (Jayasinghe *et al.* 1994). When BOD exceeds 20 $mg\,L^{-1}$, oxygen depletion is a danger in ponds without mechanical aeration (Haws & Boyd 2001). High concentrations of Fe^{2+} can cause slow growth of shrimp (Poernomo 1989). Impacts of sediment to shrimp are mainly stemmed from elevated organic matter (OM) accumulated on pond bottom. The degradation of sediment OM causes low DO condition, resulting in the reduced toxic substances, like nitrite, NH_3, Fe^{2+}, Mn^{2+}, H_2S and CH_4 (Haws & Boyd 2001), which can affect the growth of cultured shrimp. Links of sediment parameters to shrimp can be found in Boyd (1995).

This paper investigates the main physico-chemical characteristics of the improved extensive shrimp farming system in the coastal areas of the Mekong Delta (Southern Vietnam). It was conducted in the Cai Nuoc district, where shrimp pond areas expanded rapidly from the year 2000 on (Binh *et al.* 2005). In the district, shrimp expansion, basic pond characteristics and pollution caused by shrimp farming have partly been discussed (Binh *et al.* 2005; Tho, Vromant, Hung & Hens 2006, 2008; Hens *et al.* 2009). At the end of 2008, many improved extensive shrimp farmers were in debt as a result of shrimp losses (Field data 2008). The study is the first of its kinds combining water and sediment parameters in assessing the physico-chemical characteristics of the improved extensive shrimp farming system in the Mekong Delta of Vietnam. Accordingly, it provides important information to the limited literature in this system upon which the majority of local people rely for their livelihood. It lays a sound background for further research, aiming at a more sustainable shrimp farming practice in the area.

Materials and methods

Description of the study site and the improved extensive shrimp ponds

The Cai Nuoc district coastal lowlands (39 514 km^2) is situated in the south-west of the Ca Mau province in the Mekong Delta of Vietnam (Fig. 1). This area at 8° north of the equator has two main seasons: (1) a rainy season (May–October) with an average rainfall of 2100 mm, and (2) a dry season (November–April) with an average rainfall of 200 mm (SIG 2001). A dense network of rivers and canals connects the area from the South China Sea to the Gulf of Thailand. The area experiences a complex tidal regime. In 2008, the improved extensive shrimp farming system (including small ponds in garden areas) occupied $>70\%$ of the district's total land area and 88% of all shrimp-related areas (data from the Agriculture and Rural Development Division of Cai Nuoc district). The rice–shrimp farming system (one rice crop in the rainy season, one shrimp crop in the dry season) is also practised in a village north of the district where a salt prevention sluice gate has still been operated. The local government would like to expand the rice–shrimp area westwards. However, not much success has been achieved due to salinity problem.

Farmers construct the improved extensive shrimp ponds by digging a deep trench (2–2.5 m width, 0.6–0.8 m depth) around the traditional rice fields. The central platform of the field, which accounts for most of the pond surface area, remains undisturbed (Fig. 2). Each pond has a concrete gate near the corner closest to the river. The pond is connected to the river through a settlement channel, which opens to the river also via a concrete gate. Farmers collect river water into the settlement channel by direct pumping or just opening the channel gate at high tides (in areas of higher tidal amplitude). Before entering the settlement channel, river water has to pass a screen

Figure 2 A typical improved extensive shrimp pond in the Cai Nuoc district.

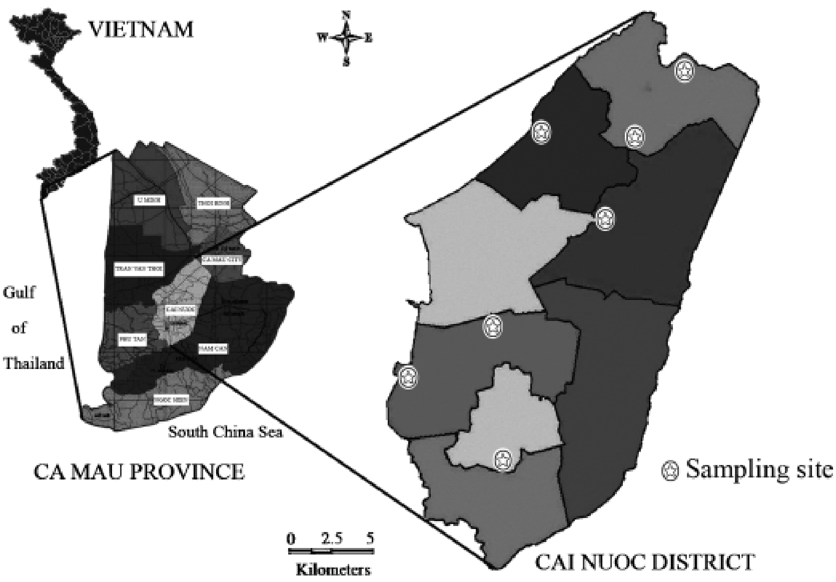

Figure 1 Location of the Cai Nuoc district and the sampling sites.

for the exclusion of undesirable objects. Some farmers store river water for some time in the settlement channel before filling their ponds. Stocking density is low (1–3 seeds m^{-2}) and most farmers stock supplementary shrimp larvae (amounting to 50–100% of the original amount stocked) over the following months. No feeding of the shrimps is applied. Pond water is not exchanged unless farmers observe shrimp mortality or too much turbidity. Sediment is removed from the trench, usually once or twice a year. In some cases, due to financial difficulty, farmers leave the pond sediment behind for 2 years or even more. Generally, shrimps are cultured all year round. Market-sized shrimps are harvested daily using a large-sized net placed in the trench, usually after 5 months of culture. Major production inputs are costs of (1) seed stocks (16 000–35 000 VND per 1000 postlarvae), (2) lime (CaO, $CaCO_3$) and fertilizers (NPK, Urea) and (3) labour, mostly for sediment dredging and disposal. While the first one can be roughly estimated, the last two items are hard to quantify as farmers do not keep records of pond inputs. While in principle considered as 'monoculture', the ponds are usually stocked with shrimps and several other aquaculture species, such as fish or crabs, mainly for an increased economic output (Field data 2008). This system requires little investment and knowledge, and is widely adopted by the low- and middle-income households. The system was slightly affected by the 2008 world economic crisis. During fieldwork in 2008, most improved extensive shrimp farmers argued that they could not afford appropriate sediment dredging and disposal due to increased labour cost.

Sampling

Pond water and sediment were sampled five times for physico-chemical characteristics in seven shrimp ponds (Fig. 1). On a 2-month basis, pond water was sampled in the trench with the hypothesis that water quality in the trench and the platform do not differ for most of the parameters. Pond sediment was sampled in both the trench and the platform at 0–5 and 5–10 cm depths, taking into account that the quality of the top sediment may differ between the locations, and that these differences can have an impact on shrimp health. Sampling was conducted while farmers followed their own practices of farming.

Sampling of pond water

Temperature, pH, DO, turbidity and salinity were measured *in situ* using a TOA instrument (WQC-22A, DKK-TOA Corporation, Tokyo, Japan). Sampling of H_2S was conducted at the water–sediment interface using 125 mL dark glass bottles. The other parameters were sampled in mid-depth of the trench at three locations in the ponds and mixed to form a composite sample for analysis. A 2 L plastic bottle was filled up for TSS, NO_2-N, NO_3-N, TAN, total N, PO_4-P, total P, Cl^-, SO_4^{2-} and alkalinity. Samples for BOD were collected in 1 L plastic bottles and kept in the dark. Samples for total Fe were collected in 125 mL dark glass bottles and fixed by concentrated HNO_3, while those for Fe^{2+} were collected and stored in 125 mL dark glass bottles. COD samples were collected in 125 mL bright glass bottles and fixed by H_2SO_4 4 M. All samples were stored at approximately 4 °C and transported to the lab the same day for analysis.

