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Original Article

Environmental impact of white shrimp culture during 2012–2013 at Bandon Bay, Surat Thani Province: A case study investigating farm size

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ABSTRACT

The environmental impact was studied due to water consumption and pollution loading from white shrimp culture at various shrimp farm scales. Field observation and in-depth interviews were carried out in 19 selected shrimp farms. The 38 water samples and 19 sediment samples from the shrimp farms from January–October, 2013 were analyzed and determined for their pollution loading from the wastewater and sediment discharged from the culture ponds. The results showed that for the same production, small-scale farms generated the highest pollution loading in wastewater and sediment, with respective values of per tonne production of 21.95 kg total Kjeldahl nitrogen and 1.12 kg total Kjeldahl nitrogen, 18.36 g Pb and 3.63 g Pb and 31.30 g As and 1.94 g As. However, for any-sized farm, the average total suspended solids and ammonia nitrogen of effluent from harvesting could not pass the Thai Effluent Standard for Coastal Aquaculture. In large-scale farms, the highest pollution loading per tonne production in wastewater discharged was 12.55 g Cu, while the highest pollution loadings per tonne production from the sediment generated were 20.98 kg organic matter, 0.079 g Cd and 26.65 g Cu. The large-scale farms used the highest proportion of refilled water (45.90%) and generated the highest amount of effluent during culture (39.26%). Only large-scale farms could manage their own control of water use to reduce environmental impacts. These results will be used further to determine the sustainability of shrimp farms at various scales.

Introduction

The coastal area of Bandon Bay is located in eastern Surat Thani province, Thailand. It is an area of intensive coastal aquaculture, especially for white shrimp and in particular *Litopenaeus vannamei*, which is the major economic product, with production from Bandon Bay during 2005–2011 in the range 40,480–61,392 t/yr and averaging 50,175 t, while the production in 2012 was 64,820 t which was the highest white shrimp production in the country (Department of Fisheries, 2014). Surat Thani Coastal Fisheries Research and Development Center (2014) reported that the total area of shrimp farms and shrimp culture ponds at Bandon Bay in 2012 was 5691 ha and 2984 ha, respectively. The main culture pond areas and shrimp production in Bandon Bay were in Kanchanadit district accounting for 47.42% of the total culture pond area and 42.88% of total shrimp production, with 58.62% of large-scale farms (exceeding 16.1 ha for culture pond area) and 45.65% of medium-scale farms (in the range 8.1–16.0 ha for culture pond area) in Kanchanadit district, while Phunphin district had only 36.08% of small-scale farms in Bandon Bay (less than 8.0 ha for culture pond area) but in the district 95.45% of shrimp farms were small-scale, similar to Mueang district (Department of Fisheries, 2014; Surat Thani Coastal Fisheries Research and Development Center, 2014).

In 2013, shrimp farm areas and shrimp production in each district in Bandon Bay were reduced by outbreaks of early mortality syndrome. In particular, production in Kanchanadit and Phunphin districts was reduced by 17,370 t and 4750 t, equaling a production decline of approximately 37% and 54% compared with 2012 (Department of Fisheries, 2014; Surat Thani Coastal Fisheries Research and Development Center, 2014). The number of shrimp farms in Kanchanadit district was 219 farms and in Phunphin district was 220 farms. However, it is possible that the efficiency of

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shrimp production depended on the management capabilities of the shrimp farmer to culture and manage the input or output from the culture pond, the scale of the shrimp operation, institutional support and the risks of crop failure (due to diseases, water quality problems, and environmental factors among others). The capabilities of the farmer in production management practices might be greater for large-scale and medium-scale farms than for small-scale farms. Consequently, not only could production be influenced by the farm scale, but the scale could also affect the environment. The main objective of this paper was to investigate the environmental impact from water consumption and generated pollution loading from both wastewater and sediment discharged from culture ponds, in shrimp farms of various scales. Data on the culture pond system (operation, technology, management of water used, effluent and sediment, production cost and social benefits) were collected and used for analyses in this study. The social data were compiled with the participation of stakeholders (shrimp farmers and governmental sectors related to aquaculture). All data were used to consider sustainable development concepts. The results obtained from this study, in particular the environmental management performance of different-sized shrimp culture farms will be used further to carry out sustainable development analysis of shrimp culture in Bandon Bay. In addition, the results may be used by concerned agencies in the area to manage and plan for the sustainable management of shrimp farms in Bandon Bay.

Materials and methods

Study area

The study area covered six districts from Chaiya to Don Sak (Ban Pod village), Surat Thani province, Thailand (Fig. 1). This study divided the shrimp farms into three scales depending on the culture pond area. Small-scale shrimp farms had a culture pond area of less than 8.0 ha, medium-scale shrimp farms had a culture pond area in the range 8.1–16.0 ha and large-scale shrimp farms had a culture pond area that exceeded 16.1 ha. In total, 19 selected shrimp farms were investigated, of which 5 were small-scale farms, 7 were medium-scale farms and 7 were large-scale farms. All selected farms were located along the coast of Bandon Bay and were selected according to various criteria: the position of the farm (distribution around the bay and distance from the coast and rivers), the culture experience of the farmer (exceeding 15 years), the social position and allowance of the farm owner which was an important factor for a number of the selected farms.

Data collection

Both primary and secondary data were collected from 2012 to 2013.

