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Research article

Water Quality and Sediment Quality of Cockle Culture Area in the Upper Gulf of Thailand

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Abstract

Keywords

water quality;
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This study aimed to investigate the water and sediment quality of a cockle culture area in the Upper Gulf of Thailand. Samples were collected from 26 stations for 6 months during October 2018 to March 2019. The results for water quality were as follows: salinity was an average of 12.88-23.81 psu; temperature 25.95-30.85ºC; DO 3.42-6.34 mg/l; pH 7.38-7.74; TSS 39.24-197.38 mg/l; ammonium-nitrogen 0.38-8.16 µg-N/l; nitrite-nitrogen 0.29-1.19 µg-N/l; nitrate-nitrogen 0.09-0.44 mg-N/l; phosphate-phosphorus 0.01-0.36 mg-P/l; and chlorophyll *a* 9.19-21.92 µg/l. The results for sediment quality were as follows: clay texture; percentage of sediment particles smaller than 0.06 mm was 48.33 to 71.91%; pH 6.49 to 7.17; salinity 4.58 to 12.35 psu; water content 63.55 to 69.14%; and organic matter (OM) 3.93 to 4.54%. The seawater quality in the Upper Gulf of Thailand did not meet the requirements of Standard Class 3 (seawater quality standard for aquaculture). Overall, the results demonstrated that the deterioration of water and sediment quality in the Upper Gulf of Thailand mostly occurred in the wet season (October). Therefore, farmers should learn how to monitor water quality during the wet season. Our findings can help the cockle production industry to grow efficiently and sustainably.

1. Introduction

Blood cockle (*Tegillarca granosa*), formerly known as *Anadara granosa*, is one of the most important species in the Indo-Pacific region [1, 2]. The Upper Gulf of Thailand is considered to be the

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largest cockle producing area in Thailand and represents about 70% of the total cockle culture area in the country [3]. The Upper Gulf of Thailand comprises the East coast and the West coast including Chonburi, Chanthaburi, Samut Sakhon, Samut Songkhram and Phetchaburi provinces [4]. While in Chonburi and Chanthaburi cultures mainly feature oysters and mussels, there are only few farmed cockle sites in Samut Sakhon province. However, the heaviest density of cultured cockle production was found in Samut Songkhram and Phetchaburi provinces in the Upper Gulf of Thailand. It can be explained that these two provinces are in adjoining areas located in the west of Thailand, and have upper mountainous areas upstream of the Mae Klong River and and Phetchaburi River, which flow into their estuarine areas, therefore, both of these areas have similar environmental qualities such as water quality and biodiversity [5]. Additionally, in 2017, the combined cockle production of Samut Songkhram and Phetchaburi provinces was 10,148 tons, which accounted for about 40% of the total cockle production in Thailand [1]. Therefore, cockle cultivation areas in the Upper Gulf of Thailand are predominantly generated from Phetchaburi and Samut Songkhram provinces. However, blood cockle production in the Upper Gulf of Thailand significantly decreased over the period 2013-2017. Production dwindled from 50,565 tons in 2013 to 16,307 tons in 2017 [1].

Currently, there are several issues regarding cockle farming in Samut Songkhram and Phetchaburi provinces. One of them is the discharge of industrial wastewater in Ratchaburi province into the cockle farming areas. As a result of this, the dissolved oxygen (DO) in farms was reduced to 1-2.8 mg/l, which caused the deaths of large numbers of cockles and total damage of approximately 867,656 USD [6]. Then, most recently in September 2017, the discharge of wastewater from large pig farms in Pak Tor, Ratchaburi province destroyed approximately 70% of the cockle production of the local farmers. The Regional Environment office 8 measured the DO value in Pak Tor and the result showed a value of lower than 4 mg/l, which was not suitable for blood cockle living and survival. The consequence of this factor can potentially cause an effect on the cockle cultivation [7, 8]. Furthermore, with wet season heavy daily precipitation combined with a tremendous amount of fresh water flowing into the estuary area of the farmed cockle sites, a large reduction in salinity occurred, and subsequently there was a great volume of cockles that died. This region is an area where cockle farming is cultured intensely, and high temperatures may cause reduction in cockle farming [4, 9].

To date, very few studies on the environmental factors such as water quality and sediment quality affecting cockle culture, and especially in the Upper Gulf of Thailand (Samut Songkhram and Phetchaburi provinces) which is considered to be the largest cockle production area. The study of these factors should be conducted efficiently and effectively. This will help to have a better understanding of the existing conditions of water and sediment quality in the area and will provide a great basis data for the management of the aquatic environment and cockle farming in the future.

2. Materials and Methods

2.1 The study area

The research was conducted in the Upper Gulf of Thailand. Klong Khone, Samut Songkharm province and Bang Taboon, Phetchaburi province (UTM 604845 E, 1470990 N) were selected to be representative of mainly cockle farming area according to the density and quantity of the farm and the number of affected farms. As shown in Figure 1, there were 26 sampling stations that were divided into 6 sampling stations in Klong Khone (KC 1-6) and 20 sampling stations in Bang

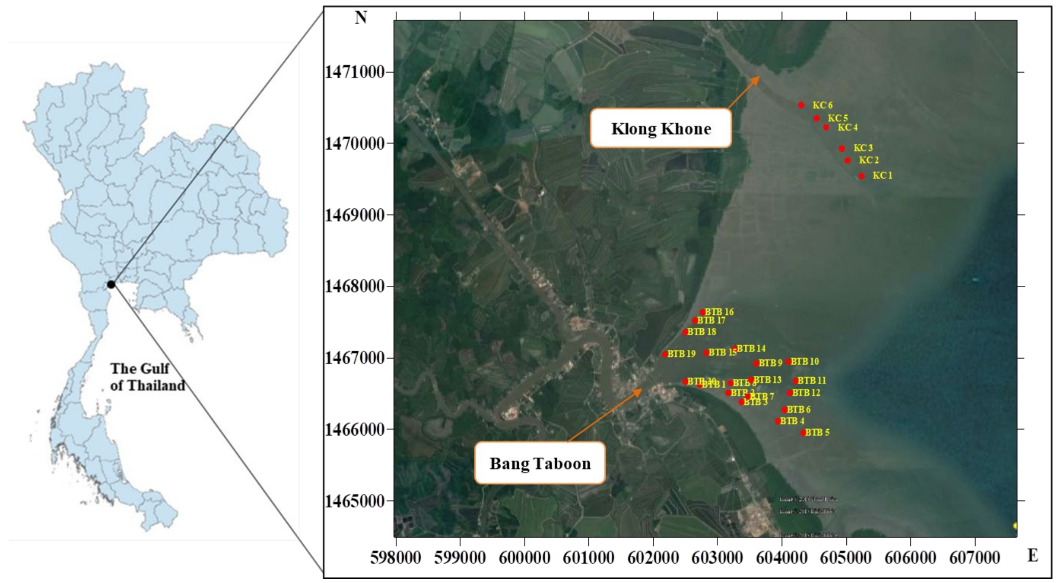

Figure 1. Map of sampling stations at the Upper Gulf of Thailand

Taboon (BTB 1-20). All of them (26 stations) were blood cockle farms located in estuaries zones. These areas were exposed to many pollutants from upstream as point and non-point sources [10]. The data were collected monthly for 6 months from October 2018 to March 2019, which represented the wet season (October to December) and the dry season (January to March) which were expected to have different loading amounts of pollution from upper land to the estuary area where cockle farms were affected. In each sampling station, data were sampled during the low tide in the spring tide season in order to evaluate the existing conditions of the water and sediment quality in these areas.