Sampling of pond sediment

The pH_w (pH of fresh sediment) and Eh (redox potential) were measured *in situ* using a combined Eh/pH meter (pH 62K, APEL Co Ltd, Saitama, Japan). A glass electrode was used for pH_w while an EMC 130 Meinsberg electrode (Sensortechnik Meinsberg GmbH, Ziegra-Knobelsdorf, Germany) was used for Eh measurement. Pond sediment was sampled (0–5 and 5–10 cm) using a stainless steel hand borer. Samples were stored in plastic boxes and placed in the ice box. Bulk density (BD) sampling was conducted once by pressing a PVC tube of 6 cm diameter into the sediment to a depth of about 20 cm. After the tube was pulled out, sediment column from 1 to 4 cm depth (representative for the 0–5 cm layer) and from 6 to 9 cm depth (representative for the 5–10 cm layer) was cut. The final sample for each depth had a volume of 84.82 cm^3. On a 2-month basis, the parameters Eh, pH_w, $pH_{1/2.5}$ and $EC_{1/5}$ were measured five times while total N, total P and OM were measured four times. On a 4-month basis, the parameters NO_2-N, NO_3-N and NH_4-N were measured three times while PO_4-P, soluble SO_4, total SO_4, Fe^{2+} and Fe^{3+} were measured twice (Table 1).

Twenty-four-hour monitoring experiment of selected parameters

To understand daily pond fluctuations, the parameters pH, DO, turbidity and temperature were measured *in situ* over a 24-hour period in three adjacent improved extensive shrimp ponds. These ponds are owned by the same farmer and completely isolated.

Table 1 Sampling times and the sediment parameters of the improved extensive shrimp system in the Cai Nuoc district, Mekong Delta, Southern Vietnam (2008)

Parameter	April	June	August	October	December	*N*
Eh, pH_w, $pH_{1/2.5}$, $EC_{1/5}$	+	+	+	+	+	140
Total N, Total P, OM	+	+	+	+		112
NO_2-N, NO_3-N, NH_4-N	+		+		+	84
PO_4-P, soluble SO_4, total SO_4, Fe^{2+}, Fe^{3+}	+		+			56
Bulk density (BD)	+					28

N, total number of samples; OM, organic matter.

Pond 1 was located in an open area of a former rice field and had no shade. Pond 2 was also constructed in a former rice field but had some shade from coconut palms and other trees on the dikes. Pond 3 was located inside a fruit garden and was almost completely shaded by large trees. Aquatic vegetation was found in all of the ponds. Water in these ponds had been filled in at different times from the same supply channel connecting to the main river. Water exchange had not been applied for at least more than 1 year before the monitoring experiment. The stocking density in these ponds was not recorded by the owner, but it was estimated around 1–3 ind m^{-2} (Field data 2008). The parameters were measured at a depth of about 20 cm under the water surface in the trench using a TOA instrument (WQC-22A). Measurement was taken every hour from 12:00 hours (27 December 2008) to 11:00 hours the next day.

Analysis of pond water

Analysis was performed using the standard methods described by the American Public Health Association (APHA 1995): (1) alkalinity: titration method, methyl orange 0.1% indicator; (2) H_2S: methylene blue method; (3) BOD: 5-day BOD test; (4) COD: oxidation by $KMnO_4$, titration method; (5) total Fe and Fe^{2+}: phenanthroline method, colorimetric method, 510 nm; (6) TSS: weight method, dried at 105 °C; (7) NO_2-N: diazo method; (8) NO_3-N: salicylate method; (9) TAN: indophenol blue method; (10) total N: digested by Kjeldahl digestion system, indophenol blue method; (11) PO_4-P and total P: ascorbic acid method; (12) Cl^-: argentometric method; and (13) dissolved SO_4^{2-}: turbidimetric method, 420 nm.

Analysis of pond sediment

To minimize sample oxidation, freshly collected sediment samples were analysed for total Fe, Fe^{2+}, NO_2-N, NO_3-N and NH_4-N within 2 days after sampling. The remaining samples were air-dried, ground in a plastic mortar and passed through a 0.25 mm sieve for the analysis of $pH_{1/2.5}$, $EC_{1/5}$, sulphate (soluble/total), OM, total N, PO_4-P and total P. The methods were summarized as follows: (1) total Fe: extracted by H_2SO_4 0.1 N, colorimetric method, 1,10-phenanthroline, $\lambda = 510$ nm; (2) Fe^{2+}: used the same extraction method as total Fe but no Fe^{3+} reduction step; (3) NO_2-N: extracted by distilled water, Griss method, $\lambda = 543$ nm; (4) NO_3-N: extracted by distilled water, exclusion of Cl^-, colorimetric method, phenoldisunphonic acid, $\lambda = 410$ nm; (5) NH_4-N: extracted by KCl 2 M, Kjeldahl method (Rowell 1994); (6) PO_4-P: extracted by $NaHCO_3$ 0.5 M, colorimetric method using ascorbic acid, $\lambda = 660$ nm (Olsen's method) (Rowell 1994); (7) $pH_{1/2.5}$: pH meter, soil:water ratio = 1:2.5 (w/v) (Rowell 1994); (8) $EC_{1/5}$: EC meter, soil:water ratio = 1:5 (w/v) (Rowell 1994); (9) soluble sulphate: extracted by distilled water, turbidimetric method ($BaCl_2$, $\lambda = 420$ nm); (10) OM: loss-on-ignition method (550 °C, 4 h); (11) total P: residues after OM determination were dissolved in HCl 1 M, colorimetric method, ammonium molybdate, $\lambda = 660$ nm; (12) total sulphate: used the same extraction method as total P, turbidimetric method ($BaCl_2$, $\lambda = 420$ nm); (13) total N: extracted by heating with concentrated H_2SO_4, catalysed by a $CuSO_4$:K_2SO_4 mixture of 1:10 ratio, Kjeldahl method (Rump & Krist 1992); and (14) BD: core method (Boyd 1995).

Statistical analysis

Descriptive statistics were applied to get an overview of ponds' physico-chemical characteristics. Analysis of variance (ANOVA) was used to clarify the effects of the categorical variables on the dependent variables (physico-chemical parameters). For water parameters, the categorical variable included the 'sampling time', which had five levels (i.e. the five sampling times). The dependent variables included all physico-chemical parameters analysed. For sediment, the categorical variables included 'depth', 'sampling position' and 'sampling time'. The first two variables had two levels (depth: 0–5 and 5–10 cm, sampling position: trench and platform). Significant differences between the levels of the categorical variables were further analysed with the Tukey Honest Significant Difference test for *post hoc* mean's comparison. All significance testing was conducted at the 0.05 level. Correlations among the parameters of interest were conducted using correlation matrices.