The secondary data on culture areas and production were collected from local governmental sectors and other sectors related to shrimp culture (Surat Thani Coastal Fisheries Research and Development Center, 2014; Department of Fisheries, 2014). In addition, coastal seawater characteristics during 2012–2013 were requested informally from the Pollution Control Department and the Surat Thani Provincial Fisheries Office and used in the analysis.

Primary data consisted of field observation and in-depth interviews carried out using a structured questionnaire. The interviews were conducted with shrimp farmers from the 19 selected farms on cultural operations, management techniques and environmental management. In addition, environmental sampling was carried out and water quality and sediment quality were analyzed. In total, 38 water samples in 19 shrimp farms were taken from the water use storage ponds and culture ponds during harvesting, when the shrimp age was in the range 80–105 d. The water samples (19) were taken at the center of ponds, at depths in the range 50–60 cm under the water surface, while the sediment samples (19) were taken at the center of the culture ponds when the water had been discharged after harvesting. The sediment samples were collected manually. The salinity and dissolved oxygen (DO) were determined on site using a salinometer (ATAGO S/Mill-E; Tokyo, Japan) and a DO meter (YSI 52; Yellow Springs, OH, USA). All sediment samples and water samples were preserved at 4 °C and analyzed in the laboratory of the Prince of Songkla University, Songkhla, Thailand. The characteristics of water samples were determined for total suspended solids (TSS), ammonia nitrogen (NH_3–N), total Kjeldahl nitrogen (TKN), chlorophyll a and heavy metals in terms of copper (Cu), cadmium (Cd), lead (Pb) and arsenic (As). The characteristics of sediment samples were determined for organic matter (OM), TKN and heavy metals, namely, Cu, Cd, Pb and As. The analysis methods used in this study were the methods described in Andrew (2005).

Data analyses

The secondary and primary data were used for analyses as follows. Seawater quality in Bandon Bay was calculated using the secondary data of seawater quality in the six districts at Bandon Bay based on representative points for the study of the selected shrimp farms in 2012–2013 reported by the Surat Thani Provincial Fisheries Office and Pollution Control Department, and were analyzed using the mean and standard deviation. These data were applied to the raw water used shrimp farming. After field observation, in-depth interviews from 19 shrimp farms, and seawater and sediment samples analysis, the data were analyzed using the secondary data to determine the water balance in the culture ponds and the pollution loads discharged from shrimp culture.

The water balance was calculated by using input and output of water amounts observed from the culture ponds (Equation (1)):

$$\text{Influent} = \text{Effluent} + \text{Loss} \tag{1}$$

where, the influent is the initial seawater used and refilled sea water during culture, effluent is the seawater discharged from the culture pond during culture and when harvesting and loss is the evaporation and percolation and harvesting.

Values were represented as the mean and standard deviation in cubic meters per tonne of product per pond per crop. Percentages were proportionate with respect to each input or output of total water amount. Seawater was pumped from the coast. Refilled water consisted of seawater and reused water. Reused water was the seawater directly discharged from culture ponds or pretreated seawater from the wastewater storage ponds. During shrimp culture, the farmers drained out around 10–50 cm water depth from the culture pond surface, depending on scale farm capacity. At the same time, they refilled the seawater to replace the discharge and the water level of the pond was maintained. The collected data of water input and output were determined from interviewing the shrimp farmers. The researchers investigated the water levels measured in the culture ponds and also after refilling.

The water pollution loading was determined by calculation from the amount of effluent when harvesting (cubic meters per crop) and the analyzed concentrations of each pollutant in the effluent (Equation (2)):

$$\text{Water pollution loading} = \text{Amount of effluent} \times \text{Concentration} \tag{2}$$