2.2 Field sampling

In this research, duplicate sampling was conducted at the 26 stations. In each station, in situ seawater quality was investigated. Salinity and pH of water were measured using a refractometer and Cybercan PC 300 (EUTECH Instruments, Singapore), respectively. Then, temperature and dissolved oxygen (DO) were analyzed in-situ by Cybercan DO 110 (EUTECH Instruments, Singapore). Finally, seawater was collected for analyses of total suspended solids (TSS), ammonium-nitrogen (NH_4^+-N), nitrite-nitrogen (NO_2^--N), nitrate-nitrogen (NO_3^--N), phosphate-phosphorus (PO_4^{3-}-P) and chlorophyll *a* in the laboratory. Sediment was sampled at 0 - 1 cm depth from sediment surface base on the cockle living area by gravity core and this was repeated three times [11]. Then, the sediment sample were stored in plastic bags to determine salinity, pH, grain size, water content (WC) and organic matter (OM) in the laboratory.

2.3 Seawater analysis

Total suspended solids (TSS) were measured by filtering the seawater through filter paper (GF/C filter paper) and drying it in a hot air oven at 103-105°C for three days [12]. After drying, the sample was weighed again and the dry weights were measured using a 4-digit analytical balance. The concentrations of NH_4^+-N, NO_2^--N, NO_3^--N and PO_4^{3-}-P were determined following standard methods [12]. Chlorophyll *a* concentration was determined by a spectrophotometric method as described in Parsons *et al.* [13].

2.4 Sediment analysis

Grain size was analyzed using a sieve with pore size of 1, 0.125 and 0.06 mm to filter sand, silt and clay, respectively. The pH and salinity were conducted as described in Beck [14]. Water content (WC), or the percentage of water in the sediment, was determined by subtraction of dry weight (after dried in hot air oven at 105ºC for three days) from wet weight. Finally, organic matter (OM) was determined using the wet oxidation method [15]. After obtaining the results of the parameters of seawater quality and sediment quality, the results were then summarized and expressed using descriptive statistics including mean ±SD, and a two-way ANOVA was used to determine the significance of seasonal (month) variation at significant lever of 99% ($\alpha = 0.01$) for the evaluation of the existing conditions. Subsequently, the relationships between the values of each parameter were analyzed using the Pearson correlation coefficient (r_{xy}).

3. Results and Discussion

The cockle cultivation areas in the Upper Gulf of Thailand are predominantly found in Samut Songkhram and Phetchaburi provinces (Klong Khone and Bang Taboon) [1]. The results and discussion of water quality and sediment quality in the Upper Gulf of Thailand are as follows.

3.1 Seawater quality

3.1.1 Salinity of seawater

In the Upper Gulf of Thailand, the salinity value was found to be in the range of 12.88-23.81 psu throughout the study period. The lowest salinity was measured in October during the wet season and the highest one was monitored in March at the start of the dry season, as shown in Table 1. Moreover, the results of the statistics analysis indicate that there were significant differences for all seawater parameters over the months of the study (P-value <0.01), showing that the season influenced seawater changes. Figure 2 shows that the distribution of salinity in October was lower than other months due to this season was still in the monsoon season. Salinity value was low on the coast and gradually increased when it was further away from the coast. Furthermore, the other impacts causing the low salinity value was the large amount of freshwater flowing from the Mae Klong River and Phetchaburi River into the estuarine areas. This result complies with Parekh and Gadhvi [16] who examined seasonal variation of seawater along the Mithirdi Coast Bhavnagar located on the western coast of India. The decreased levels of salinity were due to intense rainfall and the large quantities of freshwater flowing into estuaries in the monsoon season. Additionally, Figure 2 shows that the levels of salinity of seawater in Klong Khone area were lower than in the Bang Taboon area. This was probably due to the seawater quality in Klong Khone being more affected by freshwater from the land than was the quality of water in Bang Taboon. However, when comparing the salinity of seawater in the Klong Khone and the Bang Taboon areas with the other coastal areas such as Samut Sakhon province, Sawi Bay Chumphon province, Ban Don Bay Surat Thani province and Pattani Bay Pattani province, it was found that cockles were able to survive better in these conditions [17-23]. Commonly, cockles can spread in seawater within a

Table 1. Mean values of seawater quality at cockle culture area in the Upper Gulf of Thailand and P-values with α = 0.01

Seawater quality parameter	Sampling period Mean ±SD						
	Oct	Nov	Dec	Jan	Feb	Mar	P-values
*Salinity (psu)	12.88 ± 5.05	20.58 ± 4.42	21.72 ± 2.06	20.92 ± 1.79	20.27 ± 2.95	23.81 ± 5.45	<0.01
*Temperature (ºC)	30.85 ± 1.39	29.55 ± 0.87	29.47 ± 1.33	27.78 ± 0.90	25.95 ± 1.76	26.27 ± 2.36	<0.01
* DO ($mg \cdot l^{-1}$)	3.42 ± 0.78	4.56 ± 0.78	6.34 ± 1.25	4.64 ± 0.30	6.14 ± 0.39	5.42 ± 1.11	<0.01
*pH	7.38 ± 0.48	7.44 ± 0.13	7.74 ± 0.13	7.67 ± 0.15	7.71 ± 0.36	7.53 ± 0.16	<0.01
TSS ($mg \cdot l^{-1}$)	48.50 ± 21.34	47.63 ± 16.16	54.88 ± 23.32	39.24 ± 15.18	54.37 ± 24.04	197.38 ± 92.42	<0.01
NH_4^+-N ($\mu g \cdot l^{-1}$)	8.16 ± 4.11	1.60 ± 1.53	0.94 ± 0.98	3.58 ± 1.75	0.38 ± 0.27	3.24 ± 1.85	<0.01
NO_2^--N ($\mu g \cdot l^{-1}$)	1.18 ± 0.23	0.16 ± 0.22	0.56 ± 0.39	0.29 ± 0.10	0.35 ± 0.15	1.19 ± 0.61	<0.01
*NO_3^--N ($mg \cdot l^{-1}$)	0.44 ± 0.02	0.34 ± 0.04	0.26 ± 0.02	0.43 ± 0.05	0.09 ± 0.01	0.27 ± 0.05	<0.01
*PO_4^{3-}-P ($mg \cdot l^{-1}$)	0.36 ± 0.17	0.01 ± 0.00	0.07 ± 0.03	0.11 ± 0.02	0.05 ± 0.03	0.19 ± 0.11	<0.01
Chl *a* ($\mu g \cdot l^{-1}$)	14.58 ± 11.71	21.92 ± 10.07	14.51 ± 7.05	10.81 ± 5.28	14.71 ± 4.60	9.19 ± 4.96	<0.01

Note: * Seawater quality standard for aquaculture [24]