Results and discussion

Physico-chemical parameters of pond water

Table 2 shows the water physico-chemical characteristics of the improved extensive shrimp ponds. Temperature and pH were most optimal for shrimp farming (Jayasinghe *et al.* 1994; Haws & Boyd 2001; Lazur 2007). Most TSS measurements exceeded the limit. Salinity showed a slightly wider range than recommended (Haws & Boyd 2001; Lazur 2007). COD, BOD and nutrients (N, P) were low. NO_3-N values were about seven times higher than those in the former Cai Nuoc district (including the current Cai Nuoc and Phu Tan just to its west, see Fig. 1) in 2002–2004 (Tho *et al.* 2006), implying a recent increase in nutrients in the ponds. NO_2-N, PO_4-P and BOD were lower than intensive shrimp farms in Eastern Thailand (Tookwinas & Songsangjinda 1999). Up to 37.14% of DO measurements were lower than the recommendation by Lazur (2007), and the minimum DO value was similar to that in extensive shrimp farming system in Bac Lieu province (Bao 2009). Total iron was much higher than recommended (Haws & Boyd 2001), although being lower than the 2002–2004 figure in the former Cai Nuoc district (Tho *et al.* 2006). This was mostly because of the lesser impact of acid sulphate soils in the study area (further inland, previously rice-dominated) as compared with the former Cai Nuoc district (Phu Tan district connects to the sea and has been occupied by man-

Table 2 Water characteristics of the improved extensive shrimp system in the Cai Nuoc district, Mekong Delta, Southern Vietnam (2008) in comparison with criteria for shrimp farming

Parameter ($n = 35$)	Unit	Range/mean	Standard deviation	Acceptable range	Percentage out of acceptable range	Percentage of out-of-range measurements* April (%)	June (%)	August (%)	October (%)	December (%)
pH	–	6.25–8.95/7.59	–	7–9†	6.67				−3.33	−3.33
Temperature	°C	27.6–35.4/30.6	2.437	26–33‡	20	+8.00	+4.00	+8.00		
DO	mg L^{-1}	2.38–6.68/4.46	1.129	>4§	37.14	−8.57	−8.57	−2.86	−5.71	−11.43
Turbidity	NTU	4–66/27.21	14.139							
Salinity	g L^{-1}	3–39/14.56	12.069	5–35†	37.14	+14.29		−5.71	−11.43	−5.71
Alkalinity	mg L^{-1}	80–260/148.77	37.131	50–100§	94.29	+20.00	+17.14	+20.00	+17.14	+20.00
COD	mg L^{-1}	2.80–22/8.66	3.445							
TAN	mg L^{-1}	0.042–0.37/0.148	0.080	NH_4^+ 0.2–2† NH_3 <0.1†						
NO_2-N	mg L^{-1}	0–0.05/0.013	0.011	<0.23†						
NO_3-N	mg L^{-1}	0.02–2.31/0.755	0.571	0.2–10†						
PO_4-P	mg L^{-1}	0.015–0.033/0.029	0.003							
TSS	mg L^{-1}	17.5–309/123.21	81.095	50¶	85.71	+14.29	+17.14	+14.29	+20.00	+20.00
TP	mg L^{-1}	0.04–0.67/0.223	0.166							
TKN	mg L^{-1}	0.526–7.42/2.498	1.326							
Fe^{2+}	mg L^{-1}	0.009–0.25/0.077	0.051	0†	100	+20	+20	+20	+20	+20
Fe^{3+}	mg L^{-1}	0.236–2.01/0.700	0.419	Trace†	100	+20	+20	+20	+20	+20
Total Fe	mg L^{-1}	0.29–2.25/0.78	0.44	0.05–0.5†	77.14	+14.29	+20.00	+11.43	+14.29	+17.14
BOD	mg L^{-1}	0.32–5.68/2.86	1.693	<10‡,¶						
H_2S	mg L^{-1}	0–0.02/0.007	0.005	ND†	85.71	+20.00	+20.00	+20.00	+11.43	+14.29
Cl^-	g L^{-1}	1.66–20.42/7.38	6.109	2–20†	17.14	+5.71		−2.86	−5.71	−2.86
SO_4^{2-}	g L^{-1}	0.15–3.73/1.18	1.117	0.5–3†	57.14	+14.29		−17.14	−14.29	−11.43

*Percentage of out-of-range measurements: +, % above the range; −, % below the range.
†Haws and Boyd (2001).
‡Jayasinghe *et al.* (1994).
§Lazur (2007).
¶Vietnamese standard 5943-1995 for aquatic cultivation.
ND, not detectable.

Table 3 Minimum and maximum values of the parameters under the 24-hour monitoring experiment in the improved extensive shrimp system in the Cai Nuoc district, Mekong Delta, Southern Vietnam (2008)

	DO (mg L^{-1})		pH		Turbidity (NTU)		Temperature (°C)	
Pond	Min	Max	Min	Max	Min	Max	Min	Max
1	2.20	5.40	7.56	8.15	21.7	37.0	27.2	30.2
2	1.05	4.43	7.28	7.83	11.4	24.0	26.6	28.9
3	0.84	2.59	7.04	7.46	4.0	6.0	25.7	28.2

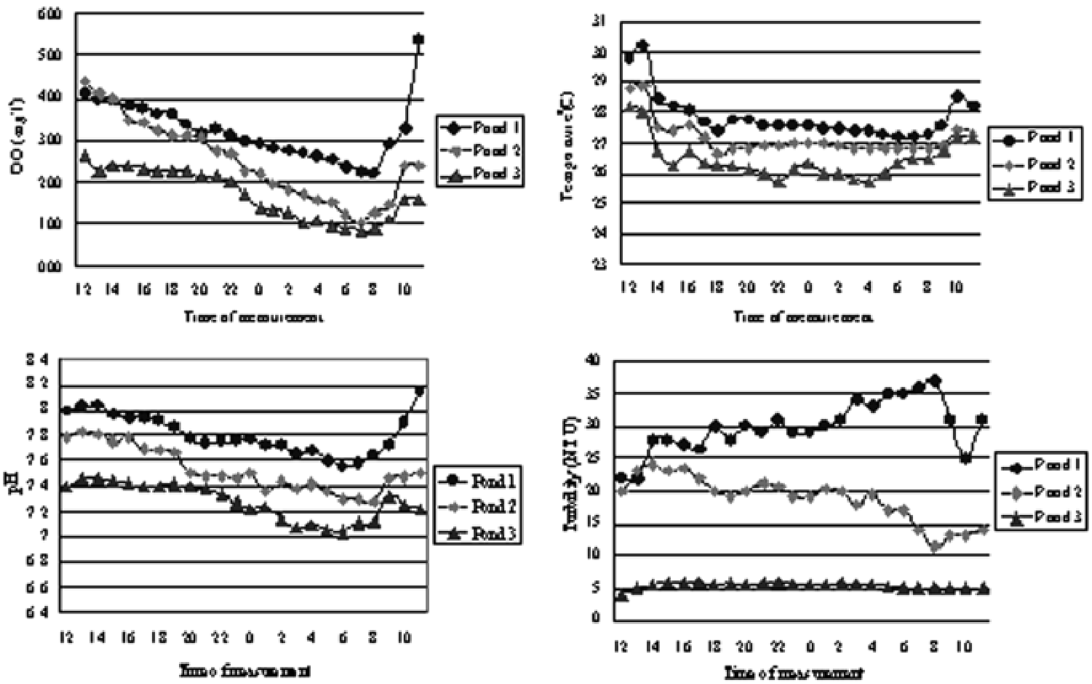

Figure 3 Variation of dissolved oxygen, temperature, pH and turbidity in pond water in the 24-hour monitoring experiment.

groves, acid sulphate soils dominated) (Fig. 1). H_2S concentrations were higher than the threshold set by Haws and Boyd (2001), but lower than those by Jayasinghe *et al.* (1994) and Lazur (2007). The presence of H_2S in the ponds was not necessarily linked to a sulphide reservoir in the soil profiles, but simply produced under anoxic pond sediment caused by a long-term accumulation of organic materials. Alkalinity, which can affect primary productivity, was higher than recommended (Lazur 2007). It was also slightly higher than that in the extensive shrimp farming system in Bac Lieu province, most probably because salinity in Cai Nuoc shrimp ponds was higher. Several key parameters (DO, TSS, alkalinity and H_2S) showed values beyond the acceptable range for shrimp farming all year round (Table 2). Indicators of organic loadings in the ponds (COD, BOD, N and P) were low due to low inputs (low stocking density, little or no fertilizers and no feeding) in this shrimp farming system.