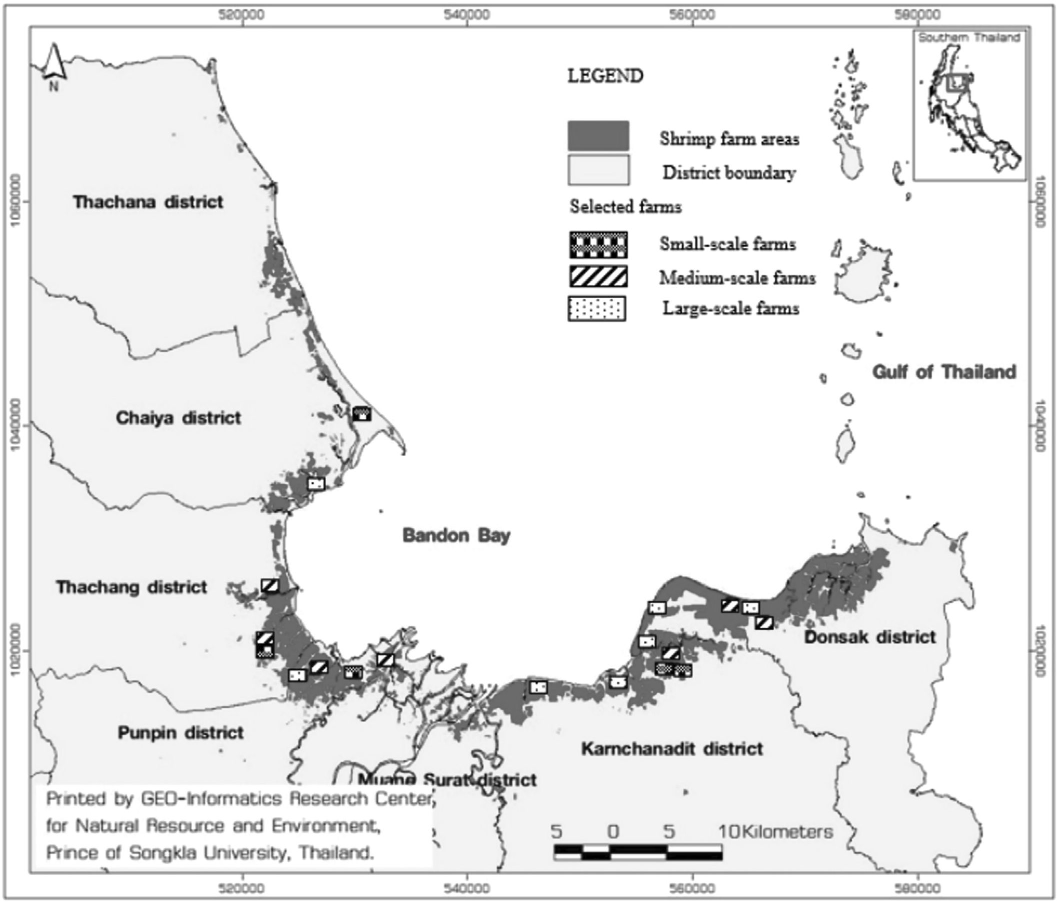

Fig. 1. Shrimp farm areas and selected farms at Bandon Bay, Surat Thani province, Thailand used for investigation (Sources: GEO-Informatics Research Center for Natural Resources and Environment, 2015).

where, the amount of effluent is that from harvesting and the concentration is the concentration of each pollutant in the effluent from harvesting.

The values were calculated and represented the mean and standard deviation based on shrimp production per pond, per crop. The water pollution loadings were determined as chlorophyll a, TSS, NH_3−N, TKN, Cd, Pb, Cu and As loadings. Similarly, the sediment pollution loading was calculated based on the mass of TSS drained out from the culture pond when harvesting occurred. Each sediment pollution loading in terms of OM, TKN, Cd, Pb, Cu and As was calculated and represented as the mean and standard deviation based on shrimp production per pond, per crop.

In 2013, six of the 19 selected farms had no discharged seawater from culture ponds during culture. Therefore, this study was concerned with pollutants discharged to the environment only from harvesting times.

Results and discussion

Overview of information of shrimp culture characterizations in Bandon Bay in 2013

Some *Penaeus monodon* cultures were reported for some farms, but not in small scale farms. Thus almost all shrimp farms in this investigation undertook culture of white shrimp (*L. vannamei*). From field observation and in-depth interviews, systematic and strongly implemented practices were found on the large-scale farms more so than in the small-scale and medium-scale ones. These concerned water refilling, the proportion of refilled water used, the duration of seawater preparation and the shrimp age for harvesting (Table 1). In addition, the highest density of post larval (PL) seeding was observed in small-scale farms and the second highest was in medium-scale farms. On the other hand, farms at both these scales obtained lower production than the large-scale farms. It was possible that the culture implementation practices were an important factor, in particular, the amount of seawater used, whether refilled water or water exchanged in the culture ponds, and the treatment of reused seawater, as respondents considered these to be important factors in obtaining high shrimp production levels.

Used water, pond structure and sediment management

The different operational conditions in each shrimp farm scale culture pond are shown in Fig. 2. Four aspects were related to the production quantity and pond environment. First, there were more seawater storage ponds in medium-scale farms and large-scale farms than on small-scale farms. This meant that more processing and more time for raw seawater pretreatment occurred in the medium-scale and large-scale farms. Additionally, different amounts of chemicals were used for seawater pretreatment for the different scales of farm and this depended on many factors, such as the farm location, seawater quality and critical outbreaks of shrimp disease. However, the use of large quantities of chemicals could

Table 1
Characteristics (mean ± SD) of shrimp culture performance based on farm scale at Bandon Bay in 2013.

Parameter	Scale of shrimp farm		
	Small ($n = 5$)	Medium ($n = 7$)	Large ($n = 7$)
Water depth in ponds (m)	1.40 ± 0.23	1.64 ± 0.27	1.76 ± 0.43
Culture pond areas (ha/pond)	0.86 ± 0.09	0.82 ± 0.06	0.86 ± 0.08
Number of culture ponds	7.20 ± 2.86	15.71 ± 3.49	34.86 ± 11.45
Number of culture crops per annum	2.20 ± 0.57	2.71 ± 0.57	2.29 ± 0.57
Water refilling (times/crop)	4.50 ± 1.00	5.00 ± 1.67	6.71 ± 2.56
Proportion of refilled water in each culture pond (percentage of the total pond volume/time)	10.61 ± 2.07	10.22 ± 7.44	11.25 ± 6.88
Volume of refilled water discharge during culture period (m^3/crop/pond)	5280.0 ± 854.2	6133.3 ± 1708.9	12,674.3 ± 1438.7
Volume of water discharge during culture period (m^3/crop/pond)	2580.0 ± 305.7	4666.7 ± 430.5	11,154.3 ± 158.2
Volume of water discharge during harvesting (m^3/crop/pond)	11,808.0 ± 2025.9	13,074.3 ± 2132.6	14,771.4 ± 4615.5
Duration of seawater preparation before shrimp culture (d)	20.80 ± 5.38	27.67 ± 7.45	29.86 ± 5.64
Shrimp age for harvesting (d)	89.60 ± 13.16	81.67 ± 9.31	93.86 ± 6.64
Density of larval input (Post larvae/ha of culture pond)	542,500 ± 330,198	671,428 ± 224,387	466,071 ± 367,048
Shrimp production (t/pond/crop)	7.04 ± 1.22	8.00 ± 1.12	10.57 ± 3.89

Sources: Survey during January–October 2013.