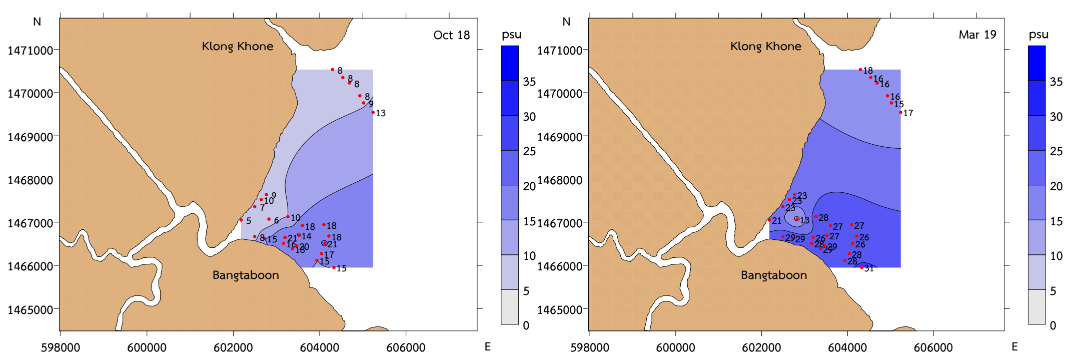

Figure 2. Distribution of salinity of seawater in October and March at the Klong Khone and Bang Taboon areas

range of salinity between 10-30 psu [21] but they are likely to die when salinity of seawater is below 5 psu [20, 22]. Therefore, when the salinity turns to be very low in October, it may lead to a mass mortality of cockles in the study area. After comparing salinity data to the criteria set by coastal water quality standards, it was found that the coastal water quality standards for aquaculture (class 3) were met. The correlation coefficient analysis revealed that the salinity of seawater was related to temperature, DO, NH_4^+-N and PO_4^{3-}-P with r_{xy} values of -0.54, 0.46, -0.52 and -0.55, respectively (Table 2). These results demonstrate that the salinity tends to decrease when temperature, NH_4^+-N and PO_4^{3-}-P are higher. On the other hand, salinity tends to increase when DO of the water increases. The major factor that caused the decrease in salinity and higher values of NH_4^+-N and PO_4^{3-}-P was the large amount of freshwater along with domestic wastewater discharges that flowed into the estuaries and also the high temperature in October (wet season). In the dry season in March, the lower amount of freshwater tended to be associated with an increase in salinity and DO. Therefore, it can be concluded that during the wet season, low salinity associated with increase in temperature, DO and nutrients; meanwhile during the dry season, salinity tended to be higher with the increase of DO. These results were in line with other researchers [16].

Table 2. Pearson correlation coefficients (r_{xy}) between the values of each parameter sampled at cockle culture areas in the Upper Gulf of Thailand

	Sal	Temp	DO	pH	TSS	NH_4	NO_2	NO_3	PO_4	Chl *a*
Sal	1									
Temp	-0.54	1								
DO	0.46	-0.43	1							
pH	0.27	-0.06	0.33	1						
TSS	0.33	-0.43	0.03	-0.08	1					
NH_4	-0.52	0.40	-0.73	-0.37	0.08	1				
NO_2	-0.18	0.05	-0.27	-0.16	0.62	0.48	1			
NO_3	-0.22	0.43	-0.66	-0.27	-0.08	0.59	0.17	1		
PO_4	-0.55	0.22	-0.46	-0.43	0.24	0.75	0.67	0.42	1	
Chl *a*	0.16	0.09	0.07	-0.02	-0.14	-0.41	-0.10	-0.00	-0.30	1

Note: Sal = Salinity (psu), Temp = Temperature (°C), DO = DO ($mg \cdot l^{-1}$), TSS = TSS ($mg \cdot l^{-1}$), NH_4 = NH_4^+-N ($\mu g \cdot l^{-1}$), NO_2 = NO_2^--N ($\mu g \cdot l^{-1}$), NO_3 = NO_3^--N ($mg \cdot l^{-1}$), PO_4 = PO_4^{3-}-P ($mg \cdot l^{-1}$) and Chl *a* = Chl *a* ($\mu g \cdot l^{-1}$)

3.1.2 Seawater temperature

The seawater temperature in the Upper Gulf of Thailand was in the range of 25.95-30.85°C. Overall, the highest average temperature was in October (wet season) and it gradually decreased in November, December, January, and February (winter), respectively. Then, it slowly rose again in March, which marked the start of summer, as shown in Table 1. The factors that may have caused the highest seawater temperature in October included the large quantity of freshwater runoff from the Mae Klong River and Phetchaburi River into the sea. This freshwater contained discharges of sediment particles that contaminated water and caused seawater turbidity. Additionally, these particles absorbed more heat generated by the sun and therefore caused the surrounding water mass to increase in temperature [25]. Furthermore, seawater temperatures at almost all stations were higher than 30°C in the month of October, at this temperature, the blood cockles become weak and may eventually die [26]. However, the study of seawater temperature distribution in the study area showed that during October, November and December 2018, the average temperature in the Bang Taboon area was slightly higher than in the Klong Khone area (Figure 3). Due to the higher temperatures throughout this period, the cockle in Bang Taboon became less productive than in the Klong Khone area. On the other hand, during January, February and March 2019, the average temperature in Bang Taboon was lower than Klong Khone area. Therefore, it can be

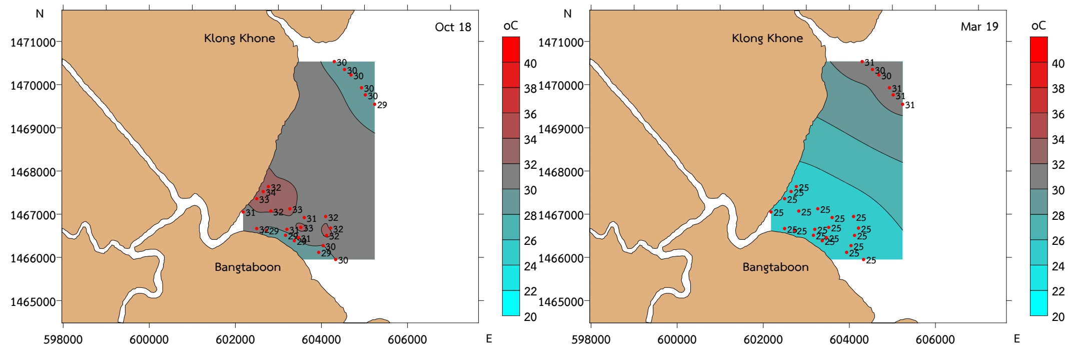

Figure 3. Distribution of seawater temperature in October and March at the Klong Khone and Bang Taboon areas

indicated that there is a different appropriate timing for the cultivating cockle for the two areas. For example, in Klong Khone the cockles should not be cultured during the month of March (beginning of the summer) because the temperature of the seawater has started to increase and as a result the cockles may become weak. Besides, cockle farmers in Bang Taboon should not raise cockles during the months of October, November and December due to the high temperatures of the seawater which may exceed 30ºC. It would probably be a better plan to wait until the seawater temperature becomes lower in the month of January before starting a new cockle cultivation. That would better provide for higher potential growth and the higher chance of cockle survival. The seawater quality assessment of seawater temperature in the Upper Gulf of Thailand indicated that it met the coastal water quality standard for aquaculture (class 3). In addition, the correlation (r_{xy}) showed that the seawater temperatures were associated with DO, TSS, NH_4^+-N and NO_3^--N with r_{xy} values of -0.43, -0.43, 0.40 and 0.43, respectively (Table 2). These results indicated that low temperatures tended to increase DO due to the fact that water at low temperature can hold more dissolved oxygen than at high temperature. While NH_4^+-N and NO_3^--N increase in water, the seawater temperature tends to increase due to high temperature during the wet season, a large quantity of water carries waste from the upper community into the estuaries.