Dissolved oxygen values below the levels at which shrimp can grow normally (Haws & Boyd 2001; Lazur 2007) were found at all sampling times (Table 2). The situation was even worse during the early morning (06:00–08:00 hours) as revealed by the 24-hour monitoring experiment (Table 3, Fig. 3). The peak values of DO were found around 11:00–12:00 hours. The values then gradually decreased to a minimum around 06:00–08:00 hours, after which they increased again. In Pond 1, a DO range between 2 and 3 mg L^{-1} lasted for about 10 h. In the other two ponds, DO values were even lower. This was not because of organic/nutrient pollution, but simply on account of diurnal fluctuations of photosynthesis and respiration intensity.

Differences in DO among the ponds are most likely caused by the different degrees of shading, rather than by the stocking densities or the quality of input water. It should be noted that DO levels are much lower near the water–sediment interface (where shrimps stay) than near the water surface (Flegel 1998). The maximum DO values at noon in all three ponds were attributed to elevated solar radiation, which led to a higher photosynthesis intensity by which a larger amount of DO was released. Elevated DO values during daytime were the result of the dominance of photosynthesis over respiration. Lowest pH in the early morning was attributed to accumulation of carbon dioxide during the night (Lazur 2007). When no solar radiation reached the water, the photosynthesis stopped while the respiration still continued in the ponds, which consumed oxygen and released carbon dioxide into the water column.

Correlation matrix using data from the 24-hour monitoring experiment revealed that both DO and pH were positively correlated (both at $P < 0.001$) with temperature (i.e. solar radiation). In fact, temperature, pH and DO in the ponds showed similar patterns (Fig. 3) and had linear correlations (Fig. 4).

In pond water, NO_3-N concentrations were about five times higher than TAN and 58 times higher than NO_2-N on average (Table 2). This, together with the positive correlation between NO_3-N and TKN ($P < 0.01$), indicated that NO_3-N accounted for the majority of the inorganic nitrogen. Positive correlations between salinity and TKN ($P < 0.01$) and NO_3-N ($P < 0.001$) were most likely the result of the effect of concentration. Total ammonium nitrogen was positively correlated with COD ($P < 0.05$) but negatively correlated with DO, pH and temperature (all at $P < 0.01$). This suggests that TAN was largely involved in the photosynthesis process though it accounted for a small percentage among the nitrogen species. While Vinatea, Gálvez, Browdy, Stokes, Venero, Haveman, Lewis, Lawson, Shuler and Leffler (2010) found no relationship between TAN and photosynthesis, Burford and Glibert (1999) demonstrated that phytoplankton plays a key role in controlling TAN in shrimp ponds. According to McCarthy (1980), ammonium is the preferred nitrogenous nutrient of many species of marine phytoplankton. During periods of high photosynthesis intensity when a vast amount of solar radiation reaches the water surface, the majority of TAN was taken up by the phytoplankton community, resulting in low TAN concentrations. During the nights (no photosynthesis) and the early mornings (little photosynthesis), TAN may be accumulated in pond water. Salinity and BOD was negatively correlated ($P < 0.001$), suggesting that ponds might have had higher biodegradable matter during the rainy season despite the dilution impact (Tho *et al.* 2006). The situation can only be explained by the contribution of OM from runoff water. Alkalinity was negatively correlated with PO_4-P ($P < 0.01$) but positively correlated with NO_3-N ($P < 0.01$). Alkalinity was positively correlated with salinity ($P < 0.01$), suggesting that alkalinity often increased at corresponding high salt concentrations. Fe^{3+} was much higher than Fe^{2+} (Table 2) and of higher positive correlation with total Fe ($P < 0.01$ vs. $P < 0.05$), indicating pond water in an oxidized state. Total suspended solid was positively correlated with turbidity ($P < 0.05$), suggesting that suspended solids were the main component of water turbidity. Besides, TSS was positively correlated with BOD ($P < 0.05$) and NO_2-N ($P < 0.01$),

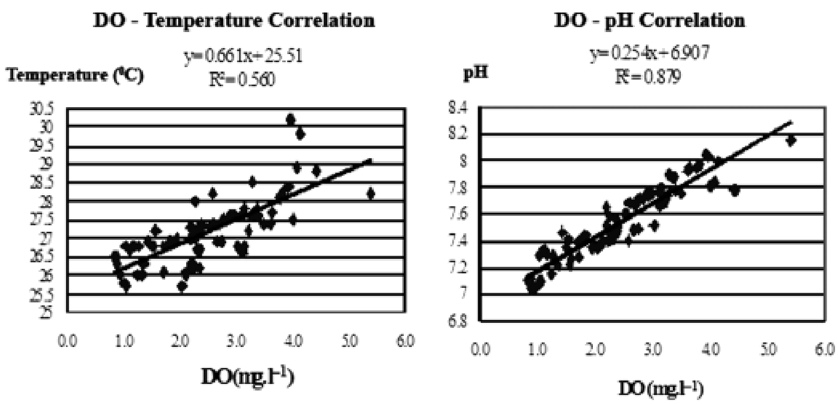

Figure 4 Linear correlations between (a) dissolved oxygen (DO) and temperature and between (b) DO and pH in the 24-hour monitoring experiment.

Table 4 ANOVA testing of the water parameters in the Cai Nuoc improved extensive shrimp system, Mekong Delta, Southern Vietnam (2008)

Parameter	Unit	Significance level: Sampling time	Means comparisons: April†	June‡	August‡	October‡	December†
pH	–	NS	–	–	–	–	–
Temperature	°C)	NS	–	–	–	–	–
DO	$mg\,L^{-1}$	NS	–	–	–	–	–
Turbidity	NTU	NS	–	–	–	–	–
Salinity	$g\,L^{-1}$	NS	36.57^{c}	15.14^{b}	5.71^{a}	6.14^{a}	9.22^{a}
Alkalinity	$mg\,L^{-1}$	**	191.43^{b}	140.50^{a}	131.43^{a}	146.07^{ab}	134.43^{a}
COD	$mg\,L^{-1}$	NS	–	–	–	–	–
TAN	$mg\,L^{-1}$	***	0.109^{ab}	0.179^{bc}	0.135^{ab}	0.069^{a}	0.249^{c}
NO_2-N	$mg\,L^{-1}$	NS	–	–	–	–	–
NO_3-N	$mg\,L^{-1}$	***	1.523^{d}	0.174^{a}	0.353^{ab}	0.712^{bc}	1.014^{c}
PO_4-P	$mg\,L^{-1}$	NS	–	–	–	–	–
TSS	$mg\,L^{-1}$	***	86.21^{a}	112.13^{a}	101.87^{a}	234.14^{b}	81.71^{a}
TP	$mg\,L^{-1}$	**	0.146^{ab}	0.090^{a}	0.352^{b}	0.313^{b}	0.217^{ab}
TKN	$mg\,L^{-1}$	**	3.70^{b}	2.76^{ab}	1.22^{a}	2.51^{ab}	2.30^{ab}
Fe^{2+}	$mg\,L^{-1}$	NS	–	–	–	–	–
Fe^{3+}	$mg\,L^{-1}$	**	0.52^{a}	1.15^{b}	0.43^{a}	0.70^{ab}	0.71^{ab}
BOD	$mg\,L^{-1}$	***	1.17^{a}	1.04^{a}	2.73^{b}	4.67^{c}	4.69^{c}
H_2S	$mg\,L^{-1}$	**	0.005^{a}	0.010^{b}	0.009^{b}	0.002^{a}	0.008^{ab}
Cl^-	$g\,L^{-1}$	***	18.36^{c}	7.92^{b}	2.89^{a}	3.09^{a}	4.63^{a}
SO_4^{2-}	$g\,L^{-1}$	***	3.19^{c}	1.18^{b}	0.40^{a}	0.43^{a}	0.71^{ab}