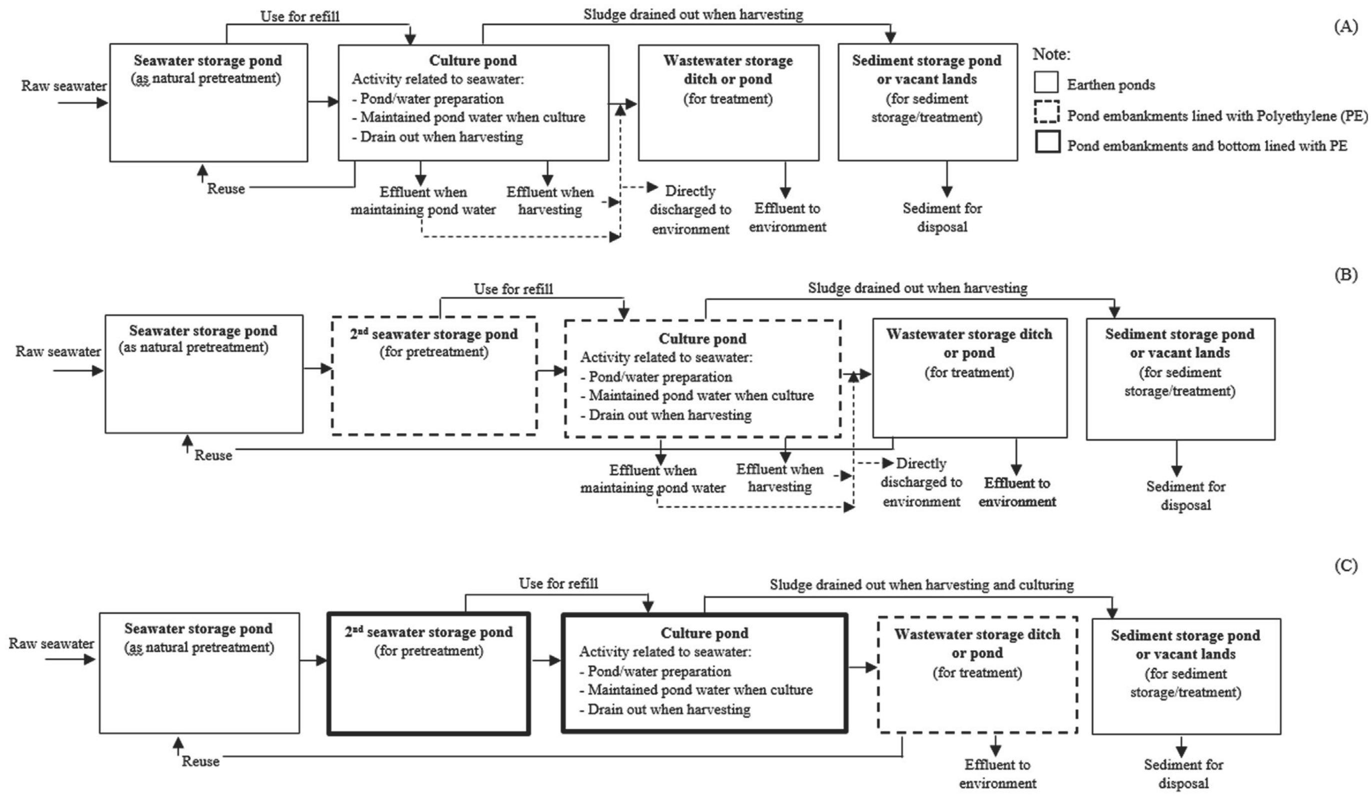

Fig. 2. Diagram of used water and water management practices at each scale of shrimp farm at Bandon Bay, Surat Thani province, Thailand: (A) small-scale farms; (B) medium-scale farms; (C) large-scale farms. (Surveyed during January–October, 2013).