3.1.3 Dissolved oxygen (DO)

As shown in Table 1, DO was found in an average of 3.42-6.34 mg/l throughout the study period and the lowest value was measured in October during the wet season. The DO levels in almost all of the stations were monitored at lower than 4 mg/l which did not meet the standard of dissolved oxygen in seawater quality for aquaculture. From this perspective, the month of October may not be a favorable time for the cockle cultivation. The lower DO may be due to the discharging of large amount of organic contamination during the raining season. Aa this contamination flowed from the land into the river through biodegradation of organic waste, a process that depleted dissolved oxygen. In addition to the study, the DO in Klong Khone area was found to be higher than in Bang Taboon area (Figure 4). For this reason, the Klong Khone area would seem to be more suitable for raising cockles than Bang Taboon area. Previous research has shown that cockles thrive in habitats where the DO of seawater is greater than 5 mg/l [17, 19-22, 27]. According to the analysis of oxygen consumption of blood cockle by previous studies [28-30], it was found that when DO was less than 3.1 mg/l, cockles closed their valves completely, stopped filtering to eat, and finally died. Moreover,

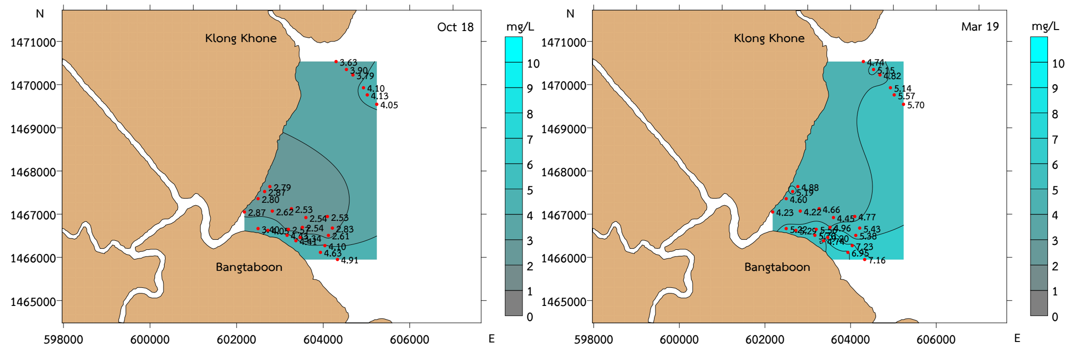

Figure 4. Distribution of DO in October and March at the Klong Khone and Bang Taboon areas

as shown Table 2, it was found that the DO was related to NH_4^+-N, NO_3^--N and PO_4^{3-}-P with r_{xy} values of -0.73, -0.66, and -0.46, respectively. These results demonstrate that DO tends to decrease when NH_4^+-N, NO_3^--N and PO_4^{3-}-P are higher. Furthermore, it would seem that the decline of DO in high nutrient concentrations (NH_4^+-N, NO_3^--N and PO_4^{3-}-P) results from discharge of domestic wastewater in the upper areas, which later flows into estuaries during the wet season [31].

3.1.4 pH

The pH scale ranged from 7.38 to 7.74, and the monthly average pH value in each month was acquired in a similar scale as shown in Table 1. Overall, the pH values in the study area were satisfactory and met the expectations according to the standard of seawater quality for aquaculture, which stated that the pH scale should range between 7.0-8.5. The lowest average pH value was found in the month of October. This may be due to tourism-related activities that caused water contamination and may have led to a slight decrease in pH. However, when comparing the results of this study with the pH of the seawater in natural sites at which cockles lived, which specified the pH range of 6.8-8.8 [17, 19-22, 27], it is clear that the pH range found in this study were acceptable for the cockle survival. In addition, the pH was related to PO_4^{3-}-P with r_{xy} value of -0.43, as shown in Table 2. These results demonstrate that the pH tends to decrease when PO_4^{3-}-P is higher. Usually, as the pH goes down with leaching of bases under the influence of quantity of freshwater as it happens in this study, phosphorous begins to accumulate more.

3.1.5 Total suspended solids (TSS)

TSS value was found in an average of 39.24-197.38 mg/l throughout the study period. The lowest and the highest TSS values were measured in January and March 2019, respectively, as shown in Table 1. According to the study, the levels of TSS in Bang Taboon was found to be higher than in Klong Khone. This may be due to Bang Taboon being located at the Phetchaburi River outlet and also due to the presence nearby the floodgates of the shrimp ponds, which caused turbidity of water (Figure 5). Moreover, these factors may cause the cultured cockles in Bang Taboon area to be more likely to die than in Klong Khone area. In nature, the blood cockle is a marine bivalve that relies on filtering the suspended particles in the water as a food consumption. Cockles may be able to tolerate an extremely high amount of TSS. One of the studies shows that living cockles can be found in seawater that contained TSS in the range of 1.3 to 557 mg/l [20]. However, the cockles may easily

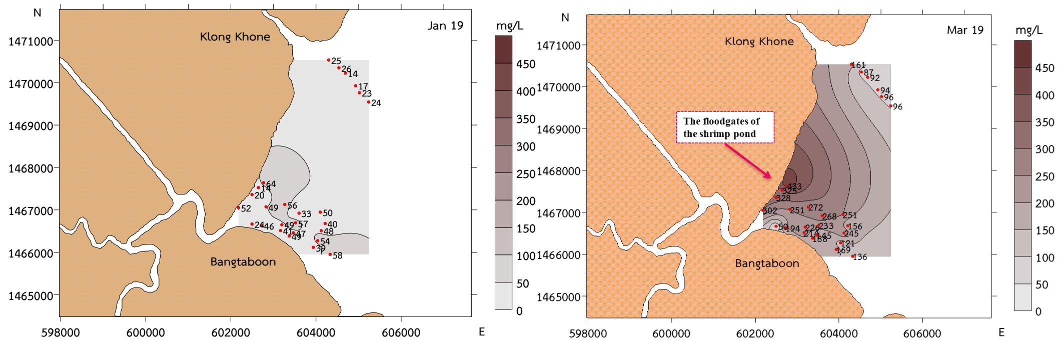

Figure 5. Distribution of TSS in January and March at the Klong Khone and Bang Taboon areas

die when TSS becomes higher than 300 mg/l [30, 32]. This may be the result of the suspended particles containing less than 10% organic matter, and this can lead to cockles dying from nutrient deficiency. Without sufficient nutrients, cockles will not grow well and will die eventually.