Indices with different superscript are significantly different at the 0.05 level.
ANOVA significance level.
$^{**}P < 0.01$; $^{***}P < 0.001$.
†Dry season.
‡Rainy season.
NS, not significant.

suggesting that OM was largely made up by suspended solids.

Total suspended solid showed the highest values in October (rainy season) while salinity, Cl^-, SO_4^{2-} and NO_3-N showed their highest values in April (end of the dry season) (Table 4). This was not necessarily a build-up of salt/OM but simply the concentration effect in the dry season. A similar situation was reported in the former Cai Nuoc district (Tho *et al.* 2006). Other indicators of organic pollution (BOD, TKN and TAN) also tended to show higher values in December or April (dry season). The highest TSS values were due to the effect of runoff water.

Physico-chemical parameters of pond sediment

The sediment quality of the shrimp ponds is represented by the 0–5 cm layer (Table 5). This is because this layer in shrimp ponds is more reactive with the water column than the deeper layers (Masuda & Boyd 1994; Munsiri, Boyd & Hajek 1995). While pH_w ranged from slightly acidic to neutral (5.16–7.67), $pH_{1/2.5}$ showed a wider range (3.97–7.91). This is similar to shrimp farms in Ecuador where $pH_{1/1}$ showed a wider range than pH_w at both ends (Sonnenholzner & Boyd 2000). In semi-intensive shrimp farms in Honduras and Bangladesh, and extensive shrimp farms in the Mekong Delta of Vietnam, neutral pH values of the sediment were reported (Munsiri, Boyd, Teichert-Coddington & Hajek 1996; Alongi *et al.* 1999; Islam, Sarker, Yamamoto, Wahab & Tanaka 2004). In Thailand, pH values of shrimp farm sediment were higher (8.14–8.29) (Towatana, Voradaj & Panapitukkul 2002). The pH of the Cai Nuoc shrimp pond sediment was lower than the optimal range for shrimp farming (7–8) (Haws & Boyd 2001). This was because of the limited investment of the Mekong Delta improved extensive shrimp farmers in chemical

Table 5 Descriptive statistics of sediment parameters (0–5 cm) in the improved extensive shrimp system in the Cai Nuoc district, Mekong Delta, Southern Vietnam (2008)

Parameter	Unit	*N*	Mean	Min	Max	Standard deviation
Eh	mV	70	−304	−422	−105	54.00
pH_w	–	70	6.68	5.16	7.67	–
$pH_{1/2.5}$	–	70	6.86	3.97	7.91	–
$EC_{1/5}$	$dS\,m^{-1}$	70	6.31	1.32	15.67	3.65
BD	$g\,cm^{-3}$	14	0.48	0.35	0.73	0.106
NO_2-N	$mg\,kg^{-1}$	42	0.103	0.035	0.304	0.061
NO_3-N	$mg\,kg^{-1}$	42	1.188	0.337	3.723	0.687
NH_4-N	$mg\,kg^{-1}$	42	22.024	2.687	61.239	14.700
Total N	%	56	0.192	0.106	0.421	0.061
OM	%	56	12.91	9.84	21.96	2.14
PO_4-P	$mg\,kg^{-1}$	28	21.97	4.42	41.70	8.44
Total P	%	56	0.013	0.006	0.022	0.003
Soluble SO_4	$mg\,kg^{-1}$	28	3212.52	916.80	4726.80	1086.76
Total SO_4	%	28	1.04	0.30	1.83	0.39
Fe^{2+}	$mg\,kg^{-1}$	28	6566.26	1165.10	10 891.04	2750.60
Fe^{3+}	$mg\,kg^{-1}$	28	774.28	128.53	2132.93	492.17
Total Fe	$mg\,kg^{-1}$	28	7340.54	1528.43	12 081.52	2908.53

N, number of observations.

inputs to buffer pH in their shrimp ponds (Field data 2008).

The sediment was anaerobic (Eh −304 mV), which can be blamed for the production and subsequent release of toxic substances (e.g. H_2S) into pond water (Physico-chemical parameters of pond water). Anaerobic condition of pond bottom was attributed to elevated OM loadings (OM 9.84–21.96%, mean 12.91%), resulting from accumulation over extended periods (> 2 years in some cases). Organic matter in Cai Nuoc shrimp pond sediment was much higher than those (1.06–1.42%) in Southern Thailand (Towatana *et al.* 2002) and Bangladesh (2.14–3.28%) (Islam, Alam, Rheman, Ahmed & Mazid 2004). While the flocculent layer of recently deposited sediment may have an OM content of 50%, the upper 2 cm sediment layer in shrimp ponds seldom has > 10% of OM (Haws & Boyd 2001). Following Mitsch and Gosselink (2000), the content of organic C of the shrimp pond sediment can be estimated at 6.46%. According to Boyd (2003), however, organic C content of shrimp pond sediment should be between 1.5% and 2.5%. High OM in the shrimp pond sediment did not relate to daily fluctuations of DO in the water column. While the former remained unchanged, the latter exhibited critical fluctuations within 1 day. The decomposition rate of OM in Cai Nuoc shrimp pond sediment was low due to suboptimal sediment pH (5.16–7.67). The best pH range for this process should be between 7.5 and 8.5 (Boyd 1992).

The anaerobic condition of the ponds was further evidenced by higher NH_4-N as compared with NO_3-N and higher Fe^{2+} as compared with Fe^{3+} (Table 5). Total Fe (7340.54 $mg\,kg^{-1}$) was much higher than that in shrimp farms in Ecuador (661 $mg\,kg^{-1}$) (Sonnenholzner & Boyd 2000). Total P (0.013%) was similar to that in Southern Thai shrimp ponds (Towatana *et al.* 2002) but lower than that in intensive shrimp farms in Australia (0.069%) (Smith 1996) and Ecuador (0.09%) (Sonnenholzner & Boyd 2000). On average, total N (0.192%) was similar to that in semi-intensive shrimp farms in Honduras (0.17–0.28%) (Munsiri *et al.* 1996), Bangladesh (0.11–0.18%) (Islam, Alam *et al.* 2004) and Ecuador (0.02–0.52%) (Sonnenholzner & Boyd 2000), but lower than that in intensive shrimp farms in Australia (0.23%) (Smith 1996). In the shrimp ponds of the former Cai Nuoc district, top sediment showed an elevated exchangeable sodium percentage (35.89–58.66%) in the 2002–2004 period (Tho *et al.* 2008). Exchangeable form of major cations (Ca, Mg, Na and K) (Tho *et al.* 2008) were similar to those in Thailand (Towatana *et al.* 2002). Anaerobic pond bottom and high OM loadings provided disadvantages for shrimp growth in these ponds, particularly the toxic reduced substances and the impacted benthic community.