have been the cause of their accumulation in shrimp products, farm systems and the environment. Second, culture pond sediment management was an important practice and 80% of large-scale farms managed sediment removal both during culture and harvesting to the sediment storage ponds or vacant lands of the shrimp farms, while 33.33% and 14.30% of small-scale and medium-scale farms, respectively, accumulated sediment in the culture ponds. The accumulation of massive amounts of sediment resulted in increased organic matter, nutrients and other pollutants in the culture ponds, which may have created problems in the next culture crop (Taparhudee, 2003). In particular, sediments of high pond age had greater concentrations of various chemical substances than new pond soils (Musig et al., 2004). Third, the large-scale farms had ponds lined with polyethylene on the embankments and pond bottoms, while the medium-scale farms had ponds lined with polyethylene only on the embankments. Culture pond lining could affect production capacity and decrease pond water loss. White shrimp usually roamed the whole area of the pond to capture feed and they are not a burrowing species (Prawitwilaikul et al., 2006). Therefore, white shrimp matured better in plastic-lined ponds compared to earthen ponds. Fourth, regarding seawater management during culture and wastewater treatment, farms of all scales used refilled water in culture ponds, but the small-scale farms normally used refilled water from the raw seawater storage pond that received water from the culture pond, whereas the medium and large-scale farms consumed water from a second seawater storage pond. In addition, 50% and 42.88% of small-scale and medium-scale farms, respectively, discharged water into the environment when harvesting and changing water during culture. However, it was noted that most wastewater from all farms was treated beforehand in storage ditches or ponds, and was discharged afterward into the environment. Medium and large-scale farms reused the wastewater from storage ditches or storage ponds by returning it to the seawater storage pond and consequently utilized it in the culture ponds for the next crop.

Seawater balance analysis in shrimp culture ponds

The results of seawater balance analysis in the shrimp culture ponds are shown in Fig. 3. It was found that the total average seawater amounts were 2817 m^3, 2470 m^3 and 2537 m^3 for shrimp culture per tonne of shrimp product in one crop for large-scale farms, medium-scale farms and small-scale farms, respectively. The results reflected that the large-scale farms consumed larger amounts of water for culture than small-scale and medium-scale farms. However, the large-scale farms used less raw seawater than the small and medium-scale farms, but utilized more reused seawater as refilled water, and generated more effluent during culture, but less when harvesting. The refilled and changed water needed to be added during crop culture to replenish losses resulting from evaporation and percolation into the soil as well as for changing water to maintain its quality in the pond (Limhang et al., 2010). However, Kaweekityota et al. (2007) reported that the rates of refilled water during culture affected the water quality as well as the growth, survival and yield of white shrimp. In the current study, the number of times refilled and changed water was used per crop were 6.71 times, 5.00 times and 4.50 times for large-scale, medium-scale and small-scale farms, respectively, with the average rates of refilled and changed water from the frequency water changed per day being as 0.05 times/d, 0.06 times/d and 0.07 times/d, respectively. These rates were similar to Lorenzen et al. (1997), who reported rates of refilled water during culture intensive shrimp farms in Asia being in the range 0.01–0.2 times/d for reduced plankton and sedimentation, but not for ammonia concentrations. However, the rates of refilled water were up to 0.3 times/d for shrimp ponds, thus reducing particulate nitrogen in the