3.1.6 Ammonium-nitrogen (NH_4^+-N)

Ammonium level was found in an average of 0.38-8.16 μg-N/l throughout the study period. The highest ammonium level was measured in October during the wet season and the lowest one was found in February in the dry season, as shown in Table 1. Figure 6 shows that the distribution of ammonium values was high on the coast and gradually decreased further away from the coast. It can be explained that the source of ammonium in the study area may cause domestic wastewater discharges from the upper areas into the estuaries. October was the month of the highest value of ammonium-nitrogen. This may be related to the opening of floodgates at the time which caused a large amount of freshwater contaminated with the community waste to flow into the estuary area. The aftermath of this event had an adverse effect on cockle production because the largest cockle producers were located in this area. Furthermore, local cockle farmers have faced major economic difficulties due to tremendous losses in the cockle cultivation. Additionally, in the cultivation area, NH_4^+-N were found in the range of nd.-500 μg-N/l [17, 19-20, 22, 27]. Nevertheless, when ammonium concentrations were greater than 0.8 mg-N/l, it may lead to the death of cockles [33]. In order to prevent the loss of cockle resources, ammonium contamination in seawater should be monitored. As shown in Table 2, ammonium-nitrogen (NH_4^+-N) concentration is related to pH. If there is high pH, ammonium-nitrogen (NH_4^+-N) changes to ammonia-nitrogen (NH_3-N), which is toxic to aquatic life. On the other hand, if the pH is low, ammonia-nitrogen remains in its ionized form (NH_4^+-N) and is less toxic.

3.1.7 Nitrite-nitrogen (NO_2^--N)

As shown in Figure 7, nitrite was found to be at a high level in October (wet season). This result was in an agreement with the level of ammonium that was high in the same season. This may be the consequence of the river runoff which possibly contained nitrite pollution from community waste. Moreover, the high level of nitrite was found again in March, at which the increasing amount of nitrite may be contaminated with suspended solids in seawater. During that time, the contamination of the nitrite-nitrogen diffusion was similar to TSS (Figure 5). The results of the

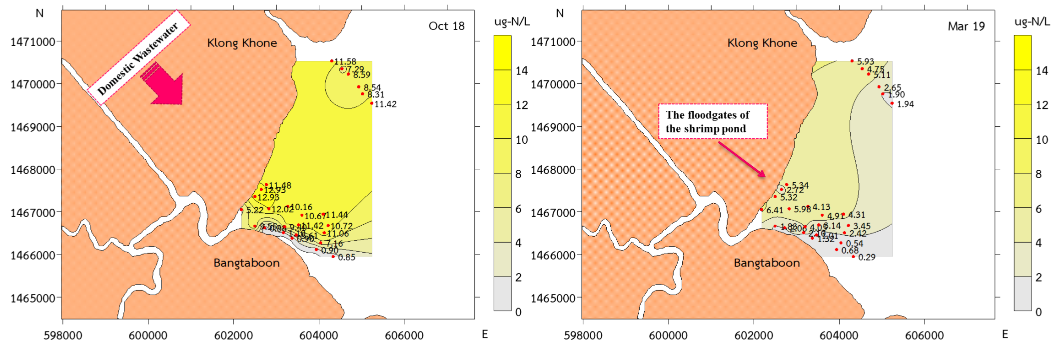

Figure 6. Distribution of NH_4^+-N in October and March at the Klong Khone and Bang Taboon areas

study were compared to the proportion of nitrite-nitrogen that was found in the cockle culture area. As a result, cockles in the Bang Taboon and Klong Khone areas are able to survive and grow up in this condition in which the amount of nitrite-nitrogen can frequently be found in natural cockle cultivation sites between nd.-30 μg-N/l, respectively [17, 19, 20, 22, 27].

3.1.8 Nitrate-nitrogen (NO_3^--N)

As shown in Figure 8, the distribution of nitrate was in the same direction as the levels of ammonium (Figure 6) and nitrite (Figure 7). The nitrate was found to be of a high level in October (wet season) and the main causative factor may be the discharge of domestic wastewater into the estuary. The result of the study showed that the level of nitrate in the Upper Gulf of Thailand did not meet the standard of seawater quality for aquaculture, which specifies that 60 μg-N/l or 0.06 mg-N/l should not be exceeded. However, the results showed that farmed cockles in the Bang Taboon and Klong Khone areas were able to survive and continue to grow under these conditions. This may indicate that nitrate in the area is still in an acceptable level for the cockle cultivating. Additionally, in natural habitats, the levels of nitrate found vary from 0.001 to 0.787 mg-N/l [17, 19, 20, 22, 27]. Therefore, even though the level of nitrate may be too high or not ideal for aquacultures, the cockles were still be capable of surviving in the high concentrations of nitrate.

3.1.9 Phosphate-phosphorus (PO_4^{3-}-P)

As shown in Figure 9, the result of phosphate-phosphorus distribution was in the same direction as those of TSS, ammonium, nitrite and nitrate. Moreover, phosphate-phosphorus was also found to be high in the month of October. As a result, phosphate-phosphorus levels in the Upper Gulf of Thailand did not meet the standard of seawater quality for aquaculture which specifies that the level of phosphate should be exceed 45 μg-P/l (0.045 mg-P/l). However, the cockles in these areas were still be able to survive even though natural cultured cockle lived in phosphate-phosphorus (PO_4^{3-}-P) concentrations of between 0.001-0.382 mg-P/l which is related to the results of previous studies [17, 19, 20, 22, 27]. This indicates that although the phosphate-phosphorus content in the study area was higher than the standard, the cockles were still be able to tolerate the high concentrations of phosphate.

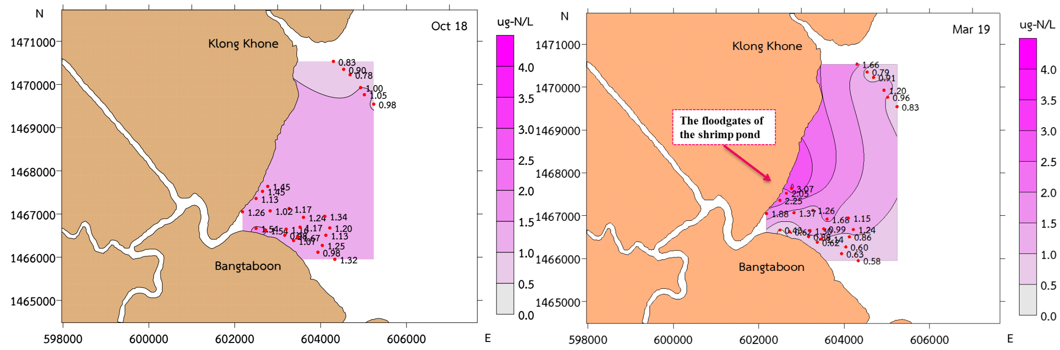

Figure 7. Distribution of NO_2^--N in October and March at the Klong Khone and Bang Taboon areas