Differences between sampling positions, between depths and between sampling times were found (Table 6). Trench sediment had higher values of NH_4-N, PO_4-P, total P and Fe^{2+} than the platform.

Table 6 ANOVA for sediment parameters in the improved extensive shrimp system in the Cai Nuoc district, Mekong Delta, Southern Vietnam (2008)

		Significance testing			Means comparison								
					Depth		Sampling position		Sampling time				
Parameter	Unit	Depth	Sampling position	Sampling time	0–5 cm	5–10 cm	Trench	Platform	April†	June‡	August‡	October‡	December†
Eh	mV	NS	NS	NS	−304.1^{a}	−299.4^{a}	−306^{a}	−297.4^{a}	−298^{a}	−292^{a}	−311^{a}	−318^{a}	−288^{a}
pH_w	–	NS	NS	***	6.68^{a}	6.70^{a}	6.73^{a}	6.65^{a}	6.91^{c}	6.48^{b}	6.04^{a}	7.12^{c}	6.91^{c}
$pH_{1/2.5}$	–	*	NS	***	6.86^{a}	7.05^{b}	7.02^{a}	6.89^{a}	6.90^{ab}	7.19^{b}	7.16^{b}	6.73^{a}	6.80^{a}
$EC_{1/5}$	$dS\,m^{-1}$	*	NS	***	6.31^{b}	5.28^{a}	6.15^{a}	5.45^{a}	9.13^{c}	7.54^{b}	3.70^{a}	3.58^{a}	5.03^{a}
BD	$g\,cm^{-3}$	***	NS	NA	0.481^{a}	0.699^{b}	0.547^{a}	0.633^{a}	NA	NA	NA	NA	NA
NO_2-N	$mg\,kg^{-1}$	NS	NS	*	0.103^{a}	0.094^{a}	0.087^{a}	0.109^{a}	0.077^{a}	–	0.115^{b}	–	0.103^{ab}
NO_3-N	$mg\,kg^{-1}$	NS	*	NS	1.19^{a}	1.09^{a}	1.00^{a}	1.29^{b}	1.05^{a}	–	1.10^{a}	–	1.29^{a}
NH_4-N	$mg\,kg^{-1}$	NS	***	**	22.02^{a}	29.91^{a}	36.57^{b}	15.01^{a}	17.12^{a}	–	29.56^{b}	–	31.26^{b}
Total N	%	*	*	NS	0.192^{b}	0.170^{a}	0.169^{a}	0.193^{b}	0.158^{a}	0.181^{a}	0.194^{a}	0.190^{a}	–
PO_4-P	$mg\,kg^{-1}$	NS	***	*	21.97^{a}	22.52^{a}	28.14^{b}	16.36^{a}	19.30^{a}	–	25.20^{b}		–
Total P	%	*	***	***	0.013^{b}	0.011^{a}	0.014^{b}	0.010^{a}	0.012^{ab}	0.014^{b}	0.012^{ab}	0.010^{a}	–
OM	%	NS	NS	**	12.91^{a}	12.49^{a}	12.43^{a}	12.97^{a}	12.29^{a}	13.75^{b}	12.84^{ab}	11.92^{a}	–
Soluble SO_4	$mg\,kg^{-1}$	***	NS	NS	3212.5^{b}	2121.9^{a}	2,591,7^{a}	2,742,7^{a}	2913.8^{a}	–	2420.6^{a}	–	–
Total SO_4	%	NS	NS	NS	1.04^{a}	0.89^{a}	0.96^{a}	0.96^{a}	1.00^{a}	–	0.92^{a}	–	–
Fe^{2+}	$mg\,kg^{-1}$	NS	***	NS	6,566.3^{a}	6,398.4^{a}	7704.4^{b}	5211.9^{a}	5842.9^{a}	–	7142.3^{a}	–	–
Fe^{3+}	$mg\,kg^{-1}$	NS	NS	***	774.28^{a}	766.22^{a}	842.99^{a}	694.67^{a}	484.5^{a}	–	1066.4^{b}	–	–
Total Fe	$mg\,kg^{-1}$	NS	***	*	7340.5^{a}	7164.6^{a}	8547.4^{b}	5906.6^{a}	6327.4^{a}	–	8208.8^{b}	–	–

Indices with the same superscript are not significantly different at the 0.05 level.
ANOVA significance level.
*$P<0.05$; **$P<0.01$; ***$P<0.001$.
†Dry season.
‡Rainy season.
NA, not applicable; NS, not significant.

This was probably because (i) the trench is much deeper (thus subject to a larger amount of TSS and can attract suspended matter from the platform after re-suspension), and (ii) the trench is directly affected by the runoff water. Total N and NO_3-N, however, remained higher on the platform. Higher total N and total P and lower BD in the top layer (Table 6) suggested that the first few centimetres of sediment surface still remained active. This layer was enriched by organic materials, derived mainly from intake water, shrimp excretions or dead materials from the vegetative cover. Increases in values of several parameters (Fe^{3+}, total Fe, PO_4-P, total P and OM) at times during the rainy season were explained by the contribution of eroded material from the dikes.

The top layer showed higher $EC_{1/5}$ and soluble SO_4 values than the second layer. Sediment salinity ($EC_{1/5}$) was low at the end of the rainy season but increasing during the dry season (Table 6). For the period 2002–2004, salinity values of 3.16 and 8.88 $dS\,m^{-1}$ for, respectively, the rainy and dry season in the former Cai Nuoc district were reported (Tho *et al.* 2008). Salinity in the shrimp pond sediment was similar to that in Southern Thailand (Towatana *et al.* 2002).

Suitability of ponds' physico-chemical characteristics for shrimp (*P. monodon*) farming

The improved extensive ponds did not provide appropriate conditions for shrimp. Many water parameters show values beyond the acceptable limit for shrimp farming (Table 2). Very low DO levels can lead to direct shrimp mortality or reduce shrimp resistance to diseases (Haws & Boyd 2001; Lazur 2007). In fact, shrimp mortality in early mornings has been observed (Field data 2008). In the rainy season, high TSS might cause a reduction of the photosynthesis intensity, while low salinity may lead to acute stress, causing increased susceptibility of shrimp to white spot virus infection (Joseph & Philip 2007). Large salinity variations may reduce shrimp immunocompetence to *Photobacterium damselae* (Wang & Chen 2006). Alkalinity and total Fe were much higher than recommended, suggesting unfavourable conditions for shrimp.

Poor pond sediment quality can adversely affect cultured shrimp (Smith 1999; Avnimelech & Ritvo 2003; Lemonnier, Bernard, Boglio, Goarant & Cochard 2004). It is possible that toxic products are being produced under the anaerobic conditions of the shrimp pond bottom. Indeed, H_2S values beyond the accepted level were found, pointing to a negative impact to shrimp growth and survival (Ritvo, Samocha, Lawrence & Neill 1998). Increased shrimp osmotic pressure caused by low sediment pH (such as 6.5–7.4) (Lemonnier *et al.* 2004) was likely to occur. Elevated OM in the sediment may also pose impacts to shrimp by favouring greater microbial activities (Masuda & Boyd 1994).