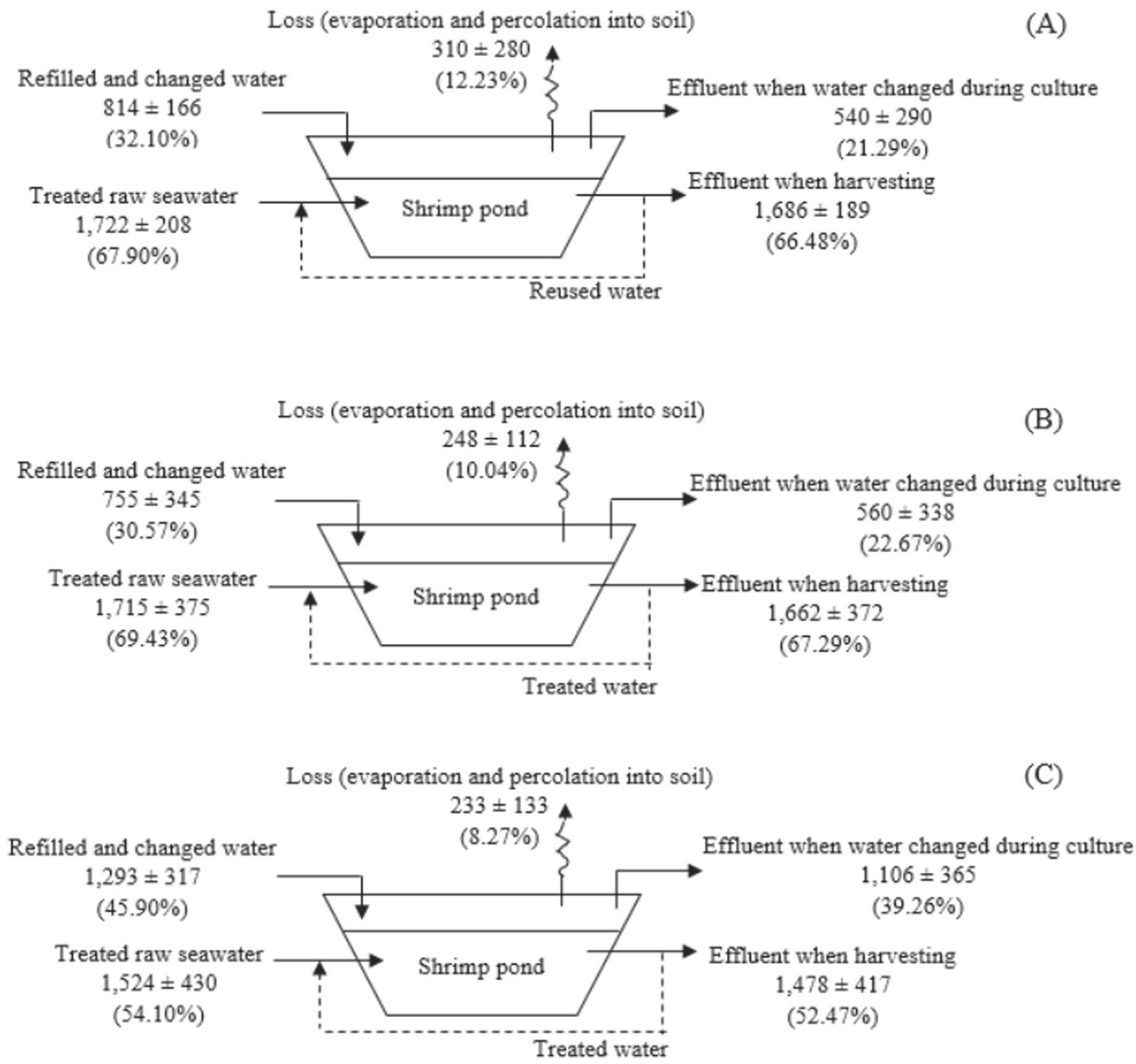

Fig. 3. Seawater balance (mean ± SD per tonne of shrimp production per crop) of shrimp culture ponds for each scale of farm: (A) small-scale farms; (B) medium-scale farms; (C) large-scale farms (Surveyed during January–October 2013).

pond. Moreover, the proportion of water loss as evaporation and percolation into the soil on small-scale and medium-scale farms were calculated to be 12.23% and 10.04% of the total water output of the culture pond, respectively, while for large-scale farms it was only 8.27%. The high percentage of water loss on the small-scale and medium-scale farms might have been due to the culture pond structure being earthen, as such ponds would have increased water percolation in the soil compared to lined ponds. There could also be seepage of seawater which could result in salinity and pollutants from the culture ponds moving into the adjacent underground water streams as well as land areas (Tanavud et al., 2001).

Characteristics of seawater and sediment in shrimp culture process and its pollution loading

Seawater

Table 2 shows the seawater characteristics in seawater storage ponds, for effluent when harvesting at the shrimp farms and the seawater in Bandon Bay that was used as the source of raw seawater for the shrimp farms. Most of the parameters for each scale of farm exceeded the average of seawater quality in Bandon Bay from 2012 to 2013 (Pollution Control Department, 2014; Surat Thani Provincial Fisheries Office, 2014) except for the values of TSS, NH_3–N and Cu. It was possible that after seawater from off site was pumped into storage ponds and purified, suspended solids (SS) settled by sedimentation and consequently changed the low concentrations of the other water quality parameters related to SS. Only Cu concentrations in the water storage ponds were observed to be lower than the seawater in Bandon Bay, and this might have been caused by sedimentation of seawater pretreatment and deposition in the sediment. However, regarding the parameters of effluent in culture ponds when shrimp harvesting, at each scale of farm there were higher concentrations than for the influent, except for salinity. This conformed with Limhang et al. (2010) who reported that the salinity decreased to 1–2 parts per trillion when the shrimp were harvested. The average parameters of effluent from harvesting at all farm scales could not pass the Thai Effluent Standard for Coastal Aquaculture, in particular TSS and NH_3–N for which the effluent standard values should be less than 70 mg/L and 1.1 mg/L, respectively (Pollution Control Department, 2005). The results indicated that the highest average TSS and NH_3–N in effluent were observed in medium-scale farms. However, the highest average TKN and As in the effluent were found in small-scale farms, but the highest average Cu was determined in large-scale farms.

Water pollution loading

The water pollution loadings discharged from the shrimp culture ponds in the small-, medium- and large-scale farms were calculated and are shown in Table 3. The small-scale farms generated the highest average loadings of TKN, Pb and As (based on one tonne of production), while the medium-scale farms produced the highest average water pollution loading amount in terms of chlorophyll a, TSS, NH_3–N and Cd. The large-scale farms generated the highest loadings of Cu. The pond structure and culture performance

Table 3
Estimated water pollution loading (mean ± SD) discharged from shrimp culture ponds, for each scale of farm.

Parameter	Scale of shrimp farm		
	Small (n = 5)	Medium (n = 7)	Large (n = 7)
Chlorophyll a (kg Chl a/t production)	0.23 ± 0.03	0.28 ± 0.17	0.18 ± 0.10
TSS (kg TSS/t production)	196.03 ± 101.88	199.27 ± 84.00	130.69 ± 51.33
NH_3–N (kg NH_3–N/t production)	1.51 ± 0.64	2.58 ± 1.52	2.06 ± 1.52
TKN (kg TKN/t production)	21.95 ± 6.19	21.48 ± 14.58	15.24 ± 12.42
Cd (g Cd/t production)	2.97 ± 1.22	3.98 ± 0.93	3.33 ± 1.91
Pb (g Pb/t production)	18.36 ± 16.29	17.16 ± 10.59	13.57 ± 5.71
Cu (g Cu/t production)	3.81 ± 3.36	7.02 ± 6.68	12.55 ± 8.94
As (g As/t production)	31.30 ± 11.35	22.69 ± 11.15	19.45 ± 11.28

TSS = total suspended solids, NH_3–N = ammonia nitrogen, TKN = total Kjeldahl nitrogen, Cd = cadmium, Pb = lead, Cu = copper, As = arsenic. Sources: Surveyed during January–October 2013.