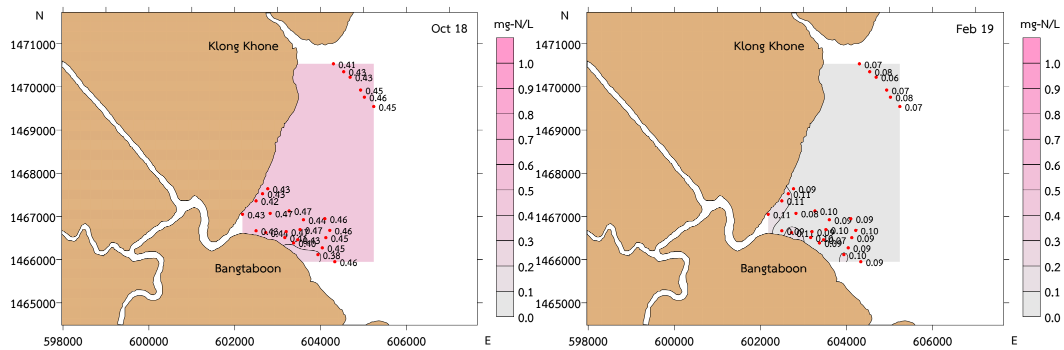

Figure 8. Distribution of NO_3^--N in October and March at the Klong Khone and Bang Taboon areas

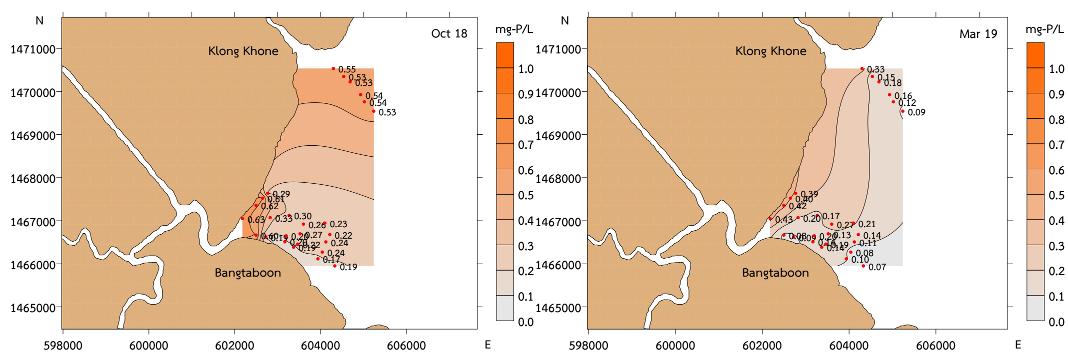

Figure 9. Distribution of PO_4^{3-}-P in October and March at the Klong Khone and Bang Taboon areas

3.1.10 Chlorophyll *a*

The value of chlorophyll *a* was found in an average of 9.19-21.92 µg-N/l throughout the study period, as shown in Table 1. Studies on the distribution of chlorophyll *a* are shown in Figure 10. There were similar values for chlorophyll *a* in Bang Taboon and Klong Khone. However, it was likely to be relatively high in November, and especially in the Klong Khone area where it was found to be higher than in the Bang Taboon area. It can be explained that the Klong Khone area tends to acquire more fertile food sources for the cockles than other areas during that period. Furthermore, when compared to the other cockle farm sites, Klong Khone and Bang Taboon cockles had higher amount of chlorophyll *a* than cultures from other places including the coast in Surat Thani province and Pattani Bay in Pattani province [21, 23]. The amount of chlorophyll *a* in the area was found in between 0-67 µg/l. The result clarified that the study area was suitable and advisable for cultivating cockles as there were sufficient food sources that could potentially benefit the growth of cockle production.

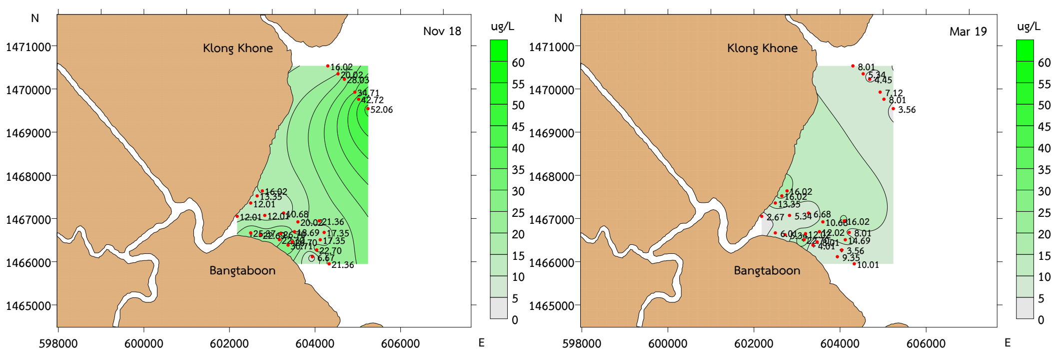

Figure 10. Distribution of chlorophyll *a* in November and March in the Klong Khone and Bang Taboon areas

3.2 Sediment quality

3.2.1 Grain size

The results of the grain size analysis that were investigated during the study period are demonstrated in Table 3. The statistical analysis revealed that there were significant differences among months for all sediment quality parameters (P-value <0.01), and that changes in season (or by month) influenced sediment quality changes. When considering the distribution characteristics of each size of sediment, it was found that in the Klong Khone area, the proportion of sediment size (<0.06 mm) was greater than in Bang Tabun area (Figure 11). It can be demonstrated that the characteristic of sediment in Klong Khone was more liquid and finer than in Bang Taboon. Additionally, from October 2018 to March 2019, the sediment that was smaller than 0.06 mm was found to have increased in proportion (Table 3). This was probably because October was in the wet season and influenced by monsoons. In this regard, it caused tremendous quantities of freshwater to flow into the estuarine zone. As a result, small sediments were dispersed in water masses. However, when the winter started (from November onwards) the monsoon began to decline, and then the particle of sediments floating in the water mass were gradually deposited as small sediment particles on the benthic zone. However, when the characteristic of sediments in Khong Khone and Bang Taboon

Table 3. Mean values of sediment quality at cockle culture area in the Upper Gulf of Thailand and P-values with $\alpha = 0.01$

Sediment quality factors	Sampling period (Mean ±SD) Oct	Nov	Dec	Jan	Feb	Mar	P-values
Salinity (psu)	4.58 ± 0.76	6.73 ± 1.25	11.27 ± 1.66	9.73 ± 1.34	12.10 ± 1.94	12.35 ± 2.10	<0.01
pH	6.49 ± 0.37	6.87 ± 0.56	7.04 ± 0.42	6.97 ± 0.35	7.17 ± 0.13	6.93 ± 0.35	<0.01
Grain size composition (%) 0.125-1 mm	38.91 ± 11.47	36.82 ± 7.09	29.00 ± 12.71	18.38 ± 6.71	15.93 ± 6.58	16.88 ± 8.46	<0.01
0.06-0.125 mm	12.76 ± 10.27	7.92 ± 6.18	9.23 ± 7.36	10.14 ± 8.56	12.16 ± 11.62	12.95 ± 11.98	<0.01
<0.06 mm	48.33 ± 14.62	55.27 ± 8.84	61.78 ± 14.90	71.48 ± 10.03	71.91 ± 13.39	70.18 ± 11.32	<0.01
WC (%)	68.93 ± 7.31	67.52 ± 7.09	69.14 ± 7.19	69.09 ± 7.96	67.32 ± 7.79	63.55 ± 11.05	<0.01
OM (%)	3.93 ± 0.57	4.26 ± 0.55	4.54 ± 0.81	4.21 ± 0.45	4.24 ± 0.52	4.36 ± 0.70	<0.01

Note: There is no sediment quality standards.