Conclusion

The unfavourable physico-chemical characteristics of the improved extensive shrimp ponds are not optimal for shrimp farming. Poor water and sediment quality can stress the cultured shrimp and increase their susceptibility to diseases. Appropriate planning and modifications of farming techniques are strongly recommended for a better shrimp production in the coastal parts of the Mekong Delta of Vietnam. To improve the pond's physico-chemical condition, the following measures should be taken (1) allowing sedimentation before filling shrimp culture ponds; (2) covering dikes using endemic vegetation to reduce the effect from runoff water; (3) including no-culture breaks between shrimp crops; (4) drying and exposing pond bottom to sunlight for a reasonable period of time after every production cycle; (5) removing all sediment produced after two production cycles; and (6) controlling the pond's vegetation to mitigate the condition of oxygen shortage.

Future research in the area should focus on (1) planning of a synchronous irrigation system for a better water management within the dense river/canal system; (2) optimal pond construction and management (e.g. stocking density, management of pond water and sediment); (3) study of native organisms (such as oysters, crabs, fish and vegetation) that can be incorporated into shrimp ponds for both economic and environmental values; (4) building up a common and most appropriate cropping calendar for the whole district; and (5) wise use of small land plots and the deposited sediment for the diversification of income sources for shrimp farmers.

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References

ADB/MoFi (1996) Vietnam coastal aquaculture sector review. In: *Industrial Transformation and Shrimp Aquaculture in Thailand and Vietnam: Pathways to Ecological, Social, and Economic Sustainability?* (ed. by L. Lebel, N.H. Tri, A. Saengnoree, S. Pasong, U. Buatama & L.K. Thoa. *Ambio* **31,** 311–323.

Alongi D.M., Tirendi F. & Trott L.A. (1999) Rates and pathways of benthic mineralization in extensive shrimp ponds of the Mekong Delta, Vietnam. *Aquaculture* **175**, 269–292.

APHA (1995) *Standard Methods for the Examination of Water and Wastewater*, 19th edn. American Public Health Association, Washington, DC, USA.

Avnimelech Y. & Ritvo G. (2003) Shrimp and fish pond soils: processes and management. *Aquaculture* **220**, 549–567.

Bao T.Q. (2009) *Impact of extensive shrimp farming on a tropical river ecosystem (Bac Lieu province - Viet Nam).* PhD thesis, Vrije Universiteit Brussel, Belgium.

Binh C.T. & Lin C.K. (1995) Shrimp culture in Vietnam. *World Aquaculture* **26**, 27–33.

Binh T.N.K.D., Vromant N., Hung N.T., Hens L. & Boon E.K. (2005) Land cover changes between 1968 and 2003 in Cai Nuoc, Ca Mau Peninsula, Vietnam. *Environment, Development and Sustainability* **7**, 519–536.

Boyd C.E. (1992) Shrimp pond bottom soil and sediment management. In: *Proceedings of the Special Session on Shrimp Farming* (ed. by J. Wyban), pp. 166–181. World Aquaculture Society, Baton Rouge, LA, USA.

Boyd C.E. (1995) *Bottom Soils, Sediment, and Pond Aquaculture*. Department of Fisheries and Allied Aquacultures at Auburn University, Chapman & Hall, New York, NY, USA.

Boyd C.E. (2003) *Best management practices for water and soil management in shrimp farming.* Workshop, 23 June to 25 June 2003 in Mazatlán, México.

Brennan D., Preston N., Clayton H. & Be T.T. (2002) *An evaluation of rice-shrimp farming systems in the Mekong Delta.* Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment, Work in Progress for Public Discussion, Published by the Consortium, 10pp.

Burford M.A. & Glibert P.M. (1999) Short-term nitrogen cycling in early and late growth-phase shrimp ponds. In: *Modeling Nitrogen Dynamics in Intensive Shrimp Ponds: the Role of Sediment Remineralization* (ed. by M.A. Burford & K. Lorenzen. *Aquaculture* (2004), **229,** 129–145.

Chien Y.-H. (1992) Water quality requirements and management for marine shrimp culture. In: *Proceedings of the Special Session on Shrimp Farming* (ed. by J. Wyban), pp. 144–156. World Aquaculture Society, Baton Rouge, LA, USA.

Clough B., Johnston D., Xuan T.T., Phillips M.J., Pednekar S.S., Thien N.H., Dan T.H. & Thong P.L. (2002) *Silvofishery farming systems in Ca Mau province, Vietnam.* Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment, Work in Progress for Public Discussion, Published by the Consortium, 70pp.

EJF (2003) *Risky Business: Vietnamese Shrimp Aquaculture - Impacts and Improvements.* Environmental Justice Foundation, London, UK.

EJF (2004) *Farming the Sea, Costing the Earth: Why We Must Green the Blue Revolution.* Environmental Justice Foundation, London, UK.

Flegel T.W. (1998) Advances in shrimp biotechnology. *Proceedings to the Special Session on Shrimp Biotechnology*, 5th Asian Fisheries Forum, 11–14 November, Chiengmai, Thailand.

Haws M.C. & Boyd C.E. (2001) *Methods for Improving Shrimp Farming in Central America.* Central American University Press-UCA, Managua, Nicaragua.

Hena Abu M.K., Sharifuzzaman S.M., Hishamuddin O., Misri K. & Abdullah F. (2008) Pond health management of black tiger shrimp *Penaeus monodon* (Fabricius) using bacterial products. In: *Diseases in Asian Aquaculture VI. Fish Health Section* (ed. by M.G. Bondad-Reantaso, C.V. Mohan, M. Crumlish & R.P. Subasinghe), pp. 469–476. Asian Fisheries Society, Manila, Philippines.

Hens L., Vromant N., Tho N. & Hung N.T. (2009) Salination of surface water, groundwater, and soils in the shrimp farming areas of the coastal Cai Nuoc district, South Vietnam. *International Journal of Environmental Studies* **66**, 69–81.

Islam M.L., Alam M.J., Rheman S., Ahmed S.U. & Mazid M.A. (2004) Water quality, nutrient dynamics and sediment profile in shrimp farms of the Sundarbans mangrove forest, Bangladesh. *Indian Journal of Marine Sciences* **33**, 170–176.

Islam M.S., Sarker M.J., Yamamoto T., Wahab M.A. & Tanaka M. (2004) Water and sediment quality, partial mass budget and effluent N loading in coastal brackishwater shrimp farms in Bangladesh. *Marine Pollution Bulletin* **48**, 471–485.

Jayasinghe J.M.P., Corea S.L. & Wijegunawardana P.K.M. (1994) *Affordable water supply and sanitation – deterioration of sanitary conditions in coastal waters.* The 20th WEDC Conference Colombo, Sri Lanka.

Joseph A. & Philip R. (2007) Acute salinity stress alters the haemolymph metabolic profile of *Penaeus monodon* and reduces immunocompetence to white spot syndrome virus infection. *Aquaculture* **272**, 87–97.

Lazur A. (2007) *Growout Pond and Water Quality Management.* University of Maryland, College Park, MD, USA.

Lemonnier H., Bernard E., Boglio E., Goarant C. & Cochard J.C. (2004) Influence of sediment characteristics on shrimp physiology: pH as principal effect. *Aquaculture* **240**, 297–312.

Masuda K. & Boyd C.E. (1994) Phosphorus fractions in soil and water of aquaculture ponds build on clayey, ultisols at Auburn, Alabama. In: *Chemical and Physical Properties of Shrimp Pond Bottom Soils in Ecuador* (ed. by S. Sonnenholzner & C.E. Boyd). *Journal of the World Aquaculture Society* **31,** 358–375.