Table 2
Seawater characteristics (mean ± SD) in storage ponds and effluent when harvesting for small-, medium- and large-scale farms from January–October, 2013 and for seawater in Bandon Bay in 2012–2013.

Parameter[a]	Influent (water in the storage pond)[b]			Effluent when harvesting[b]			Seawater quality in Bandon Bay	Sample number (n)data	Reviewed effluent when harvesting
	Small	Medium	Large	Small	Medium	Large			
Chlorophyll a (mg/m^3)	37.73 ± 33.65	17.33 ± 19.83	16.41 ± 11.48	141.35 ± 23.30	162.16 ± 98.78	125.01 ± 66.30	8.10 ± 57.46[c]	294	20–250[f]
Salinity (ppt)	17.80 ± 8.25	22.83 ± 9.15	19.14 ± 8.51	14.80 ± 9.37	19.50 ± 6.72	16.43 ± 5.68	13.55 ± 9.70[d]	310	–
TSS (mg/L)	11.00 ± 8.49	12.63 ± 6.63	13.81 ± 6.78	120.26 ± 71.58	121.17 ± 48.43	87.82 ± 17.03	36.98 ± 23.21[d]	313	119–225[f], 116[h]
NH_3–N (mg/L)[a]	0.12 ± 0.13	0.13 ± 0.10	0.22 ± 0.18	0.91 ± 0.41	1.57 ± 0.80	1.40 ± 1.09	0.29 ± 0.43[d]	294	0.66[g], 0.60[h]
TKN (mg/L)	8.20 ± 4.44	4.57 ± 2.56	3.33 ± 1.03	13.20 ± 4.27	13.05 ± 8.36	10.46 ± 9.19	–	–	–
DO (mg/L)	5.63 ± 2.34	5.93 ± 0.82	5.99 ± 1.12	7.75 ± 2.52	9.41 ± 1.08	8.26 ± 2.07	4.30 ± 0.94[d]	315	6.75[g]
Cd (μg/L)	1.80 ± 1.52	2.28 ± 0.75	1.86 ± 0.90	2.40 ± 0.84	2.43 ± 0.53	2.28 ± 1.25	0.44 ± 0.66[e]	26	2.30[h], 2.9–11.8[j]
Pb (μg/L)	6.60 ± 3.21	6.86 ± 6.91	6.83 ± 5.49	10.60 ± 9.18	11.00 ± 7.96	9.67 ± 3.01	1.45 ± 1.47[e]	10	11.20[h], 1.1–18.0[i]
Cu (μg/L)	2.40 ± 2.19	3.17 ± 1.72	6.43 ± 4.50	5.50 ± 4.43	4.50 ± 4.23	9.33 ± 8.62	8.74 ± 8.87[e]	17	1.9–77.0[i], 16.2–45.2[j]
As (μg/L)	16.50 ± 12.02	12.20 ± 10.66	9.25 ± 3.86	18.00 ± 5.48	14.50 ± 10.33	12.71 ± 6.67	1.77 ± 1.72[e]	22	ND–13.0[i]

[a] ppt = parts per trillion, TSS = total suspended solids, NH_3–N = ammonia nitrogen, TKN = total Kjeldahl nitrogen, DO = dissolved oxygen, Cd = cadmium, Pb = lead, Cu = copper, As = arsenic, ND = not determined.
[b] surveyed during January–October, 2013.
[c] Surat Thani Provincial Fisheries Office (2014), data for 12 mth/yr.
[d] Calculated from Pollution Control Department (2014), data for 2 mth/yr and Surat Thani Provincial Fisheries Office (2014), data for 12 mth/yr.
[e] Pollution Control Department (2014), data for 2 mth/yr.
[f] Jenkins et al. (1999).
[g] Pingasorn (2007).
[h] Suebwattanapongsakul et al. (2009).
[i] Prapaiwong (2011).
[j] Lugsub et al. (2013).

are the two main causes for these results. First, with regard to the structure of culture ponds, high total suspended solids in the earthen ponds were due to the high erosion associated with aeration and rain, so that a lot of sediment was generated. The high sediment accumulation could then become re-suspended in the water column during harvesting. In addition, La-ongsiriwong et al. (2010) reported that plastic lined ponds for shrimp culture resulted in an increased total ammonia concentration in the water column, because nitrogen circulation could be not exchanged with surface sediments. Second, culture performance impacts were due to: 1) the number of cultured crops per year was highest for the medium-scale farms. The greater the number of cultured crops per year, the higher the possibility of generated pollutants accumulating in the ponds, particularly if there was a lack of suitable pond preparation and sediment removal from the culture ponds. This would then affect the water quality in the culture ponds, especially because of heavy metals. However, it is possible that heavy metals were adsorbed by suspended solids and organic matter in the water column, and deposited onto sediments; 2) the low proportion of refilled water during culture could result in an increase in un-ionized chemicals and pollutants in the culture pond (Kaweekityota et al., 2007); and 3) effluent from harvesting was directly reused by passing through the seawater storage ponds and pretreatment via dilution occurred. This action caused the water storage ponds to fill with large amounts of sediment and organic contents, so various pollutants could have been accumulated in the culture pond when this water was used. This affected the quality of water input (treated raw seawater and refilled water), especially in the small-scale farms.