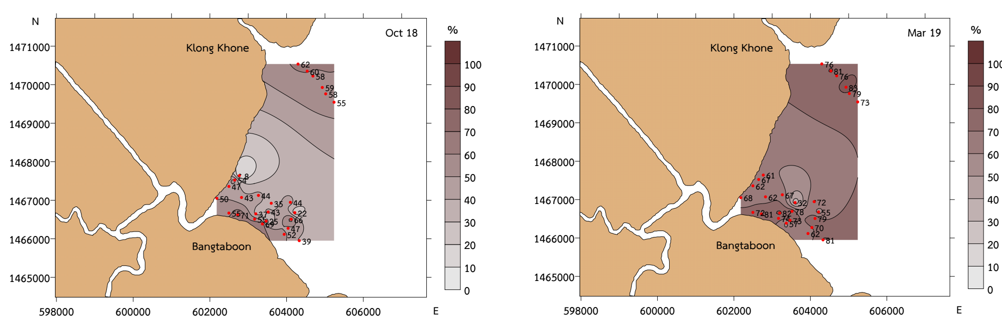

Figure 11. Distribution of grain size <0.06 mm in October and March in the Klong Khone and Bang Taboon areas

were compared to the other sites, it was found that the sediments studied appeared to be a clay texture of the same type found in the cockle farming areas in Khlong Taphar, Trang province [34]. Cockles are capable of living in various types of soil textures including silty clay loam in Ranong province, silty clay in Nakhon Si Thammarat province, loam in Ban Don Bay, Suratthani province, sandy loam in Samut Sakhon province, silt loam in Pattani bay, Pattani province and Sawi Bay, Chumphon province [17, 18, 20, 23, 35]. However, it is more likely to find high population cockle density in areas that have sediment particle sizes smaller than 0.06 mm or in areas in which the majority of the sediment is of clay texture. The reason for this is that clay has a fine texture and thus more surface area for nutrient cations to adhere to. Therefore, clay holds more nutrients than other soils and is most appropriate for cockle growth [36]. The correlation coefficient analysis revealed that sediment size (<0.06 mm) was related to sediment size (0.06-0.125 mm), sediment size (0.125-1 mm), salinity and organic matter (OM) with r_{xy} values of -0.48, -0.82, 0.50 and 0.40, respectively (Table 4). These results demonstrate that sediment size (<0.06 mm) tends to decrease when sediment size (0.06-0.125 mm) and (0.125-1 mm) are higher. On the other hand, the sediment size (<0.06 mm) tends to increase when salinity and OM increase. According to Sukudom *et al*. [37] reported that fine sediment particle size (<0.06 mm) had higher organic matter than the sandy soil which had larger particle size.

Table 4. Pearson correlation coefficients (r_{xy}) between the values of each parameter sampled at cockle culture area in the Upper Gulf of Thailand

	<0.06 mm	0.06-0.125 mm	0.125-1 mm	pH (soil)	Sal (psu)	WC (%)	OM (%)
<0.06 mm	1						
0.06-0.125 mm	-0.48	1					
0.125-1 mm	-0.82	0.01	1				
pH (soil)	0.20	0.08	-0.21	1			
Sal (psu)	0.50	-0.14	-0.39	0.28	1		
WC (%)	0.25	-0.69	0.04	-0.28	0.17	1	
OM (%)	0.40	-0.62	-0.07	0.09	0.36	0.65	1

3.2.2 pH of sediment

As shown in Table 3, the pH of sediment was found between 6.49-7.17 and the lowest value was measured in October. Moreover, during that time, the pH level was below 7 at every station. This indicated that the sediment during the wet season was slightly acidic. This may be because river runoff, in every October, caused huge quantities of freshwater discharged into the estuarine environments. Moreover, the opening of the floodgates caused the waste to flow down into the estuary making the sediment more acidic. The pH of sediment affects the diffusion of the aquatic organisms and the shell formation ability of mussels. If the sediment contains a low pH level (acidic), it causes a reduction of shell formation ability and diminishes the rate of degradation of living creatures [37]. As shown in Figure 12, the pH of sediment in Bang Taboon area was slightly more acidic than in the Klong Khone area. This was because in Bang Taboon, there was more organic matter accumulation from domestic waste pollution, and also because there was a higher density of cockle culture than in Klong Khone. For this reason, the accumulation of domestic waste increases microbial activity which leads to more acetic acid in the sediment causing a decrease of pH level and development of slightly acidity [17, 20, 38]. However, when the pH of sediment in the study area was compared with other sites, the pH value in the area was found to be slightly lower. According to previous studies on cockle farming in Ranong province, Nakhon Si Thammarat province, Suratthani province and Pattani province, the pH of sediments ranged from 7.00 to 8.33 [22, 23, 35]. This demonstrated that the study area may not be suitable for cultivating cockles in near future due to unfavorable pH level.

3.2.3 Salinity of sediment

In the Upper Gulf of Thailand, the salinity of sediment value was in the range of 4.58-12.35 psu throughout the study period, as shown in Table 3. The lowest salinity value was measured in October, and this may be because the study area was nearby the coast, closed to the Phetchaburi River outlet as well as that time was the wet season of the year. As shown in Figure 13, when considering the salinity distribution of sediment in the study area, it was found that the salinity of

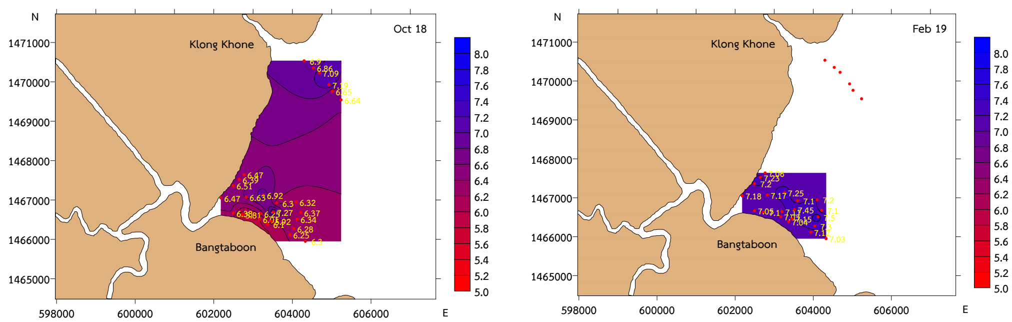

Figure 12. Distribution of pH of sediment in October and February in the Klong Khone and Bang Taboon areas