Masuda K. & Boyd C.E. (1994) Chemistry of sediment pore water in aquaculture ponds built on clayey ultisols at Autburn, Alabama. In: *Influence of Sediment Characteristics on Shrimp Physiology: pH as Principal Effect* (ed. by H. Lemonnier, E. Bernard, E. Boglio, C. Goarant & J.C. Cochard). *Aquaculture* **240,** 297–312.

McCarthy (1980) Nitrogen and phytoplankton ecology. In: *Exploring the Mechanism of Ammonium Uptake in Phytoplankton with an Ammonium Analogue, Methylamine* (ed. by W.M. Balch). *Marine Biology* **92,** 163–171.

Mitsch W.J. & Gosselink J.G. (2000) *Wetlands*, 3rd edn. John Wiley & Sons, New York, NY, USA.

Munsiri P., Boyd C.E. & Hajek B.F. (1995) Physical and chemical characteristics of bottom soil profiles in ponds at Auburn, Alabama, and a proposed system for describing pond soil horizons. In: *Chemical and Physical Properties of Shrimp Pond Bottom Soils in Ecuador* (ed. by S. Sonnenholzner & C.E. Boyd). *Journal of the World Aquaculture Society* **31,** 358–375.

Munsiri P., Boyd C.E., Teichert-Coddington D. & Hajek B.F. (1996) Texture and chemical composition of soils from shrimp ponds near Choluteca, Honduras. *Aquaculture International* **4**, 157–168.

Nhuong T.V., Luu L.T., Tu T.Q., Tam P.M. & Nguyet T.T.A. (2002) *Vietnam shrimp farming review.* Individual Partner Report for the Project: Policy Research for Sustainable Shrimp Farming in Asia. European Commission INCO-DEV Project PORESSFA No. IC4–2001-10042, CEMARE University of Portsmouth, UK, and RIA1, Bac Ninh, Vietnam.

Phuong N.T., Minh T.H. & Tuan N.A. (2004) *Overview of shrimp farming systems in the Mekong Delta of Vietnam.* Paper presented at the conference '*Development of Coastal Aquaculture Resources*', University of Agriculture and Forestry, 4 August 2004.

Poernomo A. (1989) Technical constraints in shrimp culture and how to overcome them. In: *Proceedings of the Shrimp Culture Industry Workshop (Jepara, Indonesia, 1989)*, 25–28 September 1989, (ed. by Yap W.G), pp. 59–66. FAO Fisheries and Aquaculture Department, Jepara City, Indonesia. Available at http://www.fao.org/docrep/field/003/ac058e/AC058E03.htm#ch2.3

Preston N. & Clayton H. (2003) *Rice-shrimp farming in the Mekong Delta: biophysical and socioeconomic issues.* ACIAR Technical Reports No.52e, ACIAR, Canberra, Australia, 170pp.

Raux P. & Bailly D. (2002) *Literature review on world shrimp farming.* Individual Partner Report for the Project: Policy Research for Sustainable Shrimp Farming in Asia, European Commission INCODEV Project No. IC4-2001-10042, CEMARE University of Portsmouth, UK, and CEDEM, Brest, France, 46pp.

Ritvo G., Samocha T.M., Lawrence A.L. & Neill W.H. (1998) Growth of *Penaeus vannamei* on soils from various Texas shrimp farms, under laboratory conditions. In: *Chemical and Physical Properties of Shrimp Pond Bottom Soils in Ecuador* (ed. by S. Sonnenholzner & C.E. Boyd). *Journal of the World Aquaculture Society* **31,** 385–375.

Rönnbäck P. (2001) *Shrimp Aquaculture: State of the Art. Swedish EIA Centre, Report 1.* Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden.

Rowell D.L. (1994) *Soil Science: Methods and Applications*. Department of Soil Science, University of Reading, Pearson Education, Prentice Hall, Harlow, UK.

Rump H.H. & Krist H. (1992) *Laboratory Manual for the Examination of Water, Waste Water and Soil*, 2nd edn. VCH, Weinheim, Germany.

Sels A. (2004) *Shrimp aquaculture and the socio-economic situation of the Cai Nuoc district, Ca Mau Province, Vietnam: application of the POET model.* Master Thesis in Human Ecology, Faculty of Medicine and Pharmacology, Vrije Universiteit Brussel.

SIG (2001) *Studying the Scientific Basis for the Planning Adjustment, Production Rearrangement at Cai Nuoc District, Ca Mau Province (2000–2001).* Sub-Institute of Geography, Ho Chi Minh City, Vietnam (in Vietnamese).

Smith P. T. (1996) Physical and chemical characteristics of sediments from prawn farms and mangrove habitats on the Clarence River, Australia. *Aquaculture* **146**, 47–83.

Smith P. T. (1999) *Coastal shrimp aquaculture in Thailand: key issues for research.* ACIAR Technical Reports No. 47, ACIAR, Canberra, Australia, 131pp.

Sonnenholzner S. & Boyd C.E. (2000) Chemical and physical properties of shrimp pond bottom soils in Ecuador. *Journal of the World Aquaculture Society* **31**, 358–375.

Tho N., Vromant N., Hung N.T. & Hens L. (2006) Organic pollution and salt intrusion in Cai Nuoc District, Ca Mau Province, Vietnam. *Water Environment Research* **78**, 716–723.

Tho N., Vromant N., Hung N.T. & Hens L. (2008) Soil salinity and sodicity in a shrimp farming coastal area of the Mekong Delta, Vietnam. *Environmental Geology* **54**, 1739–1746.

Thornton C., Shanahan M. & Williams J. (2003) From wetlands to wastelands: impacts of shrimp farming. Environmental justice foundation. *SWS Bulletin* **20**, 48–53.

Tookwinas S. & Songsangjinda P. (1999) Water quality and phytoplankton communities in intensive shrimp culture ponds in Kung Krabaen Bay, Eastern Thailand. *Journal of the World Aquaculture Society* **30**, 36–45.

Towatana P., Voradaj C. & Panapitukkul N. (2002) Changes in soil properties of abandoned shrimp ponds in southern Thailand. *Environmental Monitoring and Assessment* **74**, 45–65.

Vietnamese Standard 5943-1995. Available at http://khcn.mt.gov.vn/tieuchuannganh/uploads/TCVN.5943-1995.pdf (accessed 1 February 2010) (in Vietnamese).

Vinatea L., Gálvez A.O., Browdy C.L., Stokes A., Venero J., Haveman J., Lewis B.L., Lawson A., Shuler A. & Leffler J.W. (2010) Photosynthesis, water respiration and growth performance of *Litopenaeus vannamei* in a super-intensive raceway culture with zero water exchange: interaction of water quality variables. *Aquacultural Engineering* **42**, 17–24.

Vuong D.Q.T. & Lin C.K. (2001) *Rice-shrimp farming in the seawater intrusion zone of the Mekong Delta, Vietnam*. ITCZM Monograph No. 6.

Wang F.I. & Chen J.C. (2006) Effect of salinity on the immune response of tiger shrimp *Penaeus monodon* and its susceptibility to *Photobacterium damselae* subsp. *damselae*. *Fish and Shellfish Immunology* **20**, 671–681.

Wolanski E., Spagnol S., Thomas S., Moore K., Alongi D.M., Trott L. & Davidson A. (2000) Modelling and visualizing the fate of shrimp pond effluent in a mangrove-fringed tidal creek. *Estuarine, Coastal and Shelf Science* **50**, 85–97.