Sediment pollution loading

The sediment characteristics and their pollution loading discharged from the shrimp culture ponds were determined and are shown in Table 4. The medium-scale farms generated the largest amount of sediment discharged from culture ponds. It was noted that the large-scale farms produced the highest concentrations of OM, Cd and Cu in sediments, while the small-scale farms produced the highest concentrations of TKN, Pb and As. This might have been due to the ponds being lined with polyethylene on the large-scale farms. However, the high Cu loading in the water and sediment could have been related to the amount of Cu used for water pretreatment and pond water preparation with regard to feed, seawater and pond soil characteristics. Furthermore, the results from this study reflected that each scale of farm had a higher pollution loading in water than in sediment, which might have been because of the massive amount of re-suspended sediment particles being circulated back to the water phase, especially during harvesting. In addition, Thongra-ar et al. (2008) reported that OM, silt and clay were the major metal sorbents of sediment. Therefore, sediment containing high OM, clay and silt had the potential to retain heavy metals. However, Cu showed no correlation with other metals and sediment characteristics suggesting that there may be significant anthropogenic sources of Cu in the coastal area. This would explain why most heavy metals were found in water discharged from culture ponds, as mentioned before.

The results from this study indicated that the water use and the water and sediment pollution loadings discharged from shrimp culture ponds depended on culture performance on the different scales of farms. Therefore the following recommendations are provided.

1) The small-to-medium-scale farms should be concerned with techniques for reducing water loss and reducing sediment discharge. For example, a pond lined with polyethylene is one of the best alternatives for reducing such problems. Other techniques that may be adopted to prevent erosion include the correct positioning of aerators, not leaving drains open in empty ponds and the use of proper embankment slopes and compaction for ponds (Boyd, 2003).
2) Large-scale farms should be concerned with their efficiency of water consumption and OM loading reduction, especially in sediments. Technologies that can improve nutrient utilization and in particular biofloc technology (BFT) and periphyton communities, among others, could be applied to culture ponds. Refilled water during culture in BFT ponds was reported to be very low for extended periods, while utilization by periphyton communities could reduce sedimentation and accumulation of OM at the pond bottom (Bosma and Verdegem, 2011). However, these techniques could also improve the ecosystem in shrimp culture ponds, as one pillar of a sustainable development approach.
3) A readily applied action would be for local government sectors to disseminate knowledge for efficient management, consisting of: 1) guidance regarding wastewater treatment to achieve economic and environmental sustainability; 2) providing heavy metals analysis for water and sediment; 3) giving subsidies or

Table 4
Characteristics (mean ± SD) of sediments and estimated sediment pollution loading discharged from the shrimp culture ponds, for each scale of farm.

Parameter[a]	Scale of shrimp farms		
	Small ($n = 5$)	Medium ($n = 7$)	Large ($n = 7$)
Sediment characteristics (dry basis)			
TKN (g/kg)	5.98 ± 2.33	3.20 ± 1.39	5.87 ± 3.93
OM (g/kg)	75.20 ± 38.67	59.73 ± 4.22	163.63 ± 86.51
Cd (mg/kg)	0.28 ± 0.21	0.23 ± 0.19	0.60 ± 0.34
Pb (mg/kg)	17.58 ± 2.97	16.28 ± 3.36	12.96 ± 7.77
Cu (mg/kg)	54.61 ± 38.37	95.61 ± 92.96	274.21 ± 194.65
As (mg/kg)	8.05 ± 4.75	7.09 ± 3.10	7.57 ± 2.92
Sediment pollution loading (on dry basis)			
Sediment generated[b] (kg/t production)	196.04 ± 101.92	199.25 ± 84.02	130.70 ± 51.34
OM (kg OM/t production)	14.26 ± 8.35	12.40 ± 7.78	20.98 ± 14.16
TKN (kg TKN/t production)	1.12 ± 0.50	0.60 ± 0.25	0.86 ± 0.84
Cd (g Cd/t production)	0.056 ± 0.04	0.051 ± 0.05	079 ± 0.05
Pb (g Pb/t production)	3.63 ± 2.43	3.27 ± 1.61	1.84 ± 1.44
Cu (g Cu/t production)	11.61 ± 10.48	17.65 ± 14.84	26.65 ± 20.19
As (g As/t production)	1.94 ± 0.53	1.40 ± 0.84	1.07 ± 0.81

[a] OM = organic matter, TKN = total Kjeldahl nitrogen, Cd = cadmium, Pb = lead, Cu = copper, As = arsenic.
[b] Sediment generated was calculated from TSS loading of seawater discharged to the environment; Sources: Surveyed during January–October 2013.

support for improved changes to current culture technologies and to water quality and sediment quality monitoring; 4) helping small-scale farms to cooperate with medium and large-scale farms.

4) However, the sustainability of shrimp culture should be enhanced through a range of criteria regarding social, economic and ecological or environmental sustainability.

The study found that different scales of shrimp farms at Bandon Bay had differences in the amount of consumed water and generated different quantities of pollution loads via water and sediment. The small-scale farms had weak points with regards to water loss, while the large-scale farms were seen to be more efficient in water use, but discharged the highest pollution load in terms of Cu, both in water and sediment. To consider the sustainability of the shrimp culture system, farming practices are definitely considered to be factors that might influence the degree of sustainability.

Conflict of interest

There is no conflict of interest.

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