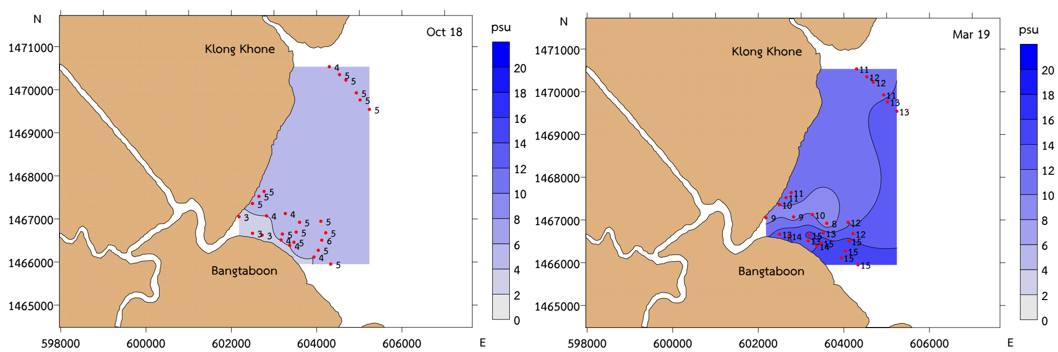

Figure 13. Distribution of salinity of sediment in October and March in the Klong Khone and Bang Taboon areas

sediment was low on the coast and gradually increased moving further away from the coast. Moreover, the salinity of sediment level increased over time from October 2018 (wet season) until March 2019 (dry season). Changes in the level of sediment salinity may be due to the influence of freshwater runoff from the river flowing into the estuarine zone. Contamination of freshwater in the estuarine area caused devaluation in the salinity of sediment. However, the salinity of the sediment in this study was similar to other cockle culture sites [22, 23, 35]. This shows that the salinity level of the sediment in these areas was in an appropriate range for the growth of cockles.

3.2.4 Water content (WC) of sediments

The water content value was found in an average of 63.55-69.14% throughout the study period, as shown in Table 3. The results for WC showed a similar trend to other factors in this study. The lowest water content was measured in March as it was the dry season, while the highest one was measured in October during the wet season. As shown in Figure 14, it was found that the channel area contained less water in the sediment than any other areas. This may be because of the intense power of the flowing water causing the soil in the area to become relatively dense. However, the water content of sediment found in this study was similar to other cockle culture areas in Surat Thani

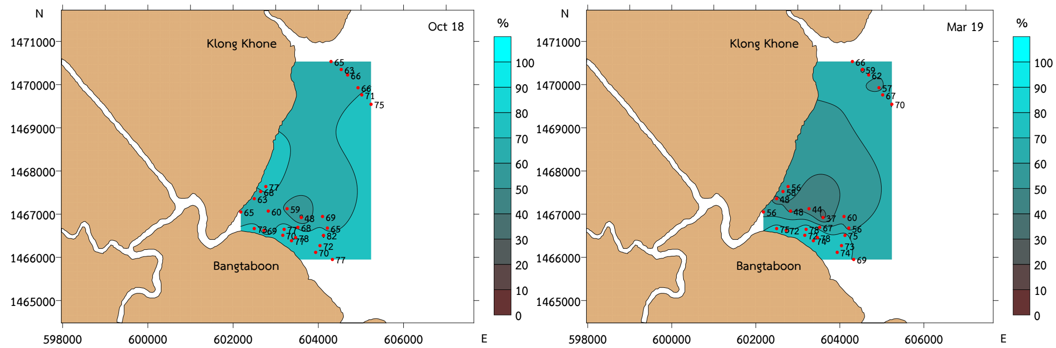

Figure 14. Distribution of WC in October and March in the Klong Khone and Bang Taboon areas

province and Chumphon province [18, 38]. It can be recognized that the water content of the sediment in the study area was in a satisfactory condition for the growth of cockles. Furthermore, as shown Table 4, it was found that the WC was related to organic matter (OM) with r_{xy} values of 0.65. These results demonstrate that the WC tends to increase when OM increases as the OM can help increase the water holding content of soils. According to Khaodon *et al*. [39], organic sediments are highly absorbent sediments that cause more gaps in the soil. Therefore, if there is a high amount of organic matter in the sediment, there will be high water content in the soil as well.

3.2.5 Organic matter (OM)

The organic matter value was found in an average of 3.93-4.54% throughout the study period, as shown in Table 3. The lowest OM was observed in October due to the area being nearby the channel zone and the mangrove forest. Considering the organic matter level in sediment which was conducted by the Department of Land Development [40], the organic content in sediment in this study was found to be moderately high and extremely high in the study area. However, when considering the organic matter distribution in sediment as in Figure 15, it appeared to be slightly different at each station (3.93-4.54%). The OM in the study area seemed to be relatively high when compared to the OM at other sites which included Samut Sakhon province, Surat Thani province, Pattani, Ranong and Nakhon Si Thammarat provinces. The value of organic matter in these areas varied in the range of 1.30 to 3.94% [17, 20, 23, 35]. This may indicate that the sediment in this study contains more organic matter than those mentioned above. This result corresponds to clay texture that increased the accumulation of organic matter in the sediment. It has caused the organic matter to degrade while acidity in sediment has increased. Previous studies suggests that these factors may cause a habitat of benthic fauna to occur, which in turn is an unsuitable condition for the thriving of any aquacultures [38, 41].

4. Conclusions

It can be concluded that the seawater quality in the Upper Gulf of Thailand did not meet the Standard Class 3 (seawater quality standard for aquaculture) for the seawater quality parameters of DO, nitrate-nitrogen (NO_3^--N) and phosphate-phosphorus (PO_4^{3-}-P). The DO values were found to be low, and the NO_3^--N and PO_4^{3-}-P values were high during the wet season. Moreover, low salinity,

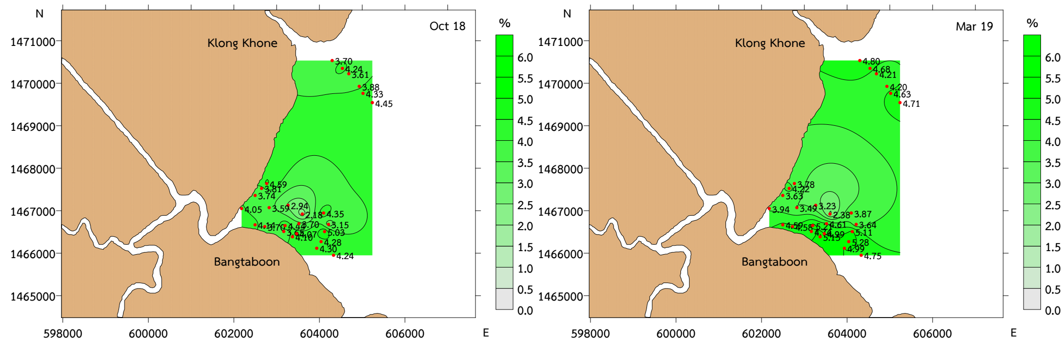

Figure 15. Distribution of OM in October and March in the Klong Khone and Bang Taboon areas

high temperature and high ammonium-nitrogen (NH_4^+-N) were also found in wet season. The analysis of sediment quality indicated that salinity, pH and organic matter (OM) were low during the wet season. Therefore, these parameters were factors that had potential negative influence on blood cockles, and especially in the wet season. In order to successfully raise new juvenile cockles, farmers should monitor water quality and continue to follow up on the results before and after cultivation. This will increase the chance of higher cockle survival rate. Moreover, farmers should learn how to monitor water quality during the wet season by observing the condition of water draining from the water gates before it flows down into the estuarine area. Such observation will help them to prevent these effects.

5. Acknowledgements

